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Developing dimensional management for the assembly of aircraft structures

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DEVELOPING DIMENSIONAL MANAGEMENT FOR THE ASSEMBLY OF AIRCRAFT STRUCTURES.

by

DAVID JEFFREYS

A Doctoral Thesis
Submitted in partial fulfilment of the
requirement for the award of
Doctor of Philosophy
Loughborough University

Loughborough University
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November 2006

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To my wife Isabel and my two children Bethan and Thomas for their extended patience, love and support.

Abstract

This research is concerned with the discipline of dimensional management (DM) and it's potential for meeting the development and production needs of future aircraft structures. The premise is that next generation military and civil aircraft development may not take full advantage of an integrated approach to DM resulting in a disconnected approach and generating silos of activity In response, the aims of this research is to propose and develop a high level DM methodology to address aircraft structure variation management, develop and review variation analysis tools to be used in key stages of aircraft structure validation, design and conduct an experiment focusing on the effect of dimensional variability on the assembly of carbon fibre composite panels to aluminium substructures.

A literature review and an industrial study were undertaken This work highlights the need for a more structured and integrated approach to DM within the aerospace sector. Particular product and process attributes were identified and the effect of uncontrolled variation highlighted An industrial study of key US and European aerospace and automotive companies identified the nature of DM and a matrix of working practices and analysis techniques were established

The proposed physical architecture robustness engineering system (PARES) methodology has been developed in response. The key steps of the methodology have been defined and mapped onto a generic aerospace integrated development process. Based on the PARES framework, key architectural chunks have also been defined and mapped onto a software solution framework. A key activity of PARES includes the development of tolerance analysis tools and techniques at key development stages

The PARES methodology outlines the need for initial front loaded assembly analysis at the early stage of development before CAD geometry is available followed later by more detailed analysis based on 3D CAD geometry In response a parametric variation analysis (PVA) tool was designed and developed for early tolerance evaluation The one dimensional PVA tool demonstrates the opportunity for early tolerance design on a wing structure and how the analysis results identify the key objectives for down stream three dimensional geometric tolerance studies Three geometric variation analysis (GVA) case studies were conducted on an Airbus commercial aircraft wing box structure The case material evaluates wing box structure variation using a commercial three dimensional tolerance analysis software tool, VSA

The impact of advanced aircraft structure materials and their manufacturing process were investigated through a number of experiments based on the design, manufacture and assembly of composite panels to aluminium substructures Key characteristics associated with the production process of panel and substructure was physically and digitally modelled

The conclusions outline the case for the development of a DM methodology, supported by analysis tools and techniques, to be incorporated as part of the integrated product development process for aircraft structure development. The PVA tool will provide an evaluation of early design intent before major geometry design and assembly specification has been committed This front loaded analysis will help determine the key areas for further detailed study which will be performed by the GVA tool when 3D CAD, manufacturing, and assembly process have been defined Further work is identified addressing the opportunity to extend the DM methodology, to develop the capability and scope of the analysis tools and techniques, and to position and integrate these tools against existing engineering disciplines. One particular area identified for exploration is the integration of finite element and geometric dimensional variation modelling techniques This integration would present an opportunity to better evaluate the effect of conforming (flexible) parts and subassemblies as part of the digital mock-up activity

Table of contents

Title page
Declaration ii
Acknowledgements iii
Abstract iv
Table of Contents vi
List of figures x
Acronyms xii

1 Introduction 1

1.1 Background 1
1.2 Aims and objectives 4
1.3 A guide to the thesis and the research approach 4

2 Literature review 6

2.1 Manufacturing methodologies chronology 6
2.1.1 Systems engineering 9
2.1.1.1 Systems engineering definitions 10
2.1.1.2 Definition of a system 11
2.1.1.3 Systems versus component thinking 11
2.1.1.4 Systems engineering process 11
2.1.2 Concurrent engineering 13
2.1.3 Quality function deployment 16
2.1.4 Design for manufacture and assembly 18
2.1.5 Failure mode and effect analysis 19
2.1.6 Robust design and quality engineering 20
2.1.6.1 Robust design 20
2.1.6.2 Quality engineering 21
2.1.6.3 Statistical process control 22
2.2 Manufacturing organisational issues 22
2.2.1 Lean manufacturing 23
2.2.2 Integrated product and process development 24
2.2.3 Agile and flexible manufacturing 26
2.3 Development of aircraft structures 28
2.3.1 Materials in aircraft structures 29
2.3.2 Aircraft assembly technologies 31
2.4 Dimensional management discipline 31
2.4.1 Product features 34
2.4.2 Key characteristics 35
2.4.3 Tolerance specification 37
2.4.3.1 Tolerance standards 38
2.4.3.2 Tolerance specification 40
2.4.3.3 Tolerance analysis and synthesis 41
2.4.4 Computer aided tolerance software tools and process 42
2.5 Manufacturing methodology critique 43
2.5.1 DM critique 44
2.6 Concluding comments 45

3 Assessing current best practice in dimensional management 46

3.1 USA study tour of leading aerospace and automotive companies 46

3 1.1 Chrysler Corporation 47
3.1 2 Ford Motor Company 49
3.1.3 McDonnell Douglas Aerospace 51
3 1 4 Raytheon Aircraft 52
3.1.5 Northrop Grumman 53
3.1 6 The Boeing Company 55
3 2 Dimensional management within European aerospace companies 56
3.2.1 BAE SYSTEMS (1998) 56
3 2.2 Swedish Aeroplane AB (1997) 57
3.2.3 Airbus (1998) 58
3 3 Dimensional management case examples 58
3 4 Dimensioanl Management best practise critique 61
3 5 Concluding comments 62

4 The need for dimensional management 63

4 1 The need for a dimensional management methodology 63
4 2 Manufacturing challenges for future aircraft 64
4 2 1 Military fixed-wing aircraft 65
4 2.2 Commercial fixed-wing aircraft 68
4.3 Supporting activities/techniques to aid the DM Process 69

5 Physical architecture robustness engineering system (PARES) 73

5.1 The PARES scope 73
5.2 PARES methodology process, tools and techniques 74
5.3 Methodology architecture 82
5 4 PARES benefits 86

6 Development of a parametric variation analysis (PVA) tool for wing box assembly 88

6.1 PVA tool development background 88
6 2 Requirements specification and scope 90
6 3 Design and development methodology 91
6 4 PVA tool functional overview 92
6 4 1 Analysis configuration 93
6 4 2 Parameter feature definition 94
6 4 3 Tolerance specification 94
6 4 4 Simulation parameter definition 95
6 4 5 Analysis output 97
6 4 6 Knowledge capture 99
6 5 Evaluation of the PVA tool 99
6 6 Benefits and limitations of the PVA tool 103
6.7 Further development work 104
6 8 Concluding remarks 105

7 Geometric variation analysis (GVA) on proposed Airbus wing box assembly 106

7 1 Background to Airbus A3XX case studies 106
7 2 Case study analysis methodology 107
7 3 Dimensional analysis for rib to complex skin assembly 108
7 3 1 Analysis aims 108
7 3 2 Analysis objectives 109
7 3 3 List assumptions 110
7 3 4 Design of assembly components and fixture 110
7 3 5 Identify key features and tolerances 111
7.3.6 Create CAD assembly model 115
7 3.7 Define assembly sequence 115
7.3.8 Identify assembly moves 115

7.3 9 Define analysis measurements .116
7 3 10 Perform assembly simulations. .117
7.3 11 Simulation results and analysis conclusions .117
7 4 Dimensional analysis for simple rib to skin assembly 118
7.4 1 Analysis aims 118
7 4 2 Analysis objectives. 118
7 4 3 Define assembly sequence 119
7 4 4 Simulation results and analysis conclusions 119
7 5 Dimensional analysis for C spar equipping assembly 120
7 5 1 Analysis aim 120
7 5 2 Analysis objectives 120
7 5.3 Define assembly sequence 121
7 5.4 Simulation results and analysis conclusions 122
7 6 Overall conclusions .122

8 Assembly of carbon fibre composite panels to aluminium substructures .124

8 1 Aims of the experiment .124
8 2 Objectives of the experimentation. .125
8 3 Design of the experiment 126
8 4 Design of panel and substructure .127
8 5 Identification of materials and manufacturing process 128
8 5 1 CFC panel manufacturing process 129
8 5 2 Aluminium substructure manufacturing process. 130
8.6 Design of the assembly process 131
8.7 Determination of assembly key characteristics 132
8 8 Determination of component design tolerances 135
8 9 Identify quality measures for investigation 138
8 10 Design of inspection methods .139
8 10.1 Controlled environment inspection methods .140
8.10 1.1 Surface profile error 140
8 10 1.2 Step and gap error 140
8 10 1.3 Virtual hole condition error 141
8 10.1 4 Multiple temperature environment inspection method 142
8 10.1.5 CMM inspection using VALISYS V5 3 1 software 143
8.11 VSA tolerance analysis .144
8.12 Experimental results .145
8 12.1 Geometric surface form error of panels and substructure. .145
8.13 Step and gap inspection results 150
8 14 Hole condition of panels and substructure 155
8.15 Assembly dowel pin inspection results .160
8.15 1 Multiple temperature environment inspection results 163
8 16 VSA tolerance analysis results 167
8.16 1 Analysis objectives. .167
8.16 2 Modelling assumption .168
8.16 3 Assembly simulation .168
8.16 4 Component datum and tolerance .168
8 16 5 Analysis measurements 169
8.16 6 Analysis results .170
8.17 Experiment discussion 171
8.18 Concluding remarks. 175

9 Discussion .177

9 1 Review of dimensional management .177
9 2 The need and nature of dimensional management .178
9 3 PARES; proposed methodology 179

9 4 Development of a PVA assembly analysis tool 181
9 5 Case study for GVA assembly analysis tool 182
9 6 CFC panel to Aluminium substructure experiment 183

10 Conclusions and further work 185

10 1 Conclusions 185
10 1 1 The need and nature of dimensional management 186
10 1.2 Proposed dimensional management methodology, PARES 187
10 1 3 PVA tool development for early wing box analysis 188
10 1.4 GVA case studies on wing box structure 190
10 1.5 CFC panel to aluminium substructure experimentation 191
10 2 Further work 192
10 2.1 DM methodology and process 192
10 2 2 DM tools and techniques 193
10 2 3 DM experimentation 194

References 195

Appendices 203

1 Tools and techniques for SPC 204
2 Computer aided tolerancing (CAT) software tools and process 208
3 Analysing tolerance accumulation 222
4 A dimensional control methodology for the variation analysis of aircraft structure assembly (Publication by author) 225
5 Dimensional control as an integral part of next generation aircraft development (Publication by author) 232
6 Stage I – VSA panel to substructure tolerance analysis results 239
7 VSA process reports 245
8 Different methods of constructing tolerance zones in CAD systems 249
9 Wing Box Assembly Analysis Tool – User manual 252
10 Publication Review, Tolerance design A handbook for developing optimal specifications 257
11 Stage I - Valisys measurement report 258

List of figures

Figure 1 Systems engineering process overview (IEEE 1995) 12
Figure 2 Sequential versus concurrent engineering methods (Prasad 1996) 14
Figure 3 Lean and integrated system (LIS) concept (Rossetto and Franceschini 1995)..... 15
Figure 4 Common CE tools for product development (Syan and Menon 1994)..... 16
Figure 5 House of quality matrix schematic (Syan and Menon 1994) 17
Figure 6. The HOQ matrix cascade (Molloy, Tilley and Warmain 1998) 17
Figure 7. An example FMEA rating chart (Fox 1993) 19
Figure 8 The quadratic loss function (Taguchi 1993)..... 21
Figure 9. High level IPPD process (JGA, Inc 1999)..... 25
Figure 10 Classification of different flexibilities (Raouf and Anjum1995) 27
Figure 11 Case examples of DM in the aerospace industry 59
Figure 12 Case examples of DM in the automotive industry 59
Figure 13 Advanced lightweight aircraft fuselage structure (ALAFS 1997) 67
Figure 14 PARES high level DM program 74
Figure 15 IPD/DM team allocation against generic airframe zones 75
Figure 16 PVA tool interface 76
Figure 17 Feature specification taxonomy..... 76
Figure 18 KC assembly flow through 77
Figure 19 PKC variation outputs..... 78
Figure 20 Component SPC database including Cp and Cpk 79
Figure 21 Post FAI SPC data definition and collection..... 81
Figure 22 PARES top level architecture chunks 82
Figure 23. Overall IDEF0 representation of the PARES process 85
Figure 24 First level IDEF0 represenation of the PARES process..... 86
Figure 25. Example wing box structure with top skin removed, courtesy of Airbus 89
Figure 26 Components within the generic wing box 91
Figure 27 PVA process 92
Figure 28. Wing box assembly process defined for this analysis 94
Figure 29 Data driver table, D nose to front spar assembly example 95
Figure 30 Example frequency chart for D nose 98
Figure 31. Example sensitivity chart for D nose 98
Figure 32. Example statistical chart for D nose 99
Figure 33. Simple 4 part assembly 100
Figure 34. VisVSA process report..... 100
Figure 35. VisVSA contributor chart 101
Figure 36. VisVSA statistics table 101
Figure 37. PVA process chart 101
Figure 38 PVA sensitivity chart 102
Figure 39 Statistical chart 102
Figure 40 Contributor report comparison 103
Figure 41 Example wing box assembly with D nose and A frame, courtesy of Airbus 107
Figure 42 Rib, complex lower skin and assembly fixture 108
Figure 43. Complex rib (dark shaded) to lower skin in generic wing box..... 109
Figure 44. Rib design schematic 110
Figure 45. Fixture design schematic 111
Figure 46. Rib critical features and tolerances schematic..... 112
Figure 47. Complex skin critical features and tolerances schematic 112
Figure 48. Fixture critical features and tolerances schematic 114
Figure 49. Assembly sequence diagram 115
Figure 50 Measurement strategy for gap condition 117
Figure 51. Assembly sequence diagram 119
Figure 52. Measurement points for C spar equipping 121

Figure 53 Assembly sequence diagram 121
Figure 54 Panel and substructure design – Stage I. 128
Figure 55 Panel and substructure design - Stage II 128
Figure 56 Lay-up and cure tooling plates - Stage I and satge II CFC panels. 129
Figure 57 Sabre 400H and Wadkin V4-6 machine centres 131
Figure 58 Panel critical features – Stage I. 133
Figure 59. Substructure critical features – Stage I 134
Figure 60. Panel critical features – Stage II 134
Figure 61 Substructure critical features – Stage II 135
Figure 62 Feature tolerance sepecification for stage I and stage II. 138
Figure 63 The VALISYS procedure 143
Figure 64 Stage I – panel 1 and panel 2 form error. 145
Figure 65 Stage I - Talysurf Series II waviness inspection results. 146
Figure 66 Stage I - panel 1 and panel 2 thickness inspection results 147
Figure 67 Stage II - panel 1 and panel 2 thickness inspection results 147
Figure 68 Stage I - panel 1 and panel 2 form inspection results 148
Figure 69 Stage I - substructure form inspection results 149
Figure 70 Stage I - panel 1, panel 2, and substructure form inspection results. 150
Figure 71 Stage I - panel 1 step condition inspection results 151
Figure 72 Stage II - panel 1 step condition inspection results 151
Figure 73 Stage II - panel 2 step condition inspection results. 152
Figure 74 Stage I - panel 1 gap condition inspection results 153
Figure 75 Stage I - panel 2 to substructure gap condition inspection results. 153
Figure 76 Stage II – panel 1 to substructure gap inspection results 154
Figure 77 Stage II – panel 2 to substructure gap inspection results 154
Figure 78 Stage I – panel 1, panel 2, and substructure hole form inspection results 155
Figure 79 Stage II – panel 1, panel 2, and substructure hole form inspection results 156
Figure 80 Stage I - panel 1 hole pitch deviation inspection results 157
Figure 81 Stage I - panel 2 hole pitch deviation inspection results 157
Figure 82 Stage I - substructure hole pitch deviation inspection results 158
Figure 83 Stage II - substructure hole pitch deviation inspection results 158
Figure 84 Stage II – panel 1 hole pitch deviation inspection results 158
Figure 85 Stage II – panel 2 hole pitch deviation inspection results 159
Figure 86 Stage I – panel 1, panel 2, and substructure hole diameter inspection results 159
Figure 87 Stage II – panel 1, panel 2, and substructure hole diameter inspection results 160
Figure 88 Dowel pin inspection results. 160
Figure 89 Stage I – panel 1 to substructure gap inspection condition. 161
Figure 90 Stage I – panel 1 to substructure step condition inspection results 162
Figure 91 Stage I – panel 2 to substructure gap inspection results 162
Figure 92 Stage I – panel 1 to substructure step condition results at different temperature 163
Figure 93 Stage I – panel 1 to substructure gap condition results at different temperature. 164
Figure 94 Stage I – panel 1 and panel 2 perpendicularity inspection results. 164
Figure 95 Stage I – substructure linear inspection results. 165
Figure 96 Stage I – substructure perpendicularity inspection results 165
Figure 97 Stage I - panel 1 hole diameter error at different temperature 165
Figure 98 Stage I - substructure hole diameter error at different temperature 166
Figure 99 Stage I – panel to substructure pin assembly condition at different temp 166
Figure 100. Substructure datum and tolerance 168
Figure 101 Panel datum and tolerance. 169
Figure 102 Pin datum and tolerance 169
Figure 103. Step, gap, and virtual hole conditions to be measured. 170
Figure 104. Gap condition at location plane 4 substructure 170
Figure 105 Step condition at location plane 4 substructure. 171
Figure 106. Hole 2 virtual hole condition. 171

Acronyms

A3XX	Airbus future commercial large aircraft
AMT	Advanced manufacturing technology
Al	Aluminium
ADCATS	Association for the Development of Computer Aided Tolerancing
AKC	Assembly process key characteristic
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
AVA	Assembly variation analysis
BS	British Standard
BIW	Body-in-white
BoM	Bill of materials
CAD	Computer aided design
CAE	Computer aided engineering
CAM	Computer aided manufacturing
CAT	Computer aided tolerancing
CE	Concurrent engineering
CEM	Complex electro mechanical
CFC	Carbon fibre composite
CIM	Computer integrated manufacturing
CIRP	International Institution for Production Engineering Research
CMM	Coordinate measuring machine
CNC	Computer numerical control
CPL	Computer profile line
DC	Dimensional control
DCS	Dimensional control systems
DDC	Design for dimensional control
DFA	Design for assembly
DFM	Design for manufacture
DFMA	Design for manufacture and assembly
DFV	Design for variation
DM	Dimensional management
DMU	Digital mock-up
DOD	Department Of Defence

DOF	Degrees of freedom
DSA	Danish Standards Association
FD&T	Functional design and tolerancing
FEA	Finite element analysis
FMEA	Failure mode effects and criticality analysis
FMECA	Failure mode and effect critical analysis
FMS	Flexible manufacturing systems
GD&T	Geometric dimensioning and tolerancing
GM	General Motors
GPS	Geometric product specification
GRP	Glass reinforced plastic
GVA	Geometric variation analysis
HOQ	House of quality
ICAF	Industrial College for the Armed Forces
ICY	Interchangeability
ILS	Integrated system support
IML	Inside mould line
IPD	Integrated product design
IPT	Integrated product team
IPPD	Integrated product and process development
ISO	International standards organisation
JGA	James Gregory Associates
JIT	Just-in-time
JSF	Joint strike fighter
KC	Key characteristic
LAI	Lean aircraft initiative
LEM	Lean enterprise model
LIS	Lean and integrated system
LOF	Line of flight
MTG	Master tooling gauge
MKC	Manufacturing process key characteristic
NC	Numerical control
NGMS	Next generation manufacturing system
OML	Outside mould line
PARES	Physical architecture robustness engineering system
PD&T	Parametric dimensioning and tolerancing
PDM	Product data management

PDP	Product development process
PKC	Product key characteristic
PLM	Product lifecycle management
PVA	Parametric variation analysis
RCS	Radar cross section
RMS	Root mean square
RSS	Root sum square
SE	Systems engineering
SPC	Statistical process control
StatKC	Statistical key characteristics
STEP	STandard for the Exchange of Product information
Ti	Titanium
TPS	Toyota production system
QAP	Quality assurance program
QE	Quality engineering
QFD	Quality function deployment
UGS	Unigraphics Solutions
VM	Variation management
VR	Variation reduction
VPM	Virtual product manager
VSA	Variation systems analysis
WC	Worst case
WIP	Work in progress

Chapter 1

1 Introduction

Objectives: This chapter will provide:

- A background to the work addressed in this thesis
- The aims and objectives of the thesis.
- A guide to the research approach and the structure of the thesis

1.1 Background

The discipline of dimensional management (DM) was conceived within the automotive industry in order to better manage the effects of variation during design, manufacture and assembly (Leaney and Marshall 2001) through the use of various tools and techniques The main driver for the implementation of DM is a right-first-time assembly of vehicles from parts that vary in size One of the key areas for analysis has been the vehicle structure known in the automotive industry as the body-in-white (BIW) More recently, dimensional analysis has been extended to other areas of the vehicle including drive train, interior and exterior trim, and suspension. From its automotive origins, DM has continued to gain momentum in supporting the concurrent engineering activity and has been adopted by a number of product sectors including electrical white goods, military vehicles, medical devices, and heavy plant equipment.

Recently, the aerospace sector has begun to review and adopt some of the DM techniques in support of aerostructure design and development. Both the commercial and military aircraft sectors of the aerospace industry are facing extensive competition from a rapidly emerging global market when attempting to win new and ongoing business contracts (Shumaker and Thomas 1998, Marguet and Mathieu 1997) This has resulted in organisations merging into large aerospace conglomerates extending their technical capability, their economy of scale efficiency and their business market share potential An example of this activity has been the amalgamation of Boeing and McDonnell Douglas creating a substantial company with a considerable share of the market (Bradley and Pirie 1997) Despite these advantages aerospace manufacturing organisations have recognized the need to increase engineering efficiency in their current and future working practices. This has been achieved in part through the adoption of a number of mature automotive

best practice techniques such as concurrent engineering, just-in-time and lean production. Some of the core objectives for these initiatives with respect to the aerospace industry are

- Reduction in aircraft development and production lead-times
- Minimize aircraft development and production costs
- Develop business practices that are more agile to market demands
- Improvements in design to reduce aircraft ownership costs.
- Organisation wide product and process quality improvement.

In response, some major aerospace companies have recognised the success of DM in the automotive industries to meet these objectives and achieve right-first-time assemblies. They have introduced a DM process to support aircraft development programs, BAE SYSTEMS on the Eurofighter Typhoon for example (Barrow 1997)

Whilst it is possible to apply the same technologies developed for the analysis of BIW structures as a means of DM for the assembly of aircraft structures fundamentally there are two major differences in the two industries that have to be considered: (1) The automobile industry is high volume and the aerospace industry is by comparison low volume; (2) The trend in aerospace is for reduced part-counts achieved through wider introduction of large structural parts moulded from composite materials. Consequently the aim of DM in the automotive sector is rapid production at low cost (usually by automation) whereas in the aerospace sector it is the production of high value products to a considerably greater degree of precision. In addition, due to the high cost of aircraft parts customers are requiring interchangeability of structural parts placing a greater demand on DM in aerospace that does not exist in the automobile sector

Dimensional variation exists in all aircraft physical architecture hardware (manufactured components, subassemblies, assemblies) and cannot be eliminated It is inherited from design, manufacturing, assembly and the inspection processes (Craig 1992). Management of variation is achieved through the specification of tolerance to nominal dimensions of size and form. An important part of the design process should be the determination of nominal dimensions and the application of an effective tolerance type and metric These need to be administered such that each individual component within a structure will meet the overall performance intent of the design Many of these issues are covered by 'blanket' company standards for the specification of component tolerance which are then left to various interpretations by the down stream activities of manufacturing, tooling, assembly and inspection The end result is shop floor assembly fitters 'adjusting' out variation problems where ever possible, leading to wasted time and money, as well as compromised product quality

This practice is possible where primary and secondary aircraft structures are manufactured predominantly from aluminium materials However, the next generation of commercial and military aircraft programs are incorporating more advanced materials and associated manufacturing processes such as carbon fibre composites for example A characteristic of this new material is its ability to demonstrate a level of geometric instability resulting from a complex manufacturing process In addition, due to their inherent properties these new materials will not be sympathetic to traditional assembly 'adjustment' techniques These issues coupled with the demand for higher interchangeability and maintenance specifications will require marked improvements in component, subassembly and assembly dimensional quality management. These improvements will best be achieved through the deployment of a concurrent and integrated DM methodology

This thesis is concerned with the development of methodology for DM in the concurrent design for manufacture and assembly of aircraft structures High-level methodologies exist in the automotive sector but such a methodology does not yet exist for the requirements of the aerospace sector It will investigate the potential of DM in meeting the design, manufacturing and assembly needs for the successful development and productionisation of robust aircraft structures Both the automotive and aerospace industry sectors will be reviewed to identify key DM elements and their effect on product development The opportunity is to be explored by proposing a DM methodology which begins at the early stages of design and continues through to series production. The methodology will be supported through the design and development of a parametric variation analysis tools designed to validate aerostructure design for manufacture and assembly at the early stage of design In addition, an experiment focusing on the effect of dimensional variability on the assembly of carbon fibre composite panels to aluminium substructures will be undertaken to identify the key issues associated with the use of new materials and manufacturing processes proposed for future aircraft structures.

This research work has two hypotheses:

i. An extended DM methodology for aerospace assembly manufacture will provide significant advantage to support a systematic approach for management of complex aircraft structures
ii. A DM methodology can be enhanced through the use of supporting software tools and techniques

1.2 Aims and objectives

The aims of the research are

i To investigate the use of a DM methodology to support the manufacture and assembly of complex aerospace structures
ii To explore the use of software tools to realise the DM methodology and illustrate its application.

The major objectives of the work are·

- Propose, develop, compare and test a high level DM methodology to support the development of aircraft structures.
- Design, develop, and test a 1D parametric variation analysis tool tailored to be used during the early stages of product design to aid the allocation of tolerance metrics in aircraft wing structure manufacture and assembly Undertake a number of geometric variation analysis case studies on aircraft wing assemblies using a commercial 3D tolerance analysis software tool based on digital geometry
- Undertake an experimental investigation into the fundamental nature of dimensional variation on the assembly of CFC panels to aluminium structures of planar and cylindrical geometric form

1.3 A guide to the thesis and the research approach

The nature of variation makes any DM discipline both complex and diverse It encroaches upon, and can naturally be integrated with, a number of formal manufacturing techniques ranging from quality function deployment at the early stage of design right through to statistical process control at aircraft series production Much of the work in this thesis has been formed through extensive involvement with the aerospace industry and is reflected in the research approach The approach consists of:

Literature review: Identify past, current and planned areas of work being undertaken in the area of DM relating to aircraft structure development The boundary limits of DM may also be defined with respect to the thesis

Dimensional management best practice bench marking: A number of automotive and aerospace companies in the USA who were perceived as being leading participants of DM were visited and bench marked Organisations were tested for DM implementation and scope.

Assessing the need for dimensional management: Based on the findings from academic review and industrial current best practise, the need for DM to form part of an integral aircraft structure development program is investigated

Methodology and variation analysis tools development: Design and development of a methodology and supporting variation analysis tools to suite the particular needs of the aerospace industry

Industrial case studies: An industrial placement and a number of industrial based case studies have provided evidence for the need for a structured and comprehensive approach to the DM discipline for aircraft structure analysis The aerostructure case study information feedback has also provided an opportunity to influence the DM related practices within the aerospace industrial organisations

Experimentation to investigate the assembly of carbon fibre composite panels to aluminium substructures: Conduct experimentation to highlight issues resulting from the assembly of carbon fibre composite panels to aluminium substructures, a particular characteristic of some future aerostructure designs. The investigation will include the effect of temperature change on both materials and their resultant assembleability

The thesis has been structured to reflect the approach taken above In the following section the literature review provides a background to the commercial and military aircraft industry, identifying manufacturing methodology and organisational issues, and providing an overview of the DM discipline

Chapter 2

2 Literature review

Objectives: This chapter reviews the literature in the domain relating to DM within the context of aerospace and automotive design for manufacture The review includes

- Manufacturing methodologies chronology
- Manufacturing organisational issues
- DM discipline

The aims of this thesis to develop a high level DM methodology and associated analysis tools to support the development of aerostructures To first understand what is required a review of current manufacturing methodologies and their background is presented in the following sections

2.1 Manufacturing methodologies chronology

Between the 1950's and the 1970's, military aerospace organisations based within Europe and the US have traditionally had one customer, this being their own respective governments (Bradley and Pirie 1997) Conversely, the governments of the day traditionally only considered one supplier which was their domestic aerospace industry This mutual monopolistic situation resulted in little incentive amongst the aerospace companies to improve business efficiency and reduce military aircraft development and production costs

During the 1980's the end of the cold war and a down turn in the world economy signalled a change within the aerospace manufacturing sector. In order to reduce defence expenditure, western governments started to look outside their domestic industry. Aerospace sector manufacturing organisations now had to respond to the threat of global market competition. This threat, coupled with increasingly aggressive product demands, triggered a number of aerospace development and production initiatives. As a result, manufacturing process technology began to increase in complexity across manufacturing industry (Leaney and Marshall 2001)

In the early 1970's design for manufacture (DFM) and design for assembly (DFA) became drawn to the forefront of manufacturing (Leaney and Wittenberg 1992). The techniques emerged in

order to address the trend towards the automation of small complex products requiring manual assembly As concepts such as flexible manufacturing systems, flexible manufacturing technology grew and with the impending integration of robotic assembly the interest in design for manufacturing and assembly (DFMA) increased It became clear that the assembly design philosophy of the day would not transfer well into an automated situation and a new design for assembly (DFA) technique would be a way of addressing this As DFA became more accepted, several techniques were developed of which the best known are:

i Assembly evaluation method (AEM), by Hitachi.

ii Boothroyd method, by Prof G Boothroyd and Dr. Dewhurst (Boothroyd, Dewhurst and Knight 1994).

iii. Lucas method, by the Lucas organization and the University of Hull

Circa 1978-1983 concepts of large scale flexible automation began to dominate future manufacturing strategies This directly led to philosophies such advanced manufacturing technology (AMT) and flexible manufacturing systems (FMS) The impending drive for flexible automation led to research into the use of robotics as a resource for the cheap and reliable assembly and manufacturing of products During the later part of this period it was realized that this scenario would never be realized on the scale first suggested mostly due to the limitation of robotics intelligence systems The declining trend towards AMS and FMS was also due to the introduction of Toyotas Just-In-Time (JIT) philosophy. The JIT approach paved the way for 'lean' production which encouraged the identification and reduction of non-value adding entities such as material storage, excessive work-in-progress (WIP), product scrap and rework (Womack, Jones and Roos 1990) The emphasis was to reduce all manufacturing buffer levels to a minimum in order that quality related defects would become more visible. This could only be achieved through improvements in batch set up and changeover performance which in turn would improve manufacturing flexibility (McIntosh, Culley, Mileham and Owen 2001) To reduce buffer stocks and to ensure limited manufacturing disruption, the need for process management became apparent and this became addressed by statistical process control (SPC).

The technique of DFMA, FMA, and AMT began to highlight the potential of considering the design, manufacturing and assembly processes simultaneously at the early stage of product development. This led to the development of simultaneous engineering which developed further into what has become to be known as concurrent engineering Concurrent engineering (CE) was seen as a key to achieving competitive advantage through the development of high-quality, highly functional products produced efficiently through the synergy of integrated product and process design, while also considering multiple life cycle factors such as functionality, serviceability,

manufacturability, marketability and recyclability (Molina *et al* 1995). CE focused on the needs of corporate structure and encouraged the business enterprise to dissolve departmental boundaries allowing greater cross functional communication

The CE paradigm considered product development through the integration of technological based computer tools such as computer aided design (CAD, computer aided manufacture (CAM), computer aided production planning (CAPP), and computer aided analysis (CAE), (Bedworth, Henderson and Wolfe 1991) These elements help generate the framework for a number of enterprise modelling techniques and their fusion into a central database is perceived to be the key to successful computer integration. This vision has mostly been pictured as computer integrated manufacturing (CIM) As computer and software technology develops and integrates with manufacturing methodologies, increasingly the industry finds itself designing, developing and testing products in a 'virtual' environment One of the fundamental problems of virtual product development is their current inability to address some real life problems, for example dimensional variation related issues Generally, design organisations only validate their work in a nominal (perfect geometric form) condition with little consideration given to the many sources of manufacturing and assembly variations acting on that nominal A developing technique designed to address this issue is DM A number of DM software tools have been developed within the CAE domain for a variety of analysis including tolerance and datum reference evaluation on product and process, assembly sequencing and constraint methodology, and quality standards validation, predicted aerostructure external step and gap dimensional variation (Whitney 2003).

Concurrent philosophies led the move towards an integrated product team (IPT) orientated approach to product development and integrated product design (IPD) techniques began to emerge IPD concepts, also known as integrated product and process development (IPPD), were driven out of complex product development and first emerged in establishments providing products to military based customers in the USA (Shumaker and Thomas 1998) Currently the Defence Advanced Research Projects Agency (DARPA) is developing the rapid design exploration and optimization (RaDeo) program, (formally MADE), (Whitney 1997) This program will focus on problems of design and manufacture of complex electro-mechanical (CEM) items, an area that does not have a single technical focus or well developed engineering models according to Whitney (1997) CEM products, such as military aircraft, are traditionally developed via a systems engineering (SE) approach where components and systems are designed together SE methodology requires a product realization process from a systems-orientated approach as opposed to a component-orientated problem (Prasad 1996) The approach relies on the decomposition and classification of the product in order to identify stakeholders within an organisation who become responsible for each product development section. The SE approach

exploits a transformation system for product realization design. The aim of the transformation strategy is to uncouple the system into mutually separable transformation states so each only affects only one set of outputs, based on Suh's first axiom (Suh 1990) Each state is then modelled and reconstructed to give a systems definition from the aggregation of the definitions of its constituent states.

Other less known methodologies that have emerged recently are·

Conformability analysis a knowledge based design technique for the prediction of variability risks in component manufacture and assembly (Batchelor and Swift 1996).
Corrective action a response to problems encountered by manufacturing firms during fabrication and assembly of the product, such as assembly of mechanical structures like automobiles and aircraft (Cunningham 1997).

A number of aerospace manufacturing methodologies have matured and currently play a major role in engineering two of which have already been identified as SE and CE These methodologies are reviewed in more detail in the next section

2.1.1 Systems engineering

The concept of SE is not a new one. A number of books have referenced the concept back to as far as the Second World War (Chase 1974; Goode and Machol 1959) In its original form SE tended to be used by mathematicians, electrical and aerospace engineers, and other scientific disciplines in order to define, analyse and manage complex problems Over the years manufacturing engineering organisations have adopted the SE concept in various different forms This has commonly occurred in organisations manufacturing CEM product types associated with high complexity, cost of manufacture, and high risk. The aerospace industry is a good example of this (Loureiro 1999) Organisations realised that to manage the development of CEM products they needed to integrate product development teams Methods of CE have focused on simultaneously solving expensive design changes some way down the development cycle but falls short in its ability to framework manage all aspects of complex design and development SE is designed to integrate with the CE methodology through a multidiscipline approach to the definition, analysis and verification of a product design and development

In order to clarify and introduce consistency to the SE concept in 1990 the international council on systems engineering (INCOSE) was formed The main objective of INCOSE is to develop a better understanding of SE through improved definition and clarification of concepts and

techniques Their work partly continues through an annual symposium held at different locations around the world There are currently two main standards which describe a process for engineering a system The first is a US national standard EIA 632 developed by the electronic industries association (EIA 1997) and the second is IEEE 1220 developed by the institute of electronic and electrical engineer (IEEE 1995). More recently the EIA/IS 731 have been developed and are available in the public domain Both the EIA 632 and IEEE 1220 standards are based on MIL-STD-499B

2.1.1.1 Systems engineering definitions

Several definitions of what SE is, and what it does, exist Blanchard (1998), a well regarded advocate of SE defines it as.

> the effective application of scientific and engineering efforts to transform an operational need into a defined systems configuration through the top-down iterative process of requirement analysis, functional analysis and allocation, synthesis, design optimization, test and evaluation It involves the design engineering process of bringing a system into being, with emphasis on an integrated top-down life-cycle approach

Blanchard's (1998) definition is based on the methodologies of the MIL-STD-499B. Current literature on SE methodology and definition appears to be based on the IEEE 1220 standard

The EIA 632 (1997) standard defines SE as a systematic approach in which to engineer a system The standard is based upon a number of best practices that have evolved since Wold War II. The approach consists of two main elements

- Division of the problem into multiple layers of manageable layers.
- The application of a process set to each element.

Each of the defined processes are defined with regard to a number of guiding principles, these being the right thing should be done first time, by the right people.

The distinction between a system being 'hard' or 'soft' has been introduced by Checkland (1981) The needs and objectives of a hard system can be well defined where as for a soft system they cannot. An example of each concept is given by Parnaby (1981) The hard system elements refer to hardware, processes, and I/O signals The soft elements include social aspects such as human interaction and are regarded outside the system domain.

2.1.1.2 Definition of a system

The word "system" has been derived from the Greek term "systema", which translated means an organised whole. The Collins English Dictionary (1988) defines the meaning as a "complex whole; organisation" These basic definitions are vague and need to be expanded in order to fully describe a system component and it's relevant to the SE concept.

There a number of definitions and classifications of what a system can be, Blanchard (1998), Martin (1997), and Blanchard and Fabrycky (1990) These range from a CEM development approach in support of military aircraft design to naturally occurring phenomenon such as a river system.

2.1.1.3 Systems versus component thinking

Since the mid-80s CE methodologies have developed in aerospace manufacturing related organisations CE methods have supported what is described as the optimisation of individual components in the belief that a product can be reduced to a collective number of self-supporting parts (Gormely and MacIsaac 1989) Organisations pursuing CE methods began to consider life cycle process requirements Components were being evaluated according to CE formal methods (DFA and DFM) to improve their individual and collective manufacturing and assembly suitability. As the complexity of products such as military aircraft increased poorly structured evolutionary development took place. CE failed to provide the framework management for the design and development phases of increasingly complex products The CE of individual components would help component evolution, but only an interdisciplinary, collaborative approach to derive, evolve and verify a life-cycle balanced system can deliver better results that meet customer expectations This approach is systems engineering (IEEE 1995).

2.1.1.4 Systems engineering process

Martin (1997) suggests the SE process is comprised of three sub processes with interfaces to the design, integrated logistics support (ILS), production and deployment processes

- SE management sub process.
- Requirements and architecture definition sub process.
- System integration and verification (SI&V) sub process.

The SE process allows a product to be decomposed into individual component and element blocks (chunks) at any level of the architecture which can then be passed on to a development team for design. The SE concept recognises each system block is an integrated whole even though composed of diverse, specialised structures and sub functions SE endeavours to optimize the balance of objectives between each of the systems in order to achieve maximum compatibility of its parts.

The systems engineering process aims to achieve the correct balance among operational (performance), economic, and logistical factors, in the evolution of functional detail design requirements (Blanchard 1998)

The SE process defines a complete system development beginning with general requirements and ending with a compliant product or process. A block diagram of the SE process at its highest level is given below (IEEE 1995)

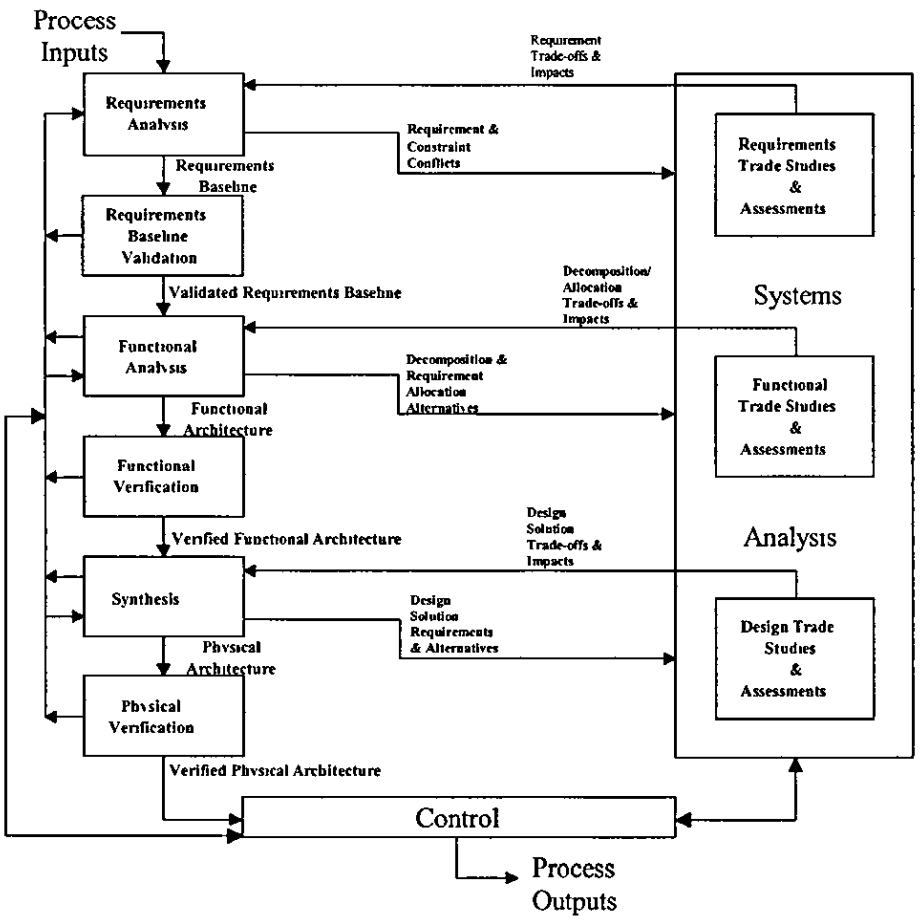


Figure 1 Systems engineering process overview (IEEE 1995).

2.1.2 Concurrent engineering

The philosophy of CE is not a novel one (Parsaei and Sullivan 1993) Its use can be traced back to as far as World War II where product accomplishments such as the P-51 Mustang prototype was designed and built in only 102 days. The use of CE formal techniques such as DFM and DFA are also recorded. Paraei and Sullivan (1993) compare the design and development of two Word War II aircraft, the Supermarine Spitfire and the ME-109. The design of the Spitfire did not consider any aspects of DFM and DFA resulting in over 13,000 man hours of production time Alternately the German ME-109's design did take these formal techniques into consideration resulting in only 4,000 man hours required to produce each aircraft.

Due to the recent globalization of market forces most aerospace engineering organisations today are faced with similar challenges, these being more demanding customers, rapid advancements in technology, environmental issues, competitive pressure on quality and cost, and shorter lead time to market with enhanced product features (Syan and Menon 1994) In the last decade western manufacturing organisations have had to contrive better ways in which to compete against Japanese imports which have infiltrated and in some cases dominated the home product markets Western manufacturing organisations began to develop technological solution with the aim of recapturing these markets with tools such as CAD/CAE/CAM/CIM It soon became apparent that just using a wholly technical approach to product manufacture would not be effective The existing engineering practices, frameworks, and product management methods were not compatible with the new technology based strategies A new approach was required encompassing all aspects of both product and process design/development which took in a much broader view of the entire manufacturing activity The CE methodology, also known as simultaneous engineering, concurrent design, life-cycle engineering, has been developed to full-fill this function

The CE methodology is described by Kusiak (1993) as a practise of incorporating various life-cycle values into the early stages of design. These values include a product's aesthetics, manufacturability, assembly, serviceability, recyclability, and not just its primary functions Life-cycle design methods consider all the phases of a products bringing into being through to disposal, these phases being design, development, production, distribution, usage and disposal. CE is designed to overcome the disadvantages of operating a sequential product design and development process, traditionally practiced in the West (Prasad 1996). Sequential engineering involves the disjointed efforts of successive engineering sections completing their functional activities and then transferring all product related information and hardware to the next stage. This approach is

also known as serial engineering, time-phased engineering, and 'over the wall engineering' A comparison of sequential and concurrent engineering is given below (Prasad 1996)

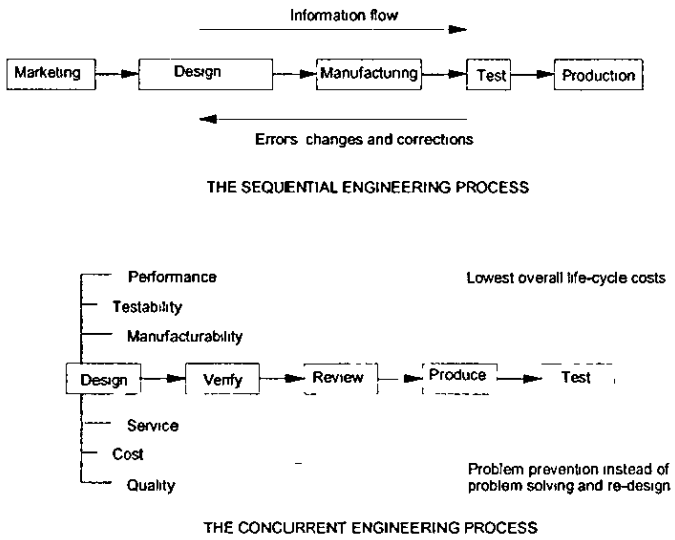


Figure 2 Sequential versus concurrent engineering methods (Prasad 1996)

A widely accepted definition of concurrent engineering is given by Winner (1988).

> a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements

CE will only be effective through the establishment of a number of elements according to Dowlatshahi (1994):

- Information systems
- CAD/CAM/CAE
- Life-cycle engineering
- DFM and DFA.
- Organisation and cultural changes

The diversity of computer software, hardware, and operating platforms coupled with the demand for data sharing has forced the development of integrated communication protocols (Molina *et al* 1995) Maximum cross functional data and information transfer could only be achieved through the exchange of data via neutral formats (i.e , IGES and STEP) The development of seamless

data interchange elements has been slower than anticipated and this in part has delayed the full technological potential of CE.

Currently there is a move to combining CE with lean manufacturing (lean manufacturing is outlined later in this review). This concept is referred to as *lean and integrated systems* (LIS), a model of which is shown below (Rossetto and Franceschini 1995).

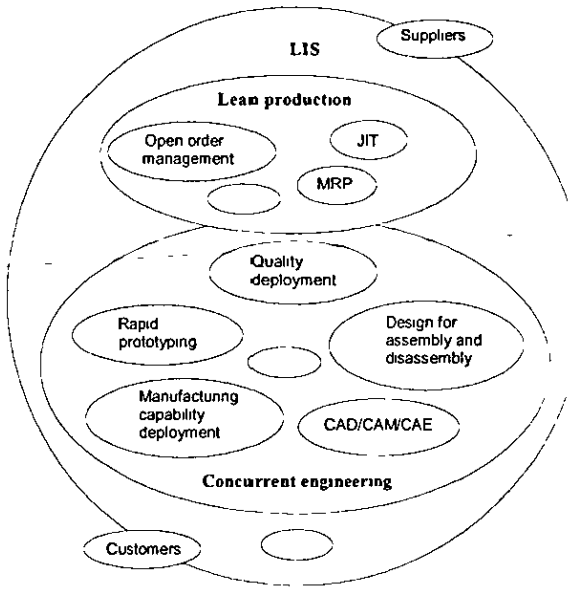


Figure 3 Lean and integrated system (LIS) concept (Rossetto and Franceschini 1995)

The main objectives of CE are summarised by Syan and Menon (1994)

- Decrease product development lead-time
- Improve profitability.
- Greater competitiveness
- Greater control of design and manufacturing costs
- Close integration between departments
- Enhance reputation of the company and its products.
- Improved product quality.
- Promotion of team spirit

The methodology of CE is supported by a number of diverse formal tools. These tools ensure a consistent approach to engineering design and development activities. The correct selection of a tool and its timely use is important to the CE process Figure 4, shown on the next page, represents the typical uses of common CE tools in the product development process (Syan and Menon 1994)

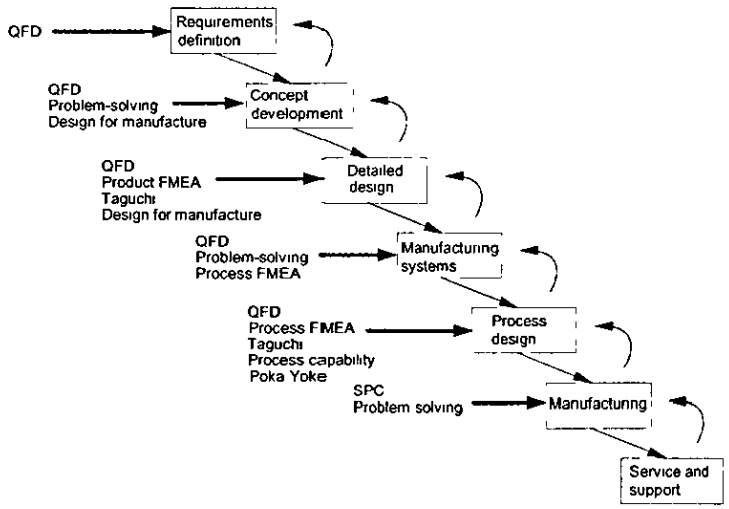


Figure 4 Common CE tools for product development (Syan and Menon 1994).

There are a number of formal manufacturing analysis tools and methods used in support of CE. These are·

- Quality function deployment.
- Design for manufacture and assembly
- Failure mode and effect analysis.
- Robust design and quality engineering
- Statistical process control
- Value engineering

An explanation of these is given in the next section

2.1.3 Quality function deployment

Quality function deployment (QFD) originated in 1972 at the Mitsubishi's Kobe shipyard site in Japan and was later adopted by Western engineering organisations during the mid-80s QFD is designed to capture and translate 'the voice of the customer' into a set of structured requirements, and then evaluate each proposed product capability in terms of its impact on meeting those needs (Cohen 1995). This technique allows primary product concerns to be traced throughout development providing a common and integrated approach to engineering and manufacture (Leaney and Marshall 1998). Once a product has been defined, QFD enables a design team to focus on key customer requirements, those elements that are defined as being very important to the customer (Bossert 1991).

The QFD process is multifunctional and normally implemented through a mixed-discipline design team, which may include personnel form marketing, design, manufacturing, logistics, maintenance and finance. The process starts through the development of a translation matrices often called the house of quality (HOQ) which progresses customer require against engineering requirement.

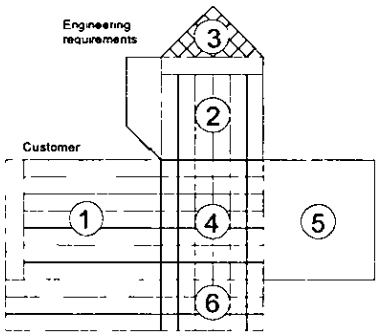


Figure 5. House of quality matrix schematic (Syan and Menon 1994)

The classic HOQ matrix (see figure above) will be made up of six main elements (Syan and Menon 1994), namely.

1 Customer prioritised requirements (What list)
2 Engineering characteristics (How list)
3 Engineering correlation matrix (HOQ roof)
4 Customer requirements interrelationship
5 Customer preference chart used to assess relative product competitiveness
6 Cost and technical assessment used to allocate resources

A number of similar interrelated matrices are then developed depending on the complexity of the product under consideration. In each matrix cell a symbol is entered which indicating the relationship between the individual elements of the 'what' and 'how' lists The symbols can be customised to suite any practitioner's requirement but usually at least three categories; weak, medium, and strong are identified

The number of matrices generated can vary but the most common set are highlighted in the table below (Molloy, Tilley and Warman 1998):

HOQ Matrix No.	The 'What' list	The 'How' list
One	Customer requirements	Engineering characteristics
Two	Engineering characteristics	Component design
Three	Component design	Process planning
Four	Process planning	Production planning

Figure 6 The HOQ matrix cascade (Molloy, Tilley and Warmain 1998)

The QFD process provides a well defined structured framework enabling customer requirements to be captured and dissolved into individual component feature specification, throughout the product life cycle.

2.1.4 Design for manufacture and assembly

Design for manufacture and assembly (DFMA) can be described as set of good engineering principles and techniques focusing on the integration of manufacturing and assembly criteria into the product design process (Molloy, Tilley and Warman 1998) It is estimated that up to 85% of product development costs are committed during the design and planning phase (Andreason, Kahler and Swift 1988, Nevis and Whitney 1989) It must be therefore reasonable to assume that if these principles and techniques are used at the design phase there is a huge potential to save manufacturing and assembly later in the product development cycle

The DFMA process can be naturally split into two separate analysis, design for manufacture (DFM) and design for assembly (DFA). The techniques associated with DFA are relatively mature where as the concepts for DFM have developed more recently and relies on a close working relationship between the product design and manufacturing activity with the aim of improving manufacturing performance (Corbett *et al* 1995) It relies on analysis that degrades individual components into individual features and validates them against planned manufacturing process DFM tools such as design for machining and design for sheet metalworking have been developed by Boothroyd and Dewhurst (Boothroyd, Dewhurst and Knight 1994).

DFA techniques have been dominated by three evaluation methods. These are·

- Assembly evaluation method (AEM) developed by Hitachi in 1967, (Leaney and Wittenberg 1992),
- Boothroyd method developed by Prof. Geoffrey Boothroyd and Dr Dewhurst in 1980, (Boothroyd, Dewhurst and Knight 1994),
- Lucas method developed by the Lucas organization and the University of Hull 1989, (Leaney and Wittenberg 1992)

All three techniques have a similar approach involving the analysis of an assembly design to ascertain its projected cost The aim of all the techniques is to reduce the cycle time and unit cost of an assembly through a number of improvements such as the reduction of components for example

DFA techniques were designed to address small scale products which can be man handled, and are made in large volume. DFA is not so effective on large scale low volume products such as aircraft for example. There is potential scope for a new DFA methodology which could evaluate large scale complex products with a primary focus on assembly quality attributes and not just on assembly cycle time and cost

2.1.5 Failure mode and effect analysis

Failure mode and effect analysis (FMEA) is a CE tool designed to help predict what failures may occur, what the effect of such failures might be on the functional operation of a system or product, and what steps might be taken to prevent the failure or its effect (Fox 1993). The primary aim of FMEA is to eliminate (or reduce) potential product or system failure effects through the identification of important characteristics that have to be measured, controlled and monitored Types of failure are characterised as (Pitt 1994):

- *Severity,* the severity of the failure in terms of customer dissatisfaction
- *Occurrence,* the probability of the occurrence of failure.
- *Detection,* the probability of the design or development process detecting the failure.

An example FMEA rating chart is shown below (Fox 1993).

Rating	Severity	Occurrence	Detection
1	Exceeds specification but not noticed by customer	Never	Very high – programme design process will detect failure
2	Noticed by customer but does not effect the product function	Very occasionally	High – programme design process is likely to detect failure
3	Noticed by customer, minor effect on product function, customer accepts condition	Very occasionally	High – programme design process is likely to detect failure
4	Customer dissatisfied with function of product	Occasionally	Medium – programme design process may detect failure
5	Significant effect on customer satisfaction	Occasionally	Medium – programme design process may detect failure
6	Significant inconvenience to customer	Frequently	Low – programme design process is unlikely to detect failure
7	Significant annoyance to customer	Frequently	Low – programme design process is unlikely to detect failure
8	Customer endangered	Very frequently	Zero – programme design process will not detect failure

Figure 7 An example FMEA rating chart (Fox 1993).

2.1.6 Robust design and quality engineering

During the reconstruction of the Japans manufacturing industry following World War II, Dr Genichi Taguchi developed a new methodology for the development of high quality products and processes. From his research in the 1950's and early 1960's he developed robust design, a concept which underpins the methodology of quality engineering

The principles of robust design and quality engineering form the corner stone of the DM discipline. Robust design, quality engineering, and DM are all concerned with the evaluation and management of product and process variation, it's potential causes, and it's resultant effects measured as a 'quality loss' on product functional attributes The current practice of DM in the UK and USA manufacturing industry is primarily concerned with product physical architecture quality attributes, for example, car bodies and engines in automotive, and airframe structure and engine propulsion in aerospace. Robustness engineering principles has traditionally been applied to all product attribute types and is not confined to the physical architecture of a product Robust design and quality engineering are described in the following sections

2.1.6.1 Robust design

Robust design draws on many ideas from statistical experimental design to plan experiments for obtaining dependable information about variables involved in making engineering decisions It addresses the following two requirements faced by product and process designers (Phadke 1989)

- Economical reduction of variation of a product's function in the customer's environment
- Ensure that decisions that are found to be optimal during laboratory experiments will prove to be so in manufacturing and in customer environments.

The main aim of robust design is to improve product quality through minimizing the effect of causes of variation without eliminating the causes This is achieved through a process of parameter design Robust design utilises two main techniques The first is signal-to-noise ratio which is used as a measure of quality and the second is orthogonal arrays which are used a study multiple design parameters simultaneously. A definition of robust design is given by Phadke (1989)

> robust design is an engineering methodology for improving productivity during research and development so that high quality products can be produced quickly and at low cost

The above definition incorporates the word quality This word means different things to different people. Taguchi's description is *we measure the quality of a product in terms of the total loss to society due to functional variation and harmful side effects* This suggests that in the ideal world the quality loss would be zero, and it follows that the greater the loss the lower the quality.

2.1.6.2 Quality engineering

The principles of quality engineering (QE) can be described as an interdisciplinary science involving engineering design, manufacturing and economics, and is concerned with the reduction of costs incurred prior to, and after, the sale of a product.

QE is synonymous with Dr Genichi Taguchi (1993) who suggests that quality engineering pertains to the evaluation and improvement of the robustness of products, tolerances specification, the design of engineering management processes, and the evaluation of the economic loss as a result of product functional variation (Marshall 1998) Taguchi (1993) suggests a three stage methodology for designing quality into products and processes The stages are:

- System design
- Parameter design
- Tolerance design.

Quality loss in QE is quantified in terms of cost and is established through the quadratic loss function The function quantifies the variation in a process which can be used to evaluate the effects of tolerance parameter revision for economic and quality improvements (Taguchi 1993)

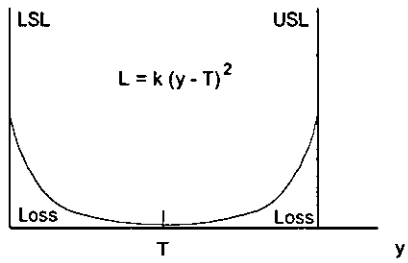


Figure 8 The quadratic loss function (Taguchi 1993).

The loss function is defined as $L(y) = k(y - T)^2$, where

k = quality loss coefficient, a constant

y = quality characteristic of a product

T = target value for y

QE's main objective is to reduce both quality loss, which is the cost incurred after the sale of a product, and the unit manufacturing cost, the cost incurred prior to product sale.

2.1.6.3 Statistical process control

Fox (1993) suggests that statistical process control (SPC) is an activity that uses statistical methods to evaluate the process of making parts and enables the application of control of that process The technique allows engineers to understand how a process behaves, enabling them to take control of the process, and serves also to assist in the redesign of the process where necessary

There are several tools which support the SPC technique These are

- Frequency histograms
- Check sheet.
- Pareto chart
- Cause-and-effect diagrams
- Control charts
- Defect concentration diagram.
- Correlation diagrams.
- Control chart.

An explanation of each of the tools can be found in the appendix of this thesis.

2.2 Manufacturing organisational issues

Practicing a CE philosophy involves the multifunctional involvement of numerous departments and business centres throughout the entire life cycle of a product or system. It is also essential to attain a computer optimised manufacturing system which is regarded as the next generation of computer integrated manufacturing (CIM) systems (Hamid and Sullivan 1993) Given this, organisational issues within a manufacturing business have become ever more important and a number of philosophies have been developed The most pertinent of these with respect to aircraft manufacture are (Shumaker and Thomas 1998).

- Lean manufacturing
- Integrated product and process development (IPPT)
- Agile and flexible manufacturing

2.2.1 Lean manufacturing

Since the mid 1980s the just-in-time (JIT) philosophy has been synonymous with manufacturing engineering through out the West. The JIT philosophy was originally derived from the Toyota production system (TPS) developed by Mr Taiichi Ohno in Japan (Ohno 1988). The strategy of the JIT production system encourages, only the necessary products, at the right time, in the required quantity are manufactured, and stock on hand is held to a minimum. The basic overlapping elements of the JIT philosophy are well documented as being (Harrison 1992, Leaney and Marshall 2001, Ohno 1988; Womack, Jones and Roos 1990).

- The elimination of waste
- Total quality
- People development

The concept of lean manufacturing was introduced to the West in 1990 through a book entitled "The machine that changed the world" by J. Womack, D. Jones and D Roos (1990) The book records the findings of a five year study on the automotive industry in order to establish how the Japanese manufacturing industry had become so competitive in comparison to its Europe and USA counterparts Womack, Jones and Roos (1990) placed lean production as the next development along the path which had so far come from craft and mass production

The aircraft manufacturing sector became aware that lean philosophy was being pursued by the automotive (Womack and Jones 2003) It began to consider if the lean manufacturing framework may be a way to restructure and establish a new culture within its own industry (Shumaker and Thomas 1998) As a result, in 1992 the lean aircraft initiative (LAI) was launched in the US funded by a number of major contractors and the US Air force (MIT 2004)

The LAI continued to gain momentum through the lean enterprise model (LEM) The LEM addressed broader issues such as factory operations, supplier systems, organisation and human resources, and external environment Bicheno (1994) suggests that there is no single definition for lean production, but most would agree that any aerospace lean enterprise should include all external activity such as supply chain management, distribution and design Bicheno (1994), goes

on to suggests that the core of any lean enterprise will be made up of three elements. These three elements are.

- JIT
- Total quality.
- Team involvement.

In general terms lean production can be described as a holistic manufacturing system comprising many parts. Some of these are JIT, zero buffer stocks, total quality control, and building quality in rather than post-build rectification, maximum delegation to direct workers, small lot production, continuous improvement, quick set-up times, standardised work, total preventative maintenance, visual control systems, and teamwork The term lean is derived from the premise that lean production requires less of everything compared with a mass production system, i e half the investment in tooling, half the human effort, half the product development time, etc., (Womack, Jones and Roos 1990) This sentiment has been embraced by the LAI strategy to reduce all elements of production. less time, less inventory, fewer management layers, less capital, and fewer suppliers for example.

The LAI can be said to include all aspects of the JIT philosophy The basic difference between JIT and lean production is that JIT stops at the organisational factory floor boundary JIT can be thought of as operating within the organisational plant boundary, and lean production extends these boundaries both internally to the organisation (i e management, marketing) and externally (i e. suppliers and distributors)

Wickens (1993) suggests that lean manufacturing is the way forward, but must be managed by people who are focused on people. Wickens believes that the future lays in a phrase coined by Sengenberger (1992) *'Synthesis between higher efficiency and higher quality of work and jobs'* From this, the term 'lean, people centred, volume production' has been developed

2.2.2 Integrated product and process development

The concept of integrated product and process development (IPPD) was initiated by the US Department of Defence (DOD) with the aim of improving systems design and acquisition (James Gregory Associates 1999, Shumaker and Thomas 1998) The DOD has comprehensive mandatory procedures for the acquisition of CEM products such as military aircraft and at the centre of this procedure lays the IPPD process

One of the key objectives of the IPPD process is to assess product and system affordability in terms of performance, production, cost of ownership, and their associated risk. The IPPD process is also supported by six sigma quality initiatives to predict the cost and risks associated with early design decisions.

James Gregory Associates (JGA) are a consultancy company in the US that provide IPPD software and service support to a number of aircraft manufacturers. A high level IPPD process flow diagram developed by JGA can be seen below

The IPPD process is defined by Blanchard (1998) as

> a management technique that simultaneously integrates all essential acquisition activities through the use of multidisciplinary teams to optimize the design, manufacturing, and supportability processes

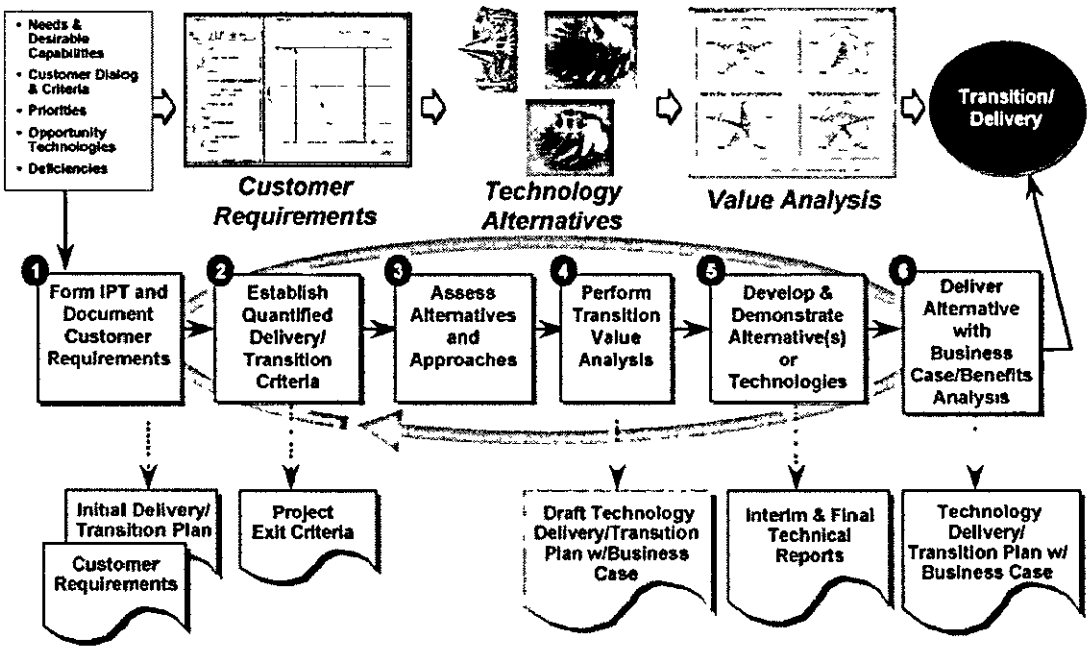


Figure 9 High level IPPD process (JGA, Inc 1999)

The IPPD process is used to define cost and performance objectives for product design through to series production, including field support. The core objectives of IPPD can be listed as (Leaney and Marshal 1998):

- Customer focus.
- Concurrent development of products and processes

- Early and continuous life cycle planning
- Maximise flexibility for optimisation and use of contractor unique approaches
- Encourage robust design and improved process capability.
- Event driven scheduling
- Multidisciplinary teamwork.
- Empowerment
- Seamless management tools.
- Proactive identification and management risk

The IPPD concept is facilitated by multidiscipline integrated product teams (IPT). Each team is assigned to one or more design/development programs to ensure its success management. The process is controlled by a number of maturity gates which control the risk of proceeding with subsequent phases of the development and ensure that the design and development parameters are constantly monitored for deviation (Barrow 1997) IPTs' can consist of both internal and external personnel (suppliers or distributors).

The principles of IPPD are supportive of both concurrent engineering and systems engineering methodologies It facilitates the core product design and development infrastructure for design to series manufacture Leaney and Marshall (1998) suggest that IPPD should be developed as a core competence, where core competence refers to the collective knowledge within an organisation.

2.2.3 Agile and flexible manufacturing

With the introduction of component interchangeability at the Ford Motor Company in the early 1900s, mass production techniques began to develop Manufacturing managers, such as Henry Ford believed that producing products and components in large batches would ultimately be more profitable. This trend was reinforced by the introduction of mechanised processes designed to replace manual labour and lead to dedicated production systems (Raouf and Anjum 1995) This concept worked effectively for a market place which could be identified with products of low complexity, long market life expectancy, and limited product choice

The future global aircraft industry will be identified with products of very high complexity, relatively short time to market, and increasing consumer choice. This situation has led to the need for development of aircraft manufacturing strategies that facilitate high product design and development efficiency, combined with flexibility

Currently, there is no agreed definition of what manufacturing flexibility or agility may be and where their respective boundaries lie With regard to flexibility, it is essential to understand the type of flexibility in question, the level at which it operates, and the context to which it is applied (Barnett and Leaney 1995) Without knowing these elements, it will become difficult to understand what is meant by flexibility. Slack (1991) suggests that there are two elements to flexibility.

- *Range flexibility,* how much a generic process can be changed, i e. capability to produce a greater variety of variant products, JSF military aircraft program for example
- *Response flexibility,* how quickly can a generic process be changed, i e. capability to respond to a revision of requirements

Slack (1991) suggests that distinction needs to be made between the flexibility of the whole operation (system flexibility), and the flexibility of an individual resource (resource flexibility) Total system flexibility can be visualised by considering the entire business operation as a single block process, and its outputs the resource flexibility functions

There are many suggested categories for flexibility and a flexibility framework. One developed by Raouf and Anjum (1995) suggests that a number of flexibility categories exist which can be frame worked into a generic structure, see table below

Category	Flexibility	
Product flexibility	Volume flexibility	Equipment flexibility
	Production flexibility	Design change flexibility
	Configuration flexibility	New product flexibility
	Modification flexibility	
Product mix flexibility	Customizing flexibility	Mix change flexibility
	Production flexibility	Expansion flexibility
	Configuration flexibility	Modification flexibility
Process flexibility	Machine flexibility	Routing flexibility
	Operation flexibility	Adaptation flexibility
	Path flexibility	Sequencing flexibility
	Quality flexibility	Material handling flexibility
Environmental flexibility	Routing flexibility	Volume flexibility
	Capacity flexibility	Delivery flexibility
	Material flexibility	Sequencing flexibility
	Demand flexibility	Application flexibility

Figure 10 Classification of different flexibilities (Raouf and Anjum1995)

Four main categories of flexibility have been identified each having several sub categories This gives some indication into the difficulty involved in primarily defining flexibility, and secondly

measuring its effectiveness Identifying critical criteria for the measurement of flexibility can be difficult. One way is to consider flexibility measurements is to rate it in terms of performance measures (Benjaafar and Ramakrishnan 1995). These include reduction capacity, volume mix, production cycle times, operational costs, and investment.

Manufacturing agility in its broadest terms is similar in nature to flexibility Agile manufacturing embraces flexibility concepts but has a greater association with time and time orientated constraints, i e , product lead-time to market etc Ironically, manufacturing organisations who wish to deploy flexibility concepts need to develop rules for flexibility constraints This is required in order to define the boundaries in which the concepts can be applied, and to what extent. Without these flexibility boundaries in place, the manufacturing organisation would attempt to become infinitely flexible in ever context, resulting in an unmanageable concept

Flexibility concepts within the aerospace industry are also begging to emerge A specific example of this can be found at BAE SYSTEMS (formally British Aerospace Military Aircraft and Aero structures). A number of large scale high performance machining cells have being developed for drilling, countersinking, and edge routing to facilitate the production of interchangeable carbon fibre composite (CFC) panels (Barrow 1997) The machine cells have highly automated fixture/tool loading and removal capability. Each of the CFC panel 'kits' associated with an aircraft type can be preloaded onto a dedicated 'picture frame' set up This concept allows the rapid changeover of CFC panel 'kit' types and enables high product mix flexibility in the manufacture of various product types The same principle is also being undertaken for light weight sub-structures

2.3 Development of aircraft structures

This section outlines the main issues with regard to aircraft structure development These have been reviewed in two main sections, these being

- Materials in aircraft structures
- Aircraft assembly technology.

The areas are both extensive and complex Due to this, the scope of this review is limited to highlighting the main issues associated with each area in the context of this research project.

2.3.1 Materials in aircraft structures

Early aircraft structures were built from simple and lightweight materials such as wood, and fabric. As manufacturing techniques for metals improved in the early 1900's, metallic components began to replace wooden components in aircraft structures (McCracken 2004) Thin metallic skins were introduced producing a more robust structure less affected by the weather Individual components such as ribs and spars were assembled through a riveting process. By 1930, the technology for aluminium alloy became available and wing structure components such as ribs and spars were manufactured from aluminium materials (Davies 1996)

Composite materials although perceived as a recent innovation have been in use in aircraft structures since the 1950's (Johnston 1997) Composite materials offer the advantage of lightweight and strong properties and are constructed from two or more organic or inorganic elements One element serves as a "matrix" binding the material together, and the other element serves as reinforcement, usually in the form of fibres which are embedded in the matrix Until recently, the most common matrix materials were "thermosetting" materials such as epoxy, bismaleimide, or polyimide These were used with glass fibre, boron fibre, carbon fibre, for reinforcement

The first composite to be used in the commercial aerostructures was fiberglass used in the Boeing 707 comprising about two percent of the structure By the 1960s, other composite materials became available, in particular carbon fibre, boron fibre and graphite, embedded in epoxy resins. The first major military production use of boron fibre was for the horizontal stabilizers on the Navy's F-14 Tomcat interceptor. By the 1980's, the British Aerospace-McDonnell Douglas AV-8B Harrier flew with over 25 percent of its structure made from composites

Inclusion of composite materials in airframe manufacture has increased Modern commercial aircraft such as the Boeing 777 has composite material making up about ten percent of its structural weight. Modern military aircraft, such as the F-22, use composites for at least a third of their structures. It is predicted that future military aircraft programs will increase the use of composite materials to as much as seventy percent This trend may not be the same for the commercial sector due to the complex maintainability issues associated with composite material.

Composites also have a number of disadvantages, some of these are

- Relatively expensive and complex to manufacture.
- Difficult to inspect for defects

- Complex process for repair.
- Manufactured part feature accuracy and repeatability can be poor
- Little opportunity for component rework
- Environmental and cost issues arising from product disposal.

More recently, new composite manufacturing processes have been developed and are used in the aerospace industry. These cannot overcome the main disadvantages outlined above, but can address issues such part accuracy and repeatability:

- Resin transfer moulding
- Resin film infusion

New concepts for composite materials

- Smart structures, structures that monitor themselves for stress and strain

Thermoplastics are a relatively new material that is replacing thermosets as the matrix material for Aluminum still remains a remarkably useful material for aircraft structures and metallurgists have worked hard to develop better aluminum alloys (a mixture of aluminum and other materials) In particular, aluminum-lithium is the most successful of these alloys It is approximately ten percent lighter than standard aluminum Its adoption by commercial aircraft manufacturers has been slower due to the expense of lithium and the greater difficulty of using aluminum-lithium. But it is likely that aluminum-lithium will eventually become a widely used material for both commercial and military aircraft

In recent years, new metallic manufacturing processes have been developed and are used in the aerospace industry These are.

- Superplastic forming
- Diffusion bonding

The aerosapce industry continues to research materials technology trying to identify new strength to weight advantages for aircraft structures This is diverse and complex area of engineering and although this reaserch acnowledges it's existence it has been considered beyond the scope of this research project. One area for future research could be to investigate the dimesional stability of these new materials and their associated manufacturing process

2.3.2 Aircraft assembly technologies

Some of the largest costs associated with aircraft structure development and production can be attributed to assembly tooling and fixturing systems, to enable product build (Thornton 1997) In order to reduce this cost the aerospace industry has initiated a number of advanced assembly technologies, one of the most significant being fixtureless assembly This technology has the following characteristics·

- Reduction of expensive 'hard' fixturing and checking systems
- Introduction of digital alignment systems back to CAD master.
- Introduction of digital checking and gauging techniques back to CAD master
- Requirement to design part-to-part direct inerfacing features to facilitate kit type assembly build
- Design of parts and assemblies to accomodate interchangeability (ICY) specification and classification.
- Usually associated with part count reduction program

Jigless assembly is achieved through the application of new 'self tooling / location' principles Each component and subassembly will be produced with inherent self locating features and tooling features, in addition to nominal functional architecture. These features will be used to facilitate part to part location for assembly purpose Significant attention is required to feature type and it's definition, and to their control with respect to geomertic tolerance control and metric The DM philosophy can significantly aid this process by using the assembly analysis tools available to predict net assembly dimensional capability.

Airbus are currently adopting this type of philosophy, avoiding where possible, large and expensive jigs, tooling and hard gauging systems (Coyne 2004) BAE SYSTEMS are also developing this technology in conjunction with flexible manufacturing techniques such as the development of advanced machine tools centres for the manufacture of parts for jigless assembly, automatic fastener installation, and sealant application (Johnston 1997).

2.4 Dimensional management discipline

As competition in the aerospace manufacturing market increases, organisations have been forced to review their business strategy and efficiency in order to survive As a consequence, a number

of different efforts are being pursued by companies to improve the 'affordability' of customer driven product specification through the concurrent involvement of engineering function. DM is becoming part of a growing field of endeavour pertinent to the design, manufacturing and assembly of complex products aircraft manufacture being one example (Leaney 1996).

This area of activity is most commonly referred to as DM (DM). Other alieses are dimensional control (DC), design for variation (DFV), variation management (VM) design for variation analysis (DVA), and assembly variation analysis (AVA) For the purpose of this report, this area of activity will be referred to as DM

There are a number of definitions for DM (Leaney 1996; Leaney and Marshall 2001; Ligget 1993), but Leaney and Marshall (2001) define it concisely as:

> the dimensional management discipline refers to total product dimensional control which recognizes and manages variation during the design, manufacture and assembly stages of development and production

Dimensional variation is inherent within any component part, subassembly, tooling and manufacturing processes and cannot be eliminated However, variation can be identified, quantified and analysed so therefore it can be managed Given this fact, there has been relatively little effort placed on optimizing tolerance allocation and evaluating potential changes in the design that would allow for increased variation in non-critical areas (Craig 1992) Conversely, critical areas having a significant impact on product specification need to be identified and their variation controlled through the appropriate specification of tolerance. These critical features and tolerances should then be designated as product key characteristics (KC) and managed throughout the product lifecycle (Boeing). Further explanation of KCs' are given in the next section.

The DM process has traditionally been undertaken to support and evaluate tolerance allocation. Tolerance analysis software tools, for example VSA, eM-TolMate, etc , have been used to evaluate the resultant assembly build parameters taking into account information such as component and fixture feature tolerance, component locator strategy, and assembly sequence (see section entitled 'Computer aided tolerancing software tools and process' for further information). The analysis model is initially based on design tolerances but with the availability of prototype or surrogate process capability data there is an opportunity to 'close the loop' and feed back information from manufacturing to design (Leaney and Marshall 2001)

In addition to the software tools there are a number of DM best practice techniques which guide engineering, some of these are (UGS PLM Solutions 2004)

- Gauge repeatability and reproducibility techniques.
- Geometric dimensioning & tolerancing
- Feature definition and assembly location strategy
- Quality measurement strategy

Pertinent research and industrial projects associated within the area of DM are:

ADCATS: Association of the Development of Computer Aided Tolerancing software, (Chase 1988) Consortium of 12 member companies interested in tolerance analysis coordinated through Dr K Chase at Brigham Young University (BYU).
http://adcats et byu edu/home html

ANDREA: program aiming to renewing and strengthening the research and education in engineering design and engineering management in Sweden Projects areas include design for manufacture, tolerancing in the aircraft industry, improved assembly quality Research base was Linkoping Institute of Technology (LiTH)
This research group is no longer active

Conformability Analysis: eCA technique is a developing tool for the analysis of quality costs associated with mechanical designs and manufacturing processes using process capability indices, FMEA, and Cost Mapping Most recent development is the adaptation of the standard eCA technique to evaluate the functional, manufacturing and test process capability of electronic circuits Projects based out of the University of Hull
http://www hull ac uk/eca

CAM-I: The CAM-I Institute for Manufacturing and Automation Research (IMAR) Projects include

- **Quality Assurance Program (QAP):** development of Dimensional Measuring Interface Specification (DMIS) now as American National Standard and being progressed as intentional standard
- **Next Generation Manufacturing System (NGMS):** project to combine the worlds best thinking on the next generation of manufacturing systems to guide the ten year NGMS, IMS R&D.
- **Robust Quality Engineering:** development of a system that will enable companies to realize the benefits of Robust Design concepts when applied to proven Quality Engineering principles earlier in the life cycle

http://www cam-i org/index html

CIRP, International Institution for Production Engineering Research: Organise the CIRP international seminars on computer aided tolerancing, (CIRP 2001).

MADLab research group: Research group based at The University of Texas at Austin currently involved with several projects relating to DM

http //www me utexas edu/~madlab/

SPE, Japan Society for Precision Engineering: Organize and promote computer aided tolerance systems.

http //www jspe or jp/english/

The International forum on design for manufacture and assembly: Organise the international seminars on DFMA, (Boothroyd and Dewhurst 2003).

http://www.dfma com

In support of the DM process there are a number of analysis techniques, tools, and methods The most significant of these are

- Product features.
- Key characteristics
- Tolerance specification
- Computer aided tolerance (CAT) analysis software tools

2.4.1 Product features

The use of features is considered by many researchers as the key to the genuine integration of many aspects of design and the planning of manufacture (Case and Gao 1993). Feature definitions can not only be used to express the design intent and form the basis for design analysis but can also provide the basic geometry knowledge for the integration of manufacturing, assembly and the dimensional inspection process

The term feature is derived form the Latin word '*Factura*' which means the *'act of making'* or *'information'*. The definition of a feature has been interpreted by research in many different ways. The problem of definition is compounded further due to the different feature interpretations for design, manufacturing and analysis. Some definition are presented highlighting the scope of the different meaning:

> a feature is a group of geometric entities with some meaning for the particular activity to be performed with them (Herbert *et al* 1990)

> a feature is a region of interest on a surface of a part (Pratt and Wilson 1985).

> a feature is a portion of the work piece generated by a certain mode of metal cutting (Choi, Barash and Anderson 1984)

Currently there is no formal way of categorizing or specifying features, therefore there are an infinite number available (Allada and Anand 1995) However, organisations divide features into related classes for easier access by design and manufacturing. These classes can be subdivided into subclasses to form a hierarchy known as a feature taxonomy. Because of the hierachial nature of taxonomy, any attributes associated with a feature class will also be related to any sub-class. The structure of any feature taxonomy will depend on the methodology used for the identification and classification of features with respect to how they are going to be utilized within an organisation

2.4.2 Key characteristics

Most modern manufacturing product development techniques include a mechanism to capture customer attributes which form the basis for product function such as QFD. These product specifications are further broken down into functional features and attributes. Techniques to ensure the identification and management of these attributes, tolerance for example, are being developed One of these techniques used to ensure product quality is key characteristics (KC) The KC technique is accredited to MIT in the US and has gained popularity with major aerospace companies such as Boeing and McDonnell Douglas, both of whom currently use KC methods in support of product development The KC technique has been defines as (Lee and Thornton 1996)

> KCs' are product features, manufacturing process parameters, and assembly features that significantly affect a product's performance, function and form.

Research work undertaken by Lee and Thornton (1996) suggest the classification of KC's into three categories The first is a product KC (PKC), the second a Manufacturing KC (MKC) and finally an assembly KC (AKC) These features are identified through a process of product decomposition firstly to subassembly, then assembly, component, and finally to component features and attributes. These elements are then built back up into the final assembled product.

Decomposition of the product down to part feature level allows the analysis to define what manufacturing processes will be required to meet the attribute and therefore what process

capability many be anticipated from related statistical process control (SPC) data As the product is built up the assembly features and attributes will also become apparent allowing an appraisal of assembly tooling requirements The product development process needs to consider both aspects of product decomposition and rebuild equally as issues relating one will have an effect on the other (Whitney 2004)

Lee and Thornton (1996) suggest a forth category of KCs', namely the StatKC The StatKC is a subset of the three main categories and is defined as a KC whose deviation from tolerance will pose significant risk to the quality of the final product It could be described as an element of a 'critical path' of manufacturing and assembly components and processes.

After the identification of KCs', they can be categorized into the following (Thornton 1997)

- Safety issues and government regulations these apply to corporate as well as international safety.
- Customer product requirements these are requirements directly relating to product performance, function and form
- Internal corporate requirements these are associated with internal corporate requirements such as schedule requirements, cost controls.

The benefits of using KC techniques, Lee and Thornton (1996), are

- Better determination of detail design decisions improved communication of critical design areas with respect to cost, manufacturing and assembly process selection.
- Root cause analysis: identification of root causes by travelling up, down and across product KC tree.
- Aid equipment decisions manufacturing and assembly equipment may be improved based on KC data
- Aid investments and make-buy decisions KC data can be used to analyse new manufacturing capabilities to help determine make-buy decisions.
- Improve product planning: areas of company weakness can be determined based on customer requirement history against receded StatCKs

The key characteristics technique has been highlighted above This technique is well documented in a number of publications.

2.4.3 Tolerance specification

The manufacture of perfect form is unrealistic, and even if it were possible we would never know because it would never be possible to verify perfect form by physical measurement (Requicha 1993) Tolerance, in the context of product development, has been defined as (Jeang 1995):

> the maximum deviation from a nominal value within which the component is still acceptable for its intended purpose.

Dimensions are controlled through the allocation of a tolerance which allows a nominal value to vary in some way by a specified amount Two main types of tolerance groups, parametric (linear) and geometric, have been developed for industrial use (Voelcker 1993) A third tolerance group has been developed to control kinematic variation which occurs from small resultant adjustments between mating parts at the assembly stage (Chase, Magleby and Gao 1997)

Tolerance information has traditionally been placed onto engineering drawings through notation, symbols, and the specification of 'blanket' company standards. However, the introduction of CAD/CAM systems has resulted in much research and development with regard to how best tolerances many be represented within these systems Aristides Requicha (1993), a Professor of Computer Science and Electrical Engineering at the University of Southern California has been responsible for the development of the mathematical and algorithm theory behind several commercial solid modelling systems His research highlights the two main syntactical approaches to tolerance definition, dimensional limit specification and geometric tolerance specification for solid modelling His current work is with the programmable automation laboratory (PAL) with a focus on computational geometry, robotics and artificial intelligence

Some of the main techniques used in computer solid model to represent tolerances are (Requicha 1993):

- Pure parametric tolerancing
- Tolerance zone semantics
- Offset zone theory.

The specification of tolerance in CAD/CAM systems needs to be comprehensively defined in mathematical terms to avoid ambiguity. Measuring equipment also needs clear geometric

specifications to ensure correct interpretation of computer reference tolerance zones Currently there are different methods of constructing tolerance zones in CAD systems, these being

- Parametric dimensioning and tolerancing
- Geometrical dimensioning and tolerancing.
- Kinematic dimensioning and tolerancing.

An explanation of each of these tolerance types is available in the rear of this report

2.4.3.1 Tolerance standards

There are many world wide tolerance standards including British, Japanese, Chinese, USA, European, and Russian The international standards organisation (ISO) is attempting to consolidate the stronger elements from predominantly western standards to form a number of its own. The following current standards are considered to be relevant to the scope of this thesis,

British Standard (BS); 113 main standards based on 'Technical product document Specification for defining, specifying, and graphically representing products':
BS8888 2002
Geometric product specification (GPS)
International Standards Organisation (ISO); 8 main standards
ISO1101, ISO2692, ISO5458, ISO5459, ISO7083, ISO10578, ISO1660, and ISO-DD16792.
American Society of Mechanical Engineers (ASME); 2 main consolidated geometric standards
ASME Y14 5M 1994 and ASME Y14.41M 2003

Tolerance standards generally designed to control parametric (linear) or geometric entities Standards such as the BS 308 (1985), ASME 14 5M-1994, and the ISO (1995) ISO/R 1101, ISO/R1101/11 and ISO/R1660 were divided into linear (including angular, radius and diameter) and geometric tolerances (Cox, McMahon and Tannock 1995)

Geometric controls of a tolerance standard are defined through geometric dimensioning and tolerancing (GD&T) schema GD&T standards are characterised through sets of symbols which are used to define part features and their tolerance zones (Moh 1996) Parametric controls are defined through boundary conditions and can be expressed as basic dimensions with a tolerance applied.

The most commonly used GD&T standard in the US is the ASME Y14 5M-1994 This has evolved out of a consolidation of other standards, ANSI Y14 5M-1982, ANSI Y14.5-1973, USASI Y14 5-1966, ASA Y14 5-1957, SAE Automotive Aerospace Drawing Standards (section A6/7 and 8-September 1963) and MIL-STD-8C, October 1963, (Foster 1994) The consolidation of all these standards was necessary and driven by members of military, industrial and educational organisations in the US The standard is required by these organisations to consolidate the definition of design and drawing requirements with respect to actual function and relationship of part features Further to this, the standard provides a functional manufacturing and quality inspection communication technique which consistently relays back to the design definition. The ASME Y14.5M standard has continued to develop through the support of the ANSI/ASME B89 3.2 dimensional measurement method (Beckwith and Parson 1994) This was developed to assist the direct measurement of component dimension and tolerance in accordance with the ASME Y14 5M standard

The ISO are developing a standard on geometrical product specifications This is being undertaken by various ISO technical committees who are identifying missing and incomplete sections on tolerance with the intention of fulfilling them (Henzold 1995) The new concept of geometrical product specifications standards have been used successfully in Denmark for tolerancing and standardisation. They have developed a system called chains of standards used on engineering drawings and CAD systems to define the geometric features of a component such as size, distance, form, orientation, location, and surface roughness (Bennnich 1994). The chain of standards consists of six links

- Product documentation indication – codification
- Definition of tolerances - theoretical definition and values
- Definition of actual features - characteristics or parameters
- Assessment of the deviation of the work piece - comparison with tolerance limits
- Measurement equipment requirements
- Calibration requirements - calibration standard

The harmonization of the two principle GD&T standards ASME Y14 5M and ISO is becoming more desirable in the west The aerospace industry has been consolidating by forming multiple alliances in order to ensure that their joint technologies and economies of scale can sustain the market share of their business. As a result, many organisations have to overcome the barriers resulting from the physical dislocations of multiple company sites Potential issues can arise, for example, between US and European based collaborations The US consortiums may have defined product tolerances using the ASME Y14 5I using imperial dimensions European companies may

favour the ISO tolerance and metric dimensions The difference between these standards will need to be well understood by both parties to avoid misinterpretation of product and process definition The development of a single integrated GD&T standard would help this situation by providing improved and consistent engineering communication for the global development of complex products

2.4.3.2 Tolerance specification

The most common tolerance specification problem encountered by engineering design is tolerance allocation, which is the distribution of the specified assembly tolerance among the components of the assembly (Chase *et al* 1990)

Designers are primarily concerned with functional tolerances ensuring the assembled product as a whole meets some dimensional quality specifications (Craig 1996) The high level functional tolerances will be made up from an accumulation of individual component tolerances that make up an assembly. Functional tolerances are driven by product specification but component tolerances are mostly derived from process capability data A potential concern for the design organisation is how to distribute the high level functional tolerances across component parts

Each component will be associated with a cost to the organisation The level of direct cost will partly depend upon component complexity, its geometric features, and their associated design tolerances One of the primary considerations for design is affordability This being the case, feature tolerance should be associated with a unit cost With this information the design engineers will be able to develop tolerance related quality loss function models and will associate these with design intention to establish the most economic and affordable solution (Creveling 1997).

There are currently several models for evaluating cost versus tolerance These are (Chase *et al* 1990)

- Lagrange multipliers
- Combinatorial process selection method.
- Zero-one discrete search method
- Univariate search method
- Nonlinear programming method

The research by Chase *et al* (1990) suggests that an exhaustive search method using a Lagrange multiplier to allocate tolerance and combinatory to test all possible process combinations. The zero-one method, a totally combinatory based method, is too inefficient to be of practical value. The sequential quadratic program (SQP search algorithm) method, based on nonlinear programming was shown to be capable of treating multiple loop assembly functions but could not guarantee identifying the global minimum The univarite search method was shown to be the most efficient. This is based on a Lagrange multiplier and a process to reduce the set of process combinations tested Although it could not guarantee finding the global minimum, it always found it for unconstrained problems and moderate-to-large constrained problems

2.4.3.3 Tolerance analysis and synthesis

Tolerance analysis and synthesis modelling is performed to

- Determine if the predicted variation levels expected from the intended manufacturing, tooling and assembly processes will achieve the dimensional specifications of the intended design.
- Perform root cause analysis on current products to mitigate functional non-conformance

The analysis of tolerances can be grouped by dimensional space and their related degrees of freedom (DOF).

1D	1 translation - 1 DOF
1 5D	2 translations - 2 DOF
2D	2 translations, 1 rotation - 3 DOF
3D	3 translations, 3 rotations - 6 DOF

There are four main groups associated with analysing tolerance accumulation (Chase, Gao and Magleby 1997, Nigam and Turner 1995), (Turner and Gangoiti 1991), (Liggett 1993):

- Worst case.
- Root-mean square (RMS) or root sum square (RSS).
- Statistical analysis
- Kinematic analysis.

An overview of these 4 groups is available in the appendices of this thesis

2.4.4 Computer aided tolerance software tools and process

A number of computer aided tolerance (CAT) and quality software tools and processes have emerged in support of the DM activity Some of the CAT software tools available are·

- UGS PLM Solutions (UGS 2006). http //www ugs com
- Dimensional Control Systems (DCS 2004) http //www 3dcs com
- CATIA V5 – Tolerance Analysis of Deformable Assemblies http //www.3ds com/en/home asp
- Varatech http.//www varatech com
- Tecnomatix Technologies Ltd http //www tecnomatix com
- Cognition Corporation http //www ci com
- CE/TI 6 sigma http·//www sigmetrix com
- Saltire Software http.//www saltire com
- Toltech

There are a number of specific benefits of using these software tools·

- Perform complex analysis to establish and improve aircraft structure dimensional capability
- Optimize the design, manufacture and assembly as a single process
- Minimize and resolve production development issues by supporting FMECA and root cause analysis
- Reduce warranty, scrap and rework caused by dimensional variation.
- Reuse dimensional quality information on future designs by creating a product and process quality knowledge base
- Identify critical product and process dimensions (KCs') and manage variation
- Aid the development of measurement process planning
- Improve communication and collaboration of product quality information throughout the enterprise and supply chain.
- Assess interchangeability and maintainability specifications
- Verify design component manufacturing and assembly specification against actual process capability
- Directly support and drive integrated product development (IPD) initiatives during product quality engineering reviews
- Facilitates product and process development process capability knowledge capture.

A review of the CAT software tools is available in the appendices of this thesis.

2.5 Manufacturing methodology critique

The manufacturing methodologies cronology outlines the key strategies adopted by western engineering organisations over the past decades Between the 1950's and 1970's the aerospace manufacturing industry operated in response to the demands of their respective defence procuerment organisation usually controlled by the government of the day. This situation changed in Europe in the 1980's with the end of the cold war and the onset of a global economic downturn . These factors triggered the search for new initiatives in the aerospace industry who now for the first time had to compete in it's own domestice and the global market place As a result, aerospace manufactuing technology began to increase in complexity in the search for competitive advantage over their new competitors.

Both in the aerospace and the wider manufacturing indstry a number of new techniques and initiatives began to appear During the 1970's DFM and DFMA became drawn to the forefront of manufacturing following the percieved demand for increased automation for the assembly of complex goods. Circa the late 1970's the concept for large scale flexible automation was also being considered by manufacturing organisations in order to accommodate customer demand for product customization. This directly led to such philosophies as AMT and FMS which were in part based on the developing Toyota JIT and lean production system

The techniques of DFA, FMA and AMT began to highlight some of the shortfalls of a design process which did not take into consideration subsequent requirements for the down stream manufacturing and assembly process It became apparent that the development and manufacturing process of complex goods needed to be better integrated to provide a more comprehensive and complete product life-cycle management (PLM) process This integrated PLM approach lead to the development of simultanious engineering which later developed into CE The development of CE lead to an increase of computer based technology development and lead to the introduction of CAD, CAE, CAM, and CAPP software A new and emerging technology supporting CAE in the automotive industry was DM These computer technology elements were developed and architected under the overall banner of CIM although at this time their integration at system level was poor.

From an organisational perspective the aerospace industry began to adopt a new strategy called IPPD supported by the IPT. This strategy was initially developed in the US in order to fully support the SE approach for total product and process development already being adopted by the aerospace industry The SE methodology has been adopted for the development and manufacture of CEM items in industry sectors such as aerospace. It differs from the CE approach in that it requires a product realisation process based on a systems-orientated approach as apposed to a component-orientated approach This allows the requirements of a complex product with a high level of electro mechanical interdependency to be designed and developed from an integrated systems and not a piece part orientation

2.5.1 DM critique

DM was initially developed in the automotive industry as an engineering discipline as a way of managing product variation during the design, manufacture and assmbly process. The emergence of DM followed the recognition that significant production costs were being incurred due to the poor understanding of product and process variation The aerospace industry has followed this lead and DM is now practised in a number of large aircraft manufacturing companies.

DM is not unique to the auto and aero sectors. It currently exists in a number of other industries each of which are developing their own set of techniques to manage assembly variation in their products Techniques such as KC, feature definition, tolerance specification, and tolerance analysis form some of the building blocks of their respective DM process

Product hierarcy can be desolved to feature definition Features are basic elements which describe product physical attributes such as a component interface for assembly constraint, basic architecture for KC designation, and piece part manufacturing architecture requirements Feature management is a fundamental part of the DM porcess and is an area that should be developed

The KC process is defined in literature as a design to manufacturing and assembly integration technique This integration 'check' is achieved through the virtual decomposition of the product to assembly, part, and feature levels which are then rebuilt for overall product validation. The KC process is currently not supported by any software tools relying on individual companies to document their own process One observation made by the author is that the KC flow diagrams could be improved through a more standard and consistent generation process

From the review, the author recognises that most products are currently designed in 3D CAD using solid modelling techniques. These CAD models form the basis of the nominal design intent

and are defined in terms of assemblies, components, and features Tolerance specification to each of these features, and related components, describe how the CAD nominal component may vary by a specified amount Tolerance specification and its application is comprehensive documented in a number of tolerance standards most of which are based on GD&T proinciples One area of weakness identifed by the author is that of tolerance cost modelling. From the literatures review it has been identified that no application is available to perform such an analysis

A number of software tools exist to aid the DM process most of which involve the simulation of assembly build using 3D CAD environments These tools allow comprehensive modelling based on 3D nominal geometry, tolerance soft gauge application, assembly constraint management, and assembly sequence One potential shortfall for the DM process is that these tools are typically used on maturing design concepts because they require detailed 3D CAD geometry and supporting data, GD&T specification, for example This presents a potential problem in that by the time a comprehensive tolerance analysis and synthesis has been undertaken, a design may be to mature for an organisation to conduct product modification.

2.6 Concluding comments

This chapter comprehensively reviews the domain relating to DM. The reviewed literature in DM has focused on manufacturing methodology, organisational issues, aircraft structure development, and the DM discipline. Although the literature research provides an in depth investigation into each of these areas it is evident that no overall DM methodology exists to support the design and development process This research aims to explore such a methodology enabling a comprehensive and generic approach to DM for the aerospace industry The author has recognised that key areas identified in the literature need to be included as part of a DM methodology Specific key areas include

- Feature definition
- Key characteristics
- Tolerance specification
- Tolerance modelling

In chapter 3 the thesis will present a fact finding assessment of current best practice in DM in both the automotive and aerospace industry sections The findings of chapter 3, together with the literature review undertaken in this chapter, form the basis for chapter 4 which outlines the need for DM.

Chapter 3

3 Assessing current best practice in dimensional management

Objectives: The literature review in chapter 2 outlines the current thinking associated within the DM domain which is dominated by the automotive and aerospace sectors To understand how these sectors currently make use of the DM discipline this chapter presents an overview of the current best practices relating to both the aerospace and automotive industries The findings are presented in the following sections.

- Present the findings of a US study tour of leading aerospace and automotive manufacturing companies practicing dimensional management
- Highlight some European aerospace companies practicing dimensional control activities
- Outline sample cases of dimensional analysis in the aerospace and automotive industries

3.1 USA study tour of leading aerospace and automotive companies

During August 1996 the author arranged a study tour of selected aerospace and automotive companies in the USA The author was accompanied on the tour by two engineers from British Aerospace Military Aircraft and Aerostructures (BAe MA&A), Samlesbury. The aim of the study tour was to assess current best practice within selected aerospace and automotive companies with regard to the use of DM techniques. The aim of the study tour was addressed through the following objectives:

- Identify companies operating DM techniques to be included in the study tour.
- Develop a structured method of capturing the scope of DM and the related implementation issues of each company visited.
- Document findings of study tour.

The following companies were selected for the study tour. Their selection was the result of various communication with parties associated with DM at that time who included personnel at Loughborough University, BAe MA&A, VSA Inc and DCS Inc

- Chrysler Corporation
- Ford Motor Company.
- McDonnell Douglas Aerospace.
- Raytheon aircraft.
- Northrop Grumman
- The Boeing Company.

A structured method was defined to capture the scope and implementation of any DM process operating within a company The scope of a company was captured in the DM scope matrix and implementation issues in an implementation matrix. Both these matrix together with their respective guidelines can be seen in addendum 5 and 6 in the study tour report (Jeffreys 1996).

The findings from each company visit are discussed in the following sections

3.1.1 Chrysler Corporation

The Chrysler Corporation visited is based at the Chrysler Technology Centre, Auburn Hills, MI

The Chrysler Corporation has been operating DM techniques since 1990. Chrysler first became involved after becoming aware of the variation simulation work undertaken at General Motors (GM), a major competitor. Claims of success by GM led to a concern that may have develop a competitive advantage forcing Chrysler to investigate the new technique. Chrysler is perceived in the automotive industry as being a leading DM practitioner. Over the last seven years they have continued to develop a DM strategy Some of the strategy has successfully been realized with in company through some of the latest vehicle programs such as the Neon and Cirrus

Currently, the DM process will typically focus on body in white structure and interior trim alignment in truck and car production. Typical considerations of the vehicle program are quality issues relating to:

- All closures to fixed panel fit and function, i e , doors, hood, trunk to BIW.
- Power train functional and assembly analysis

- Selected internal and external packaging assembly analysis, i.e , interior and exterior trim components.

Chrysler also used DM on drive train assemblies but it was not possible to identify what work had been undertaken

Vehicle program methodology captures and deploys customer target specification (i e functional attributes) through a quality function deployment (QFD) process Target vehicle specifications are identified and documented in the dimensional co-ordination manual as part of the up front design process These are established through comprehensive bench marking exercises incorporating reverse engineering techniques undertaken at the Chrysler Vehicle Research Centre Currently Chrysler perceives Toyota as best car manufacturer with respect to dimensional quality and they have therefore become the benchmark The QFD process forms part of a systems engineering type methodology This involves decomposing the whole vehicle into major assemblies, subassemblies, component parts, features and attributes Chrysler places great importance on identification, documentation and management of functional features on both component and assembly jigs

Chrysler operates an integrated product development (IPD) strategy to help drive its concurrent engineering philosophy. Within this strategy there exists a DM engineering group made up of approximately 125 engineers Each IPD team will be assigned 1 or 2 engineers who will become responsible for the dimensional quality of that product section. Important feature tolerance attributes are identified and managed by a special team of 3-4 engineers who apply all geometric dimensioning and tolerance call outs in accordance to the ASME Y14.5M, 1994 standard Only approximately 25% of the DM engineering group are Chrysler employees The remaining 75% are short to medium term contractors from various companies such as VSA, DCS and Trikon The core DM expertise is held with the company and many of the contract workers function as a flexible variation modelling resource to the core DM group The DM engineers have organized a DM technical club There is no corporate requirement to attend meeting and engineers organize their own agenda and schedule This appears to be similar in nature to the process of quality circles

Chrysler is committed to DM techniques and all current and new engineers receive in house GD&T and DM basic training Engineers considered for DM related positions are selected from the following criteria:

- Perceived as having a good understanding of DM techniques.

- DM team leaders are required to have considerable experience in tooling design/build and gauging
- Minimum academic qualification - engineering degree.

Chrysler believes that it takes up to six years of training and experience to become a competent DM engineer.

The dimensional analysis software tools at Chrysler are VSA-3D and VALISYS Assembly software for Tecnomatix Both are heavily integrated into their primary CAD system, CATIA The DCS software had also been investigated but currently was not being used. The VALISYS Programming and Inspection modules were also being used for digital inspection.

There has been one main drawback of the DM process recognized at Chrysler The engineering environment has perceived the VSA system as analytically based, and not as a practical tool set This has led to problems in terms of resistance to cross functional communication, a vital resource to the DM engineers There is also related union based problems because of what they regard as 'exposure' of some engineering operations to other parts of the organisation

Chrysler claim that the introduction of DM techniques has impacted on product quality in two areas Firstly, the reduction of vehicle program development lead-times resulting in cost savings and delivery time to market. Secondly, dimensional quality improvements in vehicles have been acknowledged.

3.1.2 Ford Motor Company

The Ford Motor Company visited is based at Vehicle Operations, Oakwood Boulevard, Dearborn, MI

Ford has been involved with DM techniques since the early 1990's Ford, similarly to Chrysler, became involved with DM techniques after becoming aware of the claimed successes at GM They currently run a large DM program and are clearly committed to the techniques. Part of the Ford strategy has been to set up and maintain a DM department located at the body and assembly - vehicle operations based at Dearborn Ford considers the whole vehicle construction for variation management including analysis on

- Door, trunk, hood to BIW fixed panel flush and gap conditions
- Drive train analysis - engine, gearbox, axle, etc

As appears to be the case with most automotive manufacturers, the primary issues address by DM techniques at Ford are aesthetics such as steps and gaps for example

As part of their product development strategy Ford are giving more up front consideration to design for manufacture (DFM) Process capability requirements are agreed at the beginning of the program based on historic SPC data and dimensional quality specifications for a vehicle program are recorded in the LB-506 document, known in Ford as the 'Gray book'. The sign off of this document becomes an important stage of the program It effectively commits many engineering sections to a product and process specification which becomes difficult to revise in the later stages of the program Important functional features are identified through the Significant Characteristic (SC) process which is similar in nature to the Key Characteristics (KC) process discussed in the review.

Ford's production policy currently does not use a geometric dimensioning and tolerancing standard (GD&T) Having spoken to members of the DM department the author is of the opinion that there is current pressure from senior management at Ford to introduce a standard such as the ASME Y14.5M for use in body design Tolerance specifications tend to be coordinate point based which references a digital model created during the reverse engineering process of vehicle clay mock-ups Manufacturing and assembly would like design to define tolerance specifications. However, design would prefer if manufacturing and DM sections became responsible The root to the problem is that currently only design can approve and release drawings and are therefore accountable for their content Design would like manufacturing and DM to provide input to the drawings but also become responsible for the content, something manufacturing appears reluctant to undertake.

Ford have developed their own comprehensive common location standard which is being used on all vehicle programs in the USA The common location scheme has helped standardizing location features and their associated tolerances on both components and manufacturing/assembly tooling Features of datum have also been included in the location standard. It is now policy for tooling design to orientate fixture part planes normal to vehicle coordinate axis system in x, y, and z

Ford has primarily been using the VSA software for circa fourteen years. They have also been using the DCS software for circa seven years Currently the DM department have engineers who can operate the computer analysis software, but some of the modelling is undertaken off site A major subcontractor to Ford is Craftline Inc Craftline manufacture assembly jigs for various vehicle programs and they use the DCS software for their own computer analysis. The build

analysis is presented to Ford as part of Craftline's quality assurance documentation Most vehicle design work is undertaken in the PDGS Ideas CAD system

The benefits claimed by Ford as a result of pursuing a DM strategy are

- Reduction in vehicle development time
- Reduced program development cost.
- Reduction in warranty claims
- Fewer problems associated with vehicle launch

3.1.3 McDonnell Douglas Aerospace

The McDonnell Douglas Aerospace visited is based at PO Box 516, St. Louis, MO 63166

McDonnell Douglas Aerospace is using DM techniques to address product design as part of a broader initiative focusing on the introduction of an integrated product development (IPD) strategy. The motive for the initial introduction of DM stems from its perceived success in the automotive industry. McDonnell Douglas believed that these techniques may bring benefits it terms of product development efficiency A DM pilot project was introduced in 1992 shortly after which it was launched over several other projects It was used in conjunction with other techniques such as design for assembly (DFA) and design for manufacturing (DFM) to aid in the development of the F18 E and F variants of the Hornet program The initial project involved the analysis of the splice between the centre/aft fuselage because of the concerns identified form previous aircraft build The VSA (22) assembly analysis product was used to model the sources of variation McDonnell Douglas claim this has resulted in savings of both cost and time with regard to product development and manufacture

The DM process is integrated with their own IPD strategy The product is spit into several zones each having an IPD team responsible for the development for that section A DM engineer is placed within each IPD team They become responsible for ensuring target dimensional quality specifications are identified, documented and managed for their product section. Dimensional quality targets for product manufacture and assembly are developed form IPD data sheets which contain functional design information They are also responsible for the cross functional communication and coordination of common datum's and locations between the product zones. The DM engineers in each IPD team make up a DM group who regularly meet and deal with dimensional quality related issues

McDonnell Douglas suggest the introduction of the geometric dimensioning and tolerancing standard Y14 5M has made a considerable impact to all sections of the organisation and has highlighted to design engineers the effects of poor tolerance, location and datum philosophy. This has been achieved by large scale training across all sections of the engineering organisation with some 1,800 staff being trained in various DM related techniques The widespread use of GD&T has led to the design intent becoming better understood by the manufacturing, tooling, inspection and assembly engineers who now share a common reference datum. This had the effect of making the communication of product development more clear and consistent and directly assists the cross functional activity required by the IPTs'

The use of DM by McDonnell Douglas is primarily for design validation and both the standalone and integrated VSA assembly analysis software and process are currently being used on all design releases.

3.1.4 Raytheon Aircraft

The Raytheon Aircraft visited is based at Central PO Box 85, Wichita, Kansas 67201-0085.

Raytheon Aircraft employees a DM process originally introduced through small pilot projects They became aware of DM through the perceived success at the Chrysler Corporation and decided to investigate the tools and techniques being used there. The original pilot project was use to aid an engineering analysis on a landing gear unit. The analysis was undertaken using the VSA software and the aim was to identify and quantify sources of potential manufacturing and assembly quality concerns. Raytheon were further interested in using DM to make improvements in the design engineering process and to gain a better understanding of their current manufacturing and assembly process capability

Raytheon are following an IPD strategy for product development and series manufacture. Customer requirements are captured up front via a QFD type technique which then identifies and quantifying the important quality attributes The product design is then split with each zone becoming the responsibility of a PDT. A DM engineer is assigned to each team and they become responsible for the management of dimensional quality issues. Each DM engineer makes up a DM group who regularly meet and discuss related issues. The DM group make up part of the quality assurance and management department which is a little unusual as most other DM groups either operate independent of any department or are associated with manufacturing and assembly

Raytheon have introduced a GD&T standard into the engineering organisation and currently have two engineers responsible for the identification and allocation of call outs on designs. They believe the placing of GD&T call outs onto drawings will play a significant role in making the design intent clearer A potential concern for the company is the level of understanding of GD&T through the engineering organisation The work undertaken by dedicated experts to place correct GD&T call outs may become undone through the incorrect interpretation by untrained shop floor and inspection personnel

One of the aims of the DM implementation was to investigate and analyze manufacturing process capability Raytheon have introduced comprehensive SPC techniques in order to help address the issue of SPC rating schemes which are required to ensure the capture and maintenance of defence business contracts. Some of the data being generated from SPC forms the basis for tolerance metrics to be used in assembly model analysis.

Raytheon claim as a result of following a DM strategy the main benefits have been to recognize the weaker areas of their manufacturing process and its resultant effect on product dimensional quality Due to a better understanding of inspection techniques, they have developed smarter ways of working which have led to a reduction in time spent on inspection The DM implementation has been managed and maintained by the quality control department Raytheon wish to promote a more cross functional approach to product development which they hope will lead to better communication and boundary demarcation throughout the engineering organizations

3.1.5 Northrop Grumman

The Northrop Grumman visited is based at One Northrop Avenue, 3855/63, Hawthorne, California 90250-3277

Northrop Grumman does not have an official DM process in place but they have been operating a variation reduction (VR) group for some years The VR group was responsible for the introduction of DM after becoming aware of the claimed success of the automotive industry. First pilot project was undertaken on an aircraft air intake which was associated with high assembly cost and lead times

Northrop develops aircraft using an IPD strategy but does not use a QFD approach to capture and deploy attribute data From top level requirements key characteristics are identified and

developed with the associated information being recorded onto IPD data sheets. This information becomes the focus of all variation reduction activities

The VR group introduced the concept of manufacturing and assembly variation and its effects on product dimensional quality Very little assembly variation modelling is undertaken by the VR group the remainder of which is contracted out to the VSA company as and when necessary. The VR group has received training on issues surrounding both the process of DM and the use of assembly modelling software from VSA. Their computer analysis has been undertaken on a DOS based VSA-3D product by they have recently moved to the VSA-3D Unigraphics integrated CAE system. Northrop Grumman also makes us of the IGRIP software imbedded within the Unigraphics CAD system for assembly modelling

Northrop Grumman has had an SPC program in place for several years Currently, they use small portable computer units known as data mites to capture the ongoing SPC data. This data is then transmitted via a company network cable to a central database This data base is mainly used for process control but it additionally used by the VR group as the basis for model analysis data.

Northrop Grumman claims that the VR group and their processes have benefited the company in several ways. As a direct result of their work and following an analysis by VSA, an estimated 90% assembly cost, and reductions in lead-times, was recognized on the initial air intake project. This was achieved by design alterations to both product and to the related lengthy shimming process. Northrop also benefited from the type of engineering analysis which often highlighted other quality related issues such as poor fixture design. One concern of the VR group was the perception of their activities by the engineering organisation. Design, manufacturing and assembly engineers perceived the VR group as being more akin to dedicated computer programmers who have become removed form the everyday challenges of aircraft engineering. This is an understandable observation and is not exclusive to the Northrop Corporation This problem occurs in many companies in the early stages and can be attributed to the amount of emphasis placed on the use of variation analysis software in an attempt to resolve an engineering concern. This is a misconception and the real value of DM will only be realized through the use of much broader activities coupled to a comprehensive company wide DM process. This problem of perception has been exasperated some what by the difficult and user-unfriendly analysis software, which is currently being addressed with its integration into CAD and visualisation systems.

3.1.6 The Boeing Company

The Boeing Company visited is based at the Commercial Airplane Group, PO Box 3707, M/S 5C-01, Seattle, WA 98124-2207

Boeing claim to be the first large aerospace company to introduce the techniques of DM into their product development strategy Their motive, as with McDonnell Douglas, was to investigate the success being claimed by the automotive companies in variation reduction and introduce these techniques it into their own organizations

DM was first introduced into the organisation in 1991 by the subcontracting of several VSA analysis engineers in house. The number of subcontractors have been steadily reduced over the years each one being replaced by a fully trained Boeing employee The strategy was to transfer the expertise and technical know how from VSA into the DM group of engineers at Boeing, therefore transferring and holding the expertise in house Making the same changes as other aerospace organizations, Boeing have partly dissolved the functional design organisation and replaced it with integrated product design teams The teams of engineers are made up from different disciplines, with each team being responsible for a section of the product. The role of the DM group is to support and work within the IPD teams taking overall responsibility for all aspects of dimensional quality. Boeing are using DM for more than product and process design validation purposes, that is they do not undertake computer analysis on every drawing released as policy. They have developed a technique known as Key Characteristics (KC) as part of a Hardware Variability Control (HVC) program This technique is used to identify product features whose uncontrolled variation will play a major factor in product fit, performance, and service life KC are identified and captured at the early stages of the design process. The process dissolves the defined customer requirements down to the system level detailed features and attributes through the 'drawing tree'. These are then built via the process of product assembly through 'build trees'. These key characteristics then become the focus for the DM process and are managed through all the design, development and manufacturing stages

Boeing have also introduced geometric dimensioning and tolerancing (GD&T) to extensive parts of their engineering organisation and have experienced the same success as McDonnell Douglas They have adopted the ASME Y14 5M standard for all tolerance call outs on certain aircraft projects

A great deal of Boeings products are subcontracted out and the variation management of these products are a major issue with regard to quality Subcontractors are trained and expected to

follow the KC techniques into their level. Boeing suggests that the DM engineers within IPD teams need have excellent communication strategies This is because often the situation exists where a subcontractor may be supplying part of a product that will include more than one IPD team

In addition to the US study tour, a number of European based aerospace manufacturers associated with DM were visited by the author. The findings of these visits are presented in the following section

3.2 Dimensional management within European aerospace companies

A further review of aerospace companies within Europe perceived as practicing DM was undertaken. These companies were:

- BAE SYSTEMS.
- Saab Military Aircraft
- Airbus

3.2.1 BAE SYSTEMS (1998)

Site visit:

Warton Aerodrome, Warton, Preston, Lancashire PR4 1AX.

Samlesbury, Balderstone, Blackburn, Lancashire BB2 7LF

BAE SYSTEMS formerly know as British Aerospace Military Aircraft and Aerostructures (BAe MA&A), were operating some pilot schemes in DM with the first emerging in approximately 1994 The motive for DM came from the assembly organisation seeking improvements in component and assembly variability. This again was to investigate claims by the automotive and aerospace industries in the successful reduction of manufacturing and assembly variation following a DM strategy

It has primarily been used to evaluate variation in airframe structure assembly and its effect on component interchangeability on the Typhoon (Eurofighter) program. The main pilot projects have concentrated on the dimensional analysis of the front fuselage structures using the VSA and VALISYS Assembly software product. Advances made in the Typhoon warplane design has

presented engineers with new challenges with regard to dimensional accuracy. Unlike previous aircraft, the Typhoon's outer panels are designed to carry a higher proportion of the dynamic loading and some are also required to be interchangeable This combination of requirements required careful analysis to facilitate the allocation of the correct tolerances In addition, it is being used to aid the development of a new advanced manufacturing process, and associated tooling and inspection philosophy. BAe MA&A use the Dassault Systemes CATIA CAE system and are using the integrated digital assembly and inspection modules of the Tecnomatix Technologies VALISYS product to analyse potential variation problems

BAe have introduced an IPD strategy into their organisation and are moving away from rigid departmental product development They are developing their own DM process which is tightly integrated into their product development process The process places emphasis on the comprehensive capture of customer requirements and their breakdown into company wide steak holders. The process follows through all stages of development and series manufacture

BAe MA&A believe that DM should not only be used to aid product design but should additionally be used to simultaneously design and develop manufacturing, assembly and tooling processes. This means both product and process become the subject of consideration and analysis. A comprehensive SPC program in now in place and this will be used to monitor, control and evaluate manufacturing and assembly process capability

GD&T is gradually being introduced into the organisation and a number of training programs are underway. BAe MA&A wish to reduce the use of company standards for tolerance allocation and focus on the comprehensive allocation of tolerance call out with a clear datum of reference. This information is also intended to be used by inspection in order to make the management of consistent dimensional quality consistent.

3.2.2 Swedish Aeroplane AB (1997)

Site visit:

Warton Aerodrome, Warton, Preston, Lancashire PR4 1AX

Swedish Aeroplane AB (SAAB) are based at Linkoping, Sweden but were visited at BAE SYSTEMS Warton.

SAAB started to introduce DM into the organization during 1996. Once again, the perceived success of other aerospace organizations in the reduction of product variation and claims of reduced development lead-times and cost provided the motivation to investigate the techniques of DM

SAAB remain at the early stages following a pilot project which began in the early part of 1997. The project addressed the area of identifying and controlling the 'key characteristics' of an interchangeable canopy assembly and how this relates to issues of GD&T control. The aim was to identify, quantify and manage these characteristics from the up front design stage through to the series manufacture The development of process and product data will be used for the purpose of variation trace ability at any stage of product development As part of this development Saab has an ongoing SPC program which is being used to identify levels of variation associated with each manufacturing process.

The main purpose of the pilot project was to develop an implementation plan for a tolerance management methodology The aim is to reduce time and cost of product development, reduce levels of rework and improve product dimensional quality.

3.2.3 Airbus (1998)

Site visit:

Airbus, New Filton House, Filton, Bristol BS99 7AR.

Airbus, Broughton, Chester, Clwyd CH4 0DR.

Both Airbus sites were visited in order to identify and define the case study work to be undertaken in support of this thesis The work undertaken following these visits are presented in chapters 6 and 7 of this thesis

A small number of European based aerospace manufacturers associated with DM were identified and visited The findings of each of these visits have been documented and presented in this section of the report. The Airbus visit was of particular interest as these led to the identification of a number of small projects which have been use to support the findings of this research project

3.3 Dimensional management case examples

The following tables highlight a selection of DM analysis cases It includes information such as company name, problem case subject, and the computer analysis tools used

The case examples were identified from the US study tour, European company activity research, and the authors own commercial knowledge. These analysis examples have been undertaken between 1996 and 2004

Some aerospace case examples are given below:

Company	Problem case	Software tools
McDonnell Douglas Aerospace	Analysis of splice between centre/aft fuselage sections on F18	VSA, UG CAD integrated, and Cognition – Mechanical Advantage
Aerospatiale	Cockpit design – linkage analysis on Rafael	Cognition – Mechanical Advantage
BAE SYSTEMS	Analysis of Typhoon (Eurofighter) front fuselage as part of Proof Of Concept study	VSA, CATIA V4 CAD integrated, and VALISYS assembly
Raytheon Aircraft	Analysis of landing gear assembly on Beechcraft	VSA, DCS Both standalone on PC
Swedish Aeroplane AB (SAAB)	Preliminary studies on Gripen canopy structure for interchangeability	Intending to use VSA, CATIA CAD integrated
Northrop Corporation	Analysis of air intake assembly (aircraft type not known)	VSA
Boeing	Analysis of large fuselage, closures, wings and flying surfaces on many commercial aerostructure designs	VSA and CATIA V4 CAD integrated, VALISYS Assembly, and Cognition – Mechanical Advantage DCS CATIA V5 integrated
Airbus	Analysis of wing box structure on A3XX concept aircraft and A400M	eM-TolMate DCS CATIA V5 integrated

Figure 11 Case examples of DM in the aerospace industry

Some automotive case examples are given below.

Company	Problem case	Software tools
Ford Motor Company	Analysis of BIW assembly, light clusters, suspension, engine decking on Focus (C170) Analysis of engine deck, and instrument panel on Mondeo (CDW162), other	VisVSA and DCS CATIA integrated
Chrysler Corporation	Analysis of BIW assembly, drive train assembly, and interior fit of Neon and a number of trucks	VisVSA and DCS CATIA integrated
Jaguar	Analysis of body assembly, bonnet and boot closures on XK8 (X100) Analysis of full body on XJ6 replacement (X200) Analysis (FEAD) on AJ28 V8 engine, other	VisVSA and eM-TolMate
MG Rover Group	Full BIW analysis on 600 series replacement (RDI) Analysis on FEAD of RDI engine Suspension analysis of Rover 75 Full BIW analysis on MGTF	VisVSA and eM-TolMate
General Motors (GM)	Analysis of BIW, (vehicles not known) Analysis of drive train assembly, (vehicle not known)	VisVSA, DCS standalone, and CATIA V4/5 integrated

Figure 12 Case examples of DM in the automotive industry

These aerospace case studies provide a valuable insight into the application of DM The most notable examples are BAE SYSTEMS, McDonald Douglas, and Boeing who used to DM technique to determine early product assembly build variation as part of a design validation process. BAE SYSTEMS also used DM techniques to help identify suitable manufacturing process specification, for example, CNC machine tool capability requirements Some case studies, namely Northrop Corporation and Raytheon Aircraft, were undertaken based on root cause analysis at the full production stage.

The following section indicates the type of product development area for DM analysis within different industrial sectors. This list has been produced by the author based on commercial knowledge, but is not exhaustive of all current DM application case studies This case study material is not available in the public domain.

Automotive sector:

Power train

- Manifold assembly
- Bearing clearances
- Timing gear alignment
- Seal location
- Timing variation (piston to valve clearances)
- Compression ratio.
- Fuel pipe alignment
- EGR pipe installation
- Exhaust bracket design
- Accessory drive belt alignment
- Engine mounts and decking
- Gearbox functional analysis.

BIW

- Complete BIW assembly capability
- BIW functional fit
- Interior/exterior packaging
- Power train packaging.
- Tooling manufacture and assembly standards evaluation
- Suspension kinematic analysis

Aerospace sector:

- Aircraft fuselage structure final alignment

- Al fuselage structure/CFC panel interchangeability function analysis.
- Aircraft structure fuselage/wing redesign evaluation
- Aircraft structure main closures fit analysis
- Wing assembly process capability studies
- Aero engine installation and alignment
- Jet engine reverse thrust shell kinematic function
- Jet engine nozzle kinematic analysis.
- Undercarriage assembly.
- Manufacturing process capability study
- Tooling manufacture and assembly standards evaluation
- Aircraft cockpit linkage kinematic analysis.
- Cockpit canopy assembly analysis

Medical equipment sector:

- Inhaler mechanism validation
- Drug dispensing machines.

Electrical goods sector:

- Thermal switching kinematics analysis
- Electrical switch gear assembly and function analysis.
- Mobile phone assembly validation
- Photocopy assembly and function
- Computer printer assembly and function

Heavy plant sector:

- Engine alignment analysis
- Engine essential equipment alignment
- Armoured vehicle hull assembly validation

3.4 Dimensioanl Management best practise critique

In order to establish DM best practise a study tour of key companies was planned and executed The tour included a number of leading automotive and aerospace companies and gave an insight to how DM methodologies were being used by these two industries The tour included visiting

two automotive and four aerospace companies in the US, and three aerospace companies in Europe.

The tour revealed that the two US automotive companies, Chrysler and Ford, have been and using DM techniques for a longer period of time compared to the aerospace companies Both companies claim to have a fully documented DM methodology as part of their overall PLM strategy and this is used in both a preventative and trouble shooting capacity. Three of US aerospace companies, McDonnell Douglas Aerospace, Raytheon Aircraft, and Northrop Grumman, only use DM techniques for the purpose of risk mitigation on limited areas of the airframe identified as being a potential problem The areas of concern are identified either from past build experience (carry over geometry) or from new and complex geometry systems None of the three US aerospace companies have an integrated approach to the use of DM with respect to an overall PLM process. The Boeing Company did however have an integrated DM methodology to support aircraft development and manufacture throughout the PLM life cycle. This methodology is called HVC and includes the extensive use of KC feature identifiers for product definition and validation.

The DM study tour was extended to include three European aerospace companies, these being BAE SYSTEMS, Saab Military Aircraft, and Airbus As is the case with the majority of the US aerospace companies, all three European companies only used DM techniques for the purpose of risk mitigation on potential problem areas and did not have an integrated methodology. The possible exception to this was Airbus Airbus do not operate a comprehensive DM methodology as part of an overall PLM process, but they do undertake complete zone analysis An example of this type of zone analysis could be the dimensional investigation of a complete wing structure

3.5 Concluding comments

The industrial review of DM practices in automotive and aerospace has complemented the literature review by exposing the industrial and commercial best practice. The literature and industrial reviews in chapter 2 and chapter 3 provide the basis information from which the DM need can be drawn This need is outlined in chapter 4

Chapter 4

4 The need for dimensional management

Objectives: The main objective of this chapter is to outline the need for a DM methodology within the aerospace industry based on evidence presented in the literature and industrial reviews presented in chapter 2 and chapter 3 respectively This chapter further outlines the case for the DM methodology and it includes

- Outline the relative importance of variation control in aircraft manufacturing
- Highlight future challenges in aircraft structure manufacture
- Make the case for DM in the development of next generation aircraft

4.1 The need for a dimensional management methodology

As previously highlighted, within the current competitive aircraft industry environment, new design, manufacturing and assembly methods are being developed to address the issues of affordability and to provide a more consistent product (Muske 1997) One area of aircraft design and development could be far better exploited in order to achieve these aims, this area is DM.

Traditionally, design engineers are primarily concerned with issues of functional requirement, structural integrity, and style The communication of tolerance, datum and location schemes of a product then becomes a secondary concern (Craig 1996) An important part of the design process requires the determination of nominal dimensions and the application of tolerances These need to be administered such that each individual part will meet the performance intent of the design and specific functional requirements, interchangeability for example Dimensions therefore not only specify the size and shape of a product, but they maintain the design integrity of the parts during manufacturing and assembly (Henzold 1995; Spotts 1983) Many of these issues are covered by blanket company and international standards and are then left to various interpretations by the down stream activities of manufacturing, tooling and assembly building in unnecessary cost into some cases This has led to the existence of the 'hidden factory' (Leaney 1996), where even at the late stages of production operators and fitters are "adjusting" out variation problems The result is production waste affecting domestic affordability, as well as compromising product quality.

Sources of waste due to variation (dimensional noise) will need to be identified and managed if aircraft manufacturing organisations wish to become more competitive Variation waste can be found in manufactured components and subassemblies, assembly fixtures and tools, the design/manufacturing/assembly/inspection processes, and human intervention (McCuistion 1994)

With the advancement of CAD/CAM/CAE systems integration and a strong requirement for enterprise collaboration there is an opportunity to further evaluate the 'digital' product and process at the early lifecycle stage to verify design, manufacture, and assembly against customer specification There are however, potential drawbacks. Most design and analysis work is undertaken in the digital environment which can become detached from the actual manufacturing world where product and process is fraught with variation. Within this virtual and precise environment the consequence of actual manufacturing and assembly variation cannot be foreseen posing an engineering development risk The DM process can address this by performing risk mitigation on product and process design by evaluating their robustness to actual upstream variation. This evaluation may be done using variation analysis software tools These software tools assist in the verification of design, manufacture, and assembly tolerance specification against product attributes such as flying surface step and gap

The introduction of dimensional variation from upstream manufacturing processes in addition to poorly defined location and datum schemes may produce major problems for an assembly organisation, (Jeffreys, Leaney and Wood 1998) Given that industry experts suggest that approximately up to 60% of series production waste is attributed to assembly process problems there seems to be justification to incorporate DM techniques in order to reduce this metric.

4.2 Manufacturing challenges for future aircraft

The Industrial College for the Armed Forces (ICAF) defines four categories of aircraft manufacture, these being (ICAF 1998)

- Commercial fixed-wing aircraft (commercial aircraft).
- Military fixed-wing aircraft (military aircraft).
- Rotorcraft
- Jet aircraft gas turbine engines.

The scope of this thesis is confined to the commercial and military fixed-wing sectors, although the broader principles relating to DM could equally be applied to the remaining sections.

The next generation of both military and commercial aircraft will be designed using novel concepts, new materials, and revised manufacturing and assembly strategies This new generation can be partly caricaturised by (Jeffreys, Leaney and Wood 1998)

- Integration of digital design and test environments - virtual product development.
- New airframe structure design concepts
- Introduction of new material types
- Development of improved aircraft maintenance systems to reduce owner-operating costs.
- Migration from master tooling gauge systems to digital inspection
- Introduction of complex component and assembly inspection analysis techniques
- Investment reductions in manufacturing and assembly tooling and fixtures.
- Part to part assembly strategy (minimum fixture tooling concepts)
- Much greater emphasis on product and process affordability.

4.2.1 Military fixed-wing aircraft

In the military sector the design and development of programs such the Eurofighter Typhoon and the joint strike fighter (JSF) has heralded a departure to conventional aircraft structure design. The major component of dynamic load in traditional aircraft is carried by the airframe structure with the exterior skins providing the aerodynamic shape. This can be likened to a car with a chassis with the outer body panels providing functional shape and aerodynamics. Traditional aircraft structures and exterior skins, such as those in the BAe MA&A Tornado GR4 and Hawk T45 for example, are mainly assembled using large numbers of mechanical fasteners such as rivets and bolts. Structure and skin components are drilled using 'hard' (fixed) jig/fixture tooling templates and the holes facilitate both down stream location and fastener insertion access features Adequate levels of process repeatability are achievable with this type of tooling regime However, it becomes difficult to make tooling adjustments in response to component or subassembly variation created in earlier upstream manufacturing and assembly activities A further disadvantage with traditional jig and fixture tooling is that it is produced from a master tooling gauge or master media which are physical representations of the aircraft subassembly design These are used to create, and transfer product standards throughout a tooling family (Fowler 1997) There is also a significant cost associated with the construction, maintenance and modification of these traditional tooling methods.

A number of military aerospace manufacturers have moving away from this traditional manufacturing and assembly methodology realising it would not be capable of delivering a product which would fulfil (or exceed) customer technical requirements given the intended future aircraft designs

The design of future military aircraft structures will be characterized by a monocoque concept. In this concept the majority of the dynamic loading of the aircraft is carried in the outer panels which also function as aerodynamic flying surfaces. The panels are then assembled to a simplified ultra lightweight metallic and composite substructure This can be likened to a modern high performance racing car where the structure and outer shape are combined into a monocoque configuration. One of the primary objectives of all military aircraft design is to increase the dynamic flight envelope and this can mainly be achieved through the reduction of aircraft mass. Current and medium term programs will achieve this through the introduction of new materials and manufacturing processes producing components with an increased strength to weight ratio. Composites such as CFC and glass reinforced plastic (GRP), and advanced metallic' such as Al and Ti are an example of materials Some composite materials have been use in a more limited way for a number of years in the aircraft industry but generally for primary structure. The introduction of major CFC panel components throughout the aircraft has allowed the monocoque design to be realised given its excellent strength/stiffness/weight ratios

Aggressive customer demands place further requirements to be absorbed into concept designs. An example of this would be the introduction of component interchangeability (ICY) on some of the primary structure CFC panels A number of the CFC panels on current and future aircraft will need to be removable to allow access for the maintenance and repair of aircraft during down time This has required a trade off in design specification between the CFC panels and corresponding substructures An example of this is for CFC panel and substructure fastener hole positional tolerance to be large enough to accommodate ICY, but also be capable of accommodating the stringent stress requirements with regard to the hole/fastener positional interface

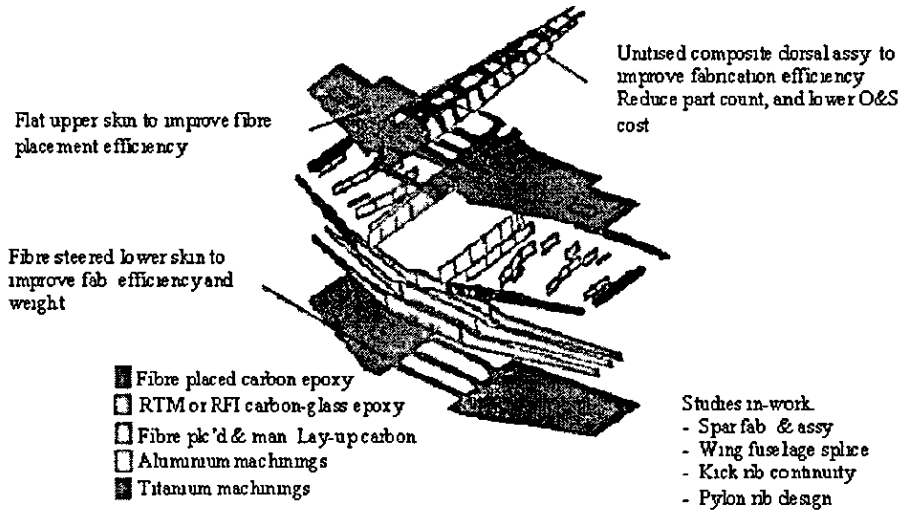


Figure 13 Advanced lightweight aircraft fuselage structure (ALAFS 1997)

In the construction of traditional aircraft the majority of structural and external skin components are made from aluminium/titanium (Al/Ti). These materials are ductile and may be stretched or flexed to suite These Al and Ti components therefore can be regarded as 'conformable' in nature This allows the variation of a component to be absorbed through 'finessing' during the assembly process. Future aircraft monocoque design concepts will reduce the opportunity for component and assembly finessing The incorporation of CFC in both the outer panel surface and substructure will be substantial and by the nature of the material will not 'conform' The concept also incorporates a reduction of structural components Where Al/Ti substructure assemblies are to be used their part count will be reduced compared to traditional aircraft, resulting in structural component being more complex, substantially stronger, and more rigid

An example of the next generation aircraft design technology has been tested on a section of the F/A-18 E/F Hornet military aircraft The purpose of the advanced lightweight aircraft fuselage structure project was to explore and develop new design methodologies by conducting a 'clean sheet' design on a section of the aircraft. This involved combining the centre fuselage and the inner wing section into an integral airframe assembly A diagram of the concept design can be seen in the figure above.

The main drivers for military aerostructures are

- Low observability, requires the aerostructure properties to have specific control with regard to step and flush specification.

- Increased flight envelope, requires an increase in aerostructure mass to dynamic strength ratio achieved through new materials and manufacturing techniques.
- Variant flexibility, design of a core common aerostructure which, with the use of modularity, may be used as the basis of several derivatives
- Reduction in aircraft unit purchase cost; achieved through the introduction of lean and agile manufacturing process and modular design principles.
- Higher maintainability standards; achieved in the main by designing customer ICY specifications.
- Target market; customers are domestic and foreign governments facing specific defence threat.

4.2.2 Commercial fixed-wing aircraft

Currently, only two major commercial aircraft manufacturing organisations exist, Boeing and Airbus. Both companies are considering future super jumbo design concepts, but Airbus has taken the initiative with the development of the A380

It is likely that the commercial sector will follow the lead of the military sector aiming for design simplification, part count reduction, and the further integration of composite with metallic materials for primary and secondary structural assemblies, particularly in wing design and development. Composites such as CFC and GRP have been an established technology for structures such as horizontal and vertical stabilisers (tail section) and wing box stringers for some years. However, it has never been used extensively as a primary structure material, for example, for an entire wing box construction This may change for future aircraft as designers pursue various concepts for weight reduction advantages.

One of the critical elements of any large aircraft design is the wing construction Airbus is exploring the possibility of producing a wing box constructed predominantly from composite material This is a significant departure to traditional wing construction that consists of mostly Al/Ti materials. Current wing box assembly involves the use of techniques known as 'fettling'. The fettling process requires designated interface surfaces on wing structure components to be deliberately manufactured with excess material which is then removed to facilitate assembly to a specific criterion. Conversely, where not enough material exists a 'shimming' process is incorporated which involves the building up of a material surface at a subassembly interface These techniques have evolved because certain wing components and subassembly interface features cannot be controlled well enough to achieve the target specification An example of this where excess material is left on the interface features of wing rib and wing skin components

known as 'variation float'. During the assembly process the required material thickness on the rib interface surface is calculated by measuring the corresponding skin thickness The fettling operation is used to remove excess aluminium material using an assembly jig mounted routing tools. This technique is necessary due to an assembly philosophy that submits to not being able to management component accuracy such that no intervention is required These techniques lead to.

- Extra cost incurred directly attributed to the assembly process.
- Lead-time of wing box assembly is longer than necessary
- Each wing box construction is geometrically unique resulting in an increased risk with regard to subsequent subassembly build operations
- Opportunities for component and subassembly interchangeability at the initial assembly stages and at subsequent maintenance stages are impaired
- Concern for environmental control on the assembly line; the fettling process results in small particles being produced and deposited on the product and tooling

The introduction of CFC materials will greatly reduce the viability of fettling techniques due to the constraining nature of the material Much greater control of component to subassembly interface features will be required and this can in part be assisted through the DM process

Commercial aerostructures main drivers:

- Cost of ownership, requires flight efficiency which is dependent on structure alignment, stringent step and flush specification to avoid turbulence
- Higher maintainability and operation flexibility; requires customer level ICY.
- Safety, requires material structural integrity.

4.3 Supporting activities/techniques to aid the DM Process

The previous section highlighted some of the new design concepts anticipated in the next generation of military and commercial aircraft Traditional aircraft engineering practices will need to be evaluated for their suitability in accommodating these new design concepts In response to the need, a number of engineering techniques and practices have been identified by the author based on the literature and industrial review These activities should be supported by a comprehensive DM program

The DM techniques and practices are highlighted on the following page

Develop new, or revise existing, manufacturing and assembly business processes; the manufacture of components from composite materials such as CFC and GRP is an expensive and specialist activity and is a marked departure from Al/Ti related processes Large Al/Ti structures elements will be geometrically complex and will need to be dimensionally robust

Adequately and effectively characterise manufacturing and assembly processes; the introduction or evaluation of current statistical process capability data for all manufacturing and assembly business processes This information should be openly available to all engineering sections of the organisation and should be presented in a clear and unambiguous format.

Reduce manufacturing and assembly jig/fixture 'hard' tooling requirements; a number of manufacturers are now using large precision (5 axis) machining tools. These machines are being used to drill/countersink and net profile CFC panel components in preparation for mechanical fasteners These precision operations allow CFC aircraft removable components to be manufactured with interchangeable characteristics. Automated assembly cells are also being considered for the drilling/countersinking and fastener insertion processes

Elimination of MTG and master media; the introduction of precision and flexible measuring equipment will reduce or eliminate the requirement for MTG and master media. These systems are based on laser interferometer technology (SMART 310 system from Lexica, for example) with dynamic tracking capability. These systems can be used in conjunction with master digital models created within the organisations CAD/CAM/CAE environments Organisations need to move away from gauging and towards a measuring philosophy.

Develop digital inspection techniques; this will provide a process for component, assembly and fixture tooling dimensional quality verification The master digital data stored within the CAD/CAM/CAE environment can be utilised as the nominal product media onto which mathematical tolerance zones known as soft gauges may be overlaid The inspection process data may be fed back into the digital CAD media to allow powerful inspection analysis Some CAD/CAE integrated systems have the capability to semi automatically develop off line inspection programming for equipment such as a co-ordinate measuring machine (CMM). This technique can also be used in conjunction with measurement equipment such as mobile CMM arms and vision based inspection systems.

Introduce geometric dimensioning and tolerancing (GD&T) concepts; in order to create clear and unambiguous component and assembly feature tolerance data a GD&T standard will need to be implemented and understood throughout the organisation. This will allow the semination of

dimensional quality requirements to engineering and will help in the characterisation of manufacturing and assembly process capability indices The application of feature and tolerance specifications should also be established in the digital CAD/CAM/CAE component and assembly database.

Use of variation analysis tools and techniques throughout the development process; to evaluate product parameter characteristics at the early stages of design, 1D and 1 5D variation analysis should be performed prior to detail CAD geometry being available. The use of parametric variation analysis (PVA) tools and techniques will validate early target product specification against manufacturing and assembly capability. The analysis findings provide the foundation for more detailed specifications to accompany master 3D CAD geometry. Comprehensive 3D synthetic geometric variation analysis (GVA) studies should be performed using full digital mock-up geometry on all aircraft zones to verify target quality product specification. These studies may later be reused to investigate an assembly process concern, for the validation of process capability levels, and for tolerance types and metrics

A key feature for future aerospace organisations will be the effective utilisation of integrated product development (IPD) strategies This will be used in an integrated product environment by integrated product teams (IPD), (Barrow 1997) Part of the DM process requires the product and process information from a number of cross-functional and multidiscipline engineering sections such as design, manufacturing, assembly and inspection. In this respect the DM activities directly promote IPD activity where each engineering section or discipline is invited to input their particular expertise ensuring that all engineering concerns and/or opportunities for improvement are taken into account

Due to the reduction of substructure component parts in the military and commercial aircraft sectors, new advanced assembly philosophies are emerging. The concept aims to eliminate a significant proportion of assembly fixture tooling and its existing cost through the application of new 'self tooling/location' principles Each component and subassembly will be produced with inherent self locating features and tooling features, in addition to its nominal functional architecture. These features will be used to facilitate component to component location for assembly purposes. Significant attention will need to given to the feature types and their control with respect to tolerance metrics if this new process is to be successful DM techniques can again play a major part in the design of individual components and minimal tooling, their features and their gauges The process could be effectively used to evaluate the risk of product none conformance and the engineering of alternative strategy.

In chapter 3 the findings of a study tour of USA and European aerospace companies by the author highlighted a number of issues relating to future airframe development programs. These issues relate to the design, manufacture, inspection and assembly processes of next generation military and commercial aircraft The product and process characteristics associated with these aircraft are more radical and demanding compared to current designs, partly triggered by the introduction of new structure materials and advanced manufacturing processes. Such developments present challenges, and opportunities, to engineers across the whole spectrum of design to series production

This thesis has already highlighted the development of an increasingly competitive aircraft industry, which demands new design, manufacturing and assembly methods to be developed at lower costs while simultaneously providing a more consistent and affordable product. In addition, there are new demands on airframe specification, for example, higher specification for interchangeability One of the major challenges engineering organisations are facing is how to ensure the control of product dimensional variation in order to achieve such aggressive specification for interchangeability as well as specific controls such as flying surface steps and gaps which fundamentally effect in service performance. This research project in part addresses the challenge by

- Developing a proposed DM methodology for use in the aerospace industry. The methodology, called PARES, is presented in chapter 5
- As part of the PARES methodology, design and develop a baseline parametric variation analysis (PVA) tool in support of early aerostructure wing box development. This is presented in chapter 6
- The PARES methodology is again supported through the geometric variation analysis (GVA) of a development wing box structure during the early detailed design phase when CAD geometry becomes available. The analysis is conducted using advanced 3D tolerance analysis software and is progressed through a series of DM case analysis examples which are presented in chapter 7

Chapter 5

5 Physical architecture robustness engineering system (PARES)

Objectives: This chapter outlines a proposed high level DM methodology in response to the need identified in cheaper 4 The physical architecture robustness engineering system (PARES) has been developed by the author in order to structure and integrate DM activity so it may complement current aerospace development initiatives such as the IPD process The approach respects the generic requirements of the aerostructure manufacturing organisations taking into account the types of analysis and engineering practices pursued The PARES methodology is presented under the following sections

- The PARES scope
- PARES methodology process, tools and techniques
- Methodology architecture.
- PARES benefits.

5.1 The PARES scope

The PARES methodology was developed by the author in response to the experience of industrial surveys and placements The process is designed to identify, analyse and manage complex product variation (product noise) from the early concept design stage through to full series production It will endeavour to manage product robustness, directly linking target specification to quality requirements management. The methodology challenges are:

- Evaluate dimensional requirements against intended design, manufacturing, assembly, and inspection process
- Maximise the use of digital product development technology therefore reducing physical prototypes to a minimum.
- Design and develop the overall quality management process to complement the product knowledge capture process
- Span the whole development and production lifecycle

5.2 PARES methodology process, tools and techniques

The proposed PARES methodology is made up of a number of concurrent activities and will be present through out the entire aircraft production phase The timing of each activity will need to be synchronised with the overall systems development and production method, for example the IPD process. The activities associated with PARES have been illustrated against a generic IPD process for military aircraft production (Barrow 1997) These activities can be seen in the figure below. The top bar indicate the major development phases and the principle maturity gates, while the middle bar depicts the phase codes

Using the IPD phases as a generic baseline the principle PARES tasks have been developed over the product lifecycle timeline. The task bars indicate the PARES methodology phases starting with innovation and ending with production The PARES activity bars are set in the middle section. The axis on this section signifies the development time line across the bottom and cost of change rising in relation The shaded areas at the bottom the illustration indicate the effort required at the early stages of development in order to save the peak of product and process change further down the time line

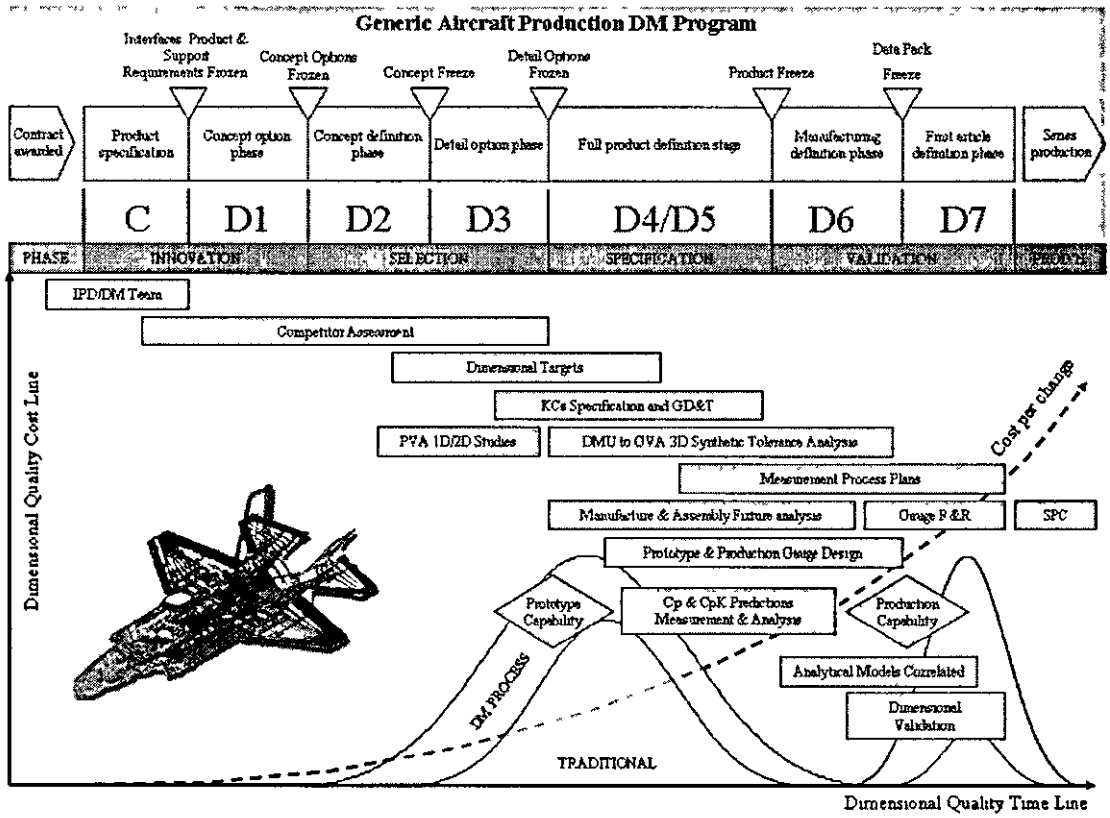


Figure 14 PARES high level DM program

The PARES development diagram can be seen in figure 14 The process tasks are described in the following section.

IPD/DM team: The first activity involves the appointment of an IPD DM team leader The IPD/TEAM leader will need to appoint a number of DM analysis engineer to act concurrently with other IPD members on specific physical zone of the airframe. An example team structure has been proposed by the author and has been association with a generic set of airframe zones as shown in the figure below

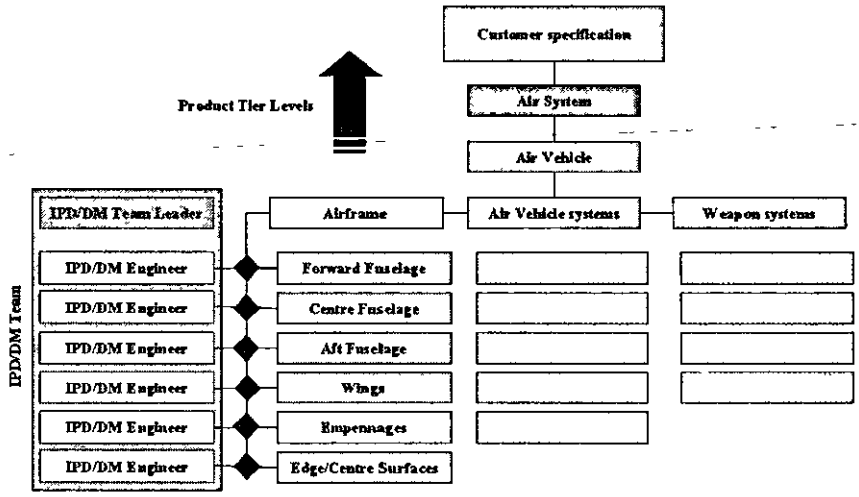


Figure 15 IPD/DM team allocation against generic airframe zones

Competitor assessment: This activity involves assessing the capability of other rival organisations This would involve a number of benchmarking activity to evaluate competitor product and process capability

Set dimensional targets: Define the dimensional targets for high level product attributes on the various defined zones of the fuselage, wings, empennages, and horizontal/vertical stabilisers. The defining of these zones must also be established. Product dimensional targets may include:

- Line of flight (LOF) profile tolerance for surface flushness (steps), gap and groves, waviness.
- Interchangeability standards for removable closures for steps, gaps, seals conditions
- Radar cross section specification for in to wind steps, gaps, fastener projection for fuselage, wings, engine air intake geometry

PVA 1D/2D studies: Undertake initial parametric variation analysis on available parameter design information This involves the use of simple generic tolerance models to help validate the

target concept design during the detail option development phase. An example of how this type of analysis may be developed is presented as a case study in chapter 6 of this thesis

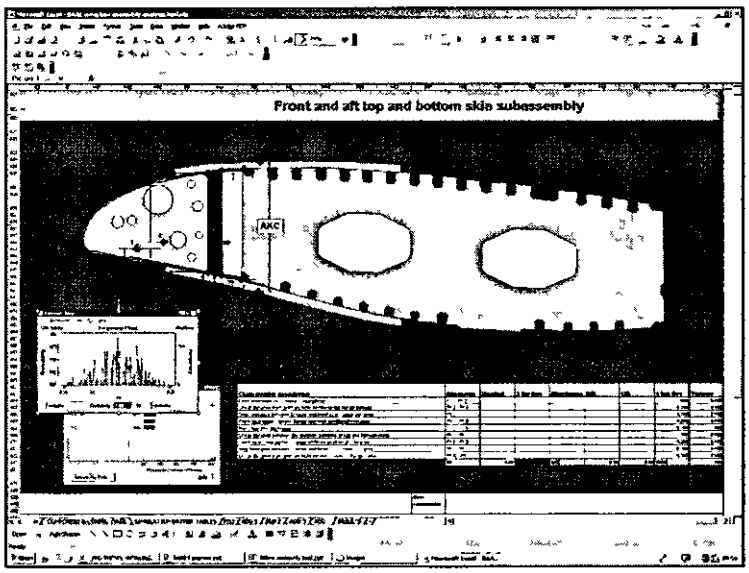


Figure 16 PVA tool interface

The PVA analysis will identify potential problem areas which become the focus for following detailed DMU geometric variation analysis performed in full 3D.

KC specification, GD&T, and feature identification: The PVA studies will established a first pass KC identification The detailed KC identification and documentation will need to be further developed by dissolving the product structure to piece part using 3D digital geometry to review manufacturing process Parts are then built back up to identify the assembly process From this activity all PKCs', MKCs', AKCs', and StatKCs' can be identified. Component and assembly features can be grouped and categorised into feature taxonomy The following table outlines such a taxonomy developed by the author as an example

Type	Domain
M	***Manufacturing feature:*** A feature used to facilitate the manufacture a component which may be subsequently removed during later process operations
F	***Functional feature:*** A detail on a component that will fundamentally effect the build quality of the aircraft
I	***Interface feature:*** Part/assembly feature which will interface with other part/assembly
D	***Datum feature:*** Component or assembly datum reference feature
L	***Location feature:*** A feature on a component used for location to an assembly fixture

Figure 17 Feature specification taxonomy

These features can themselves be further defined down to a mathematical definition. For example, a set of assembly location features on a component designated as (L) can be further defined as:

P1-z	Primary surface point 1, in Z direction
P2-z	Primary surface point 2, in Z direction
P3-z	Primary surface point 3, in Z direction
p4-z	Primary auxiliary point 4, in Z direction
H-xy	Secondary hole 1,
S-x	Tertiary slot 1

The KCs need to be defined at all assembly levels in addition to individual components. This can be achieved by breaking the product down level by level focussing on manufacturing and assembly attributes

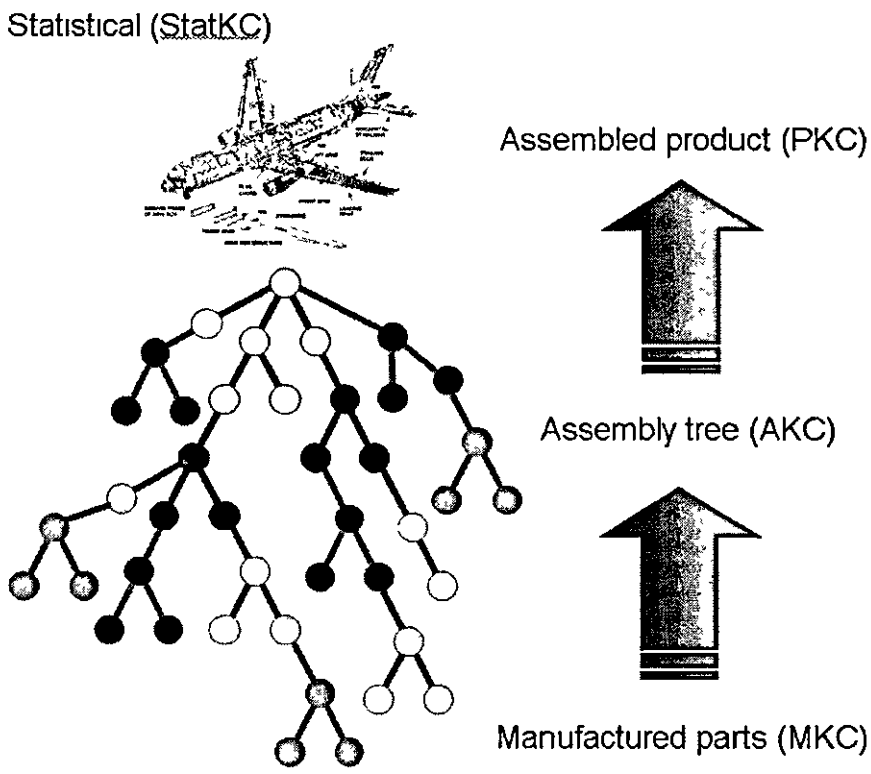


Figure 18 KC assembly flow through

Once the KCs have been defined their relevant GD&T tolerance specification can be specified as a first pass based on manufacturing and assembly process capability data. Manufacturing capability data may be categorised by component family types, material types, an advanced manufacturing types Product GD&T application is essentially done by building the product back

up level by level using the digital model where available to virtually assemble the product Part-to-part assembly tolerance allocation must be administered such that bonus tolerance systems are used in conjunction with fixed and floating fastener methodology This will ensure interchangeability and functional assembly can be achieved at each parent / sibling / child part interface

Digital mock-up (DMU) to geometric variation analysis (GVA) 3D: Once the KCs' and associated GD&T tolerance metrics have been applied a comprehensive 3D synthetic tolerance analysis study can be performed This is undertaken in a 3D CAD/CAE/DMU environment and will analyse the entire assembly process for hardware variation output. It will take into account

- Nominal clash detection and proximity analysis for all geometric sets or individual components
- Component and sub assembly sequences.
- Interaction of fixture tooling to facilitate assembly
- Intermediate stages of inspection and subsequent process alteration
- All component and assembly GD&T datum reference and tolerance metrics
- Definition of assembly move type.
- Static and kinematic assembly conditions
- Process and component assembly over constraint deformation based on FEA analysis.
- Temperature effects on assembly

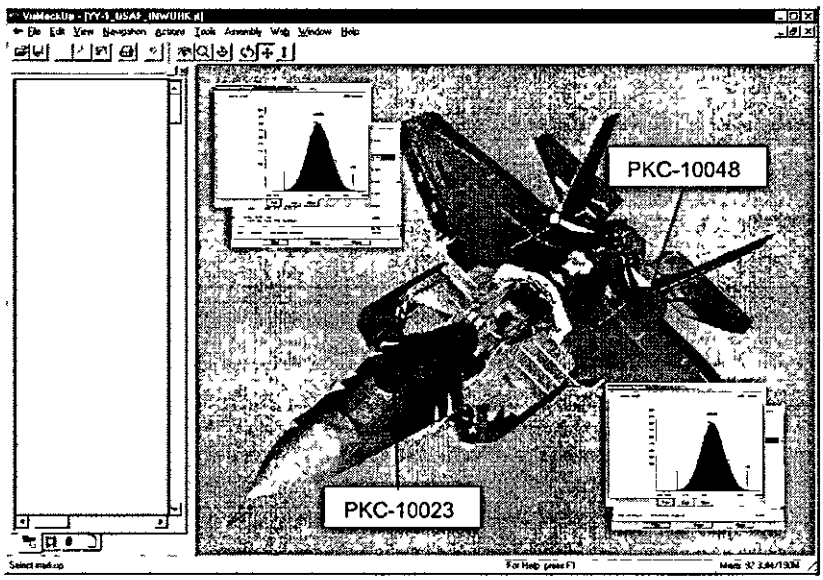


Figure 19 PKC variation outputs

The analysis can be iterative with the main product study being broken down into its major architecture zones, for example the forward, central, and aft fuselages. The analysis, to an extent, must follow the progress of 3D CAD geometry creation and the assembly process planning both of which are required to undertake the zone study. An example of this type of analysis is presented in chapter 7 of this thesis. It includes a number of wing box structure case studies

Manufacture and assembly fixture analysis: This activity is an extension of DMU product 3D synthetic tolerance analysis It has been separated in the PARES process due to the effort required to validate manufacturing and assembly fixture tooling Many aerospace organisations now outsource this activity The quality of the design and manufacture of assembly fixture tooling can have a huge impact on product quality. Products inherit much of their dimensional quality form the fixture system used to place and secure them in 3D space Traditionally, the design and manufacture of assembly fixture systems have been controlled by blanket coordinate tolerance standards which result in less than effective accuracy There is an opportunity to could be improved assembly fixture production through

- Specification of fixture KCs'.
- Application of complete GD&T geometry control.
- Evaluation of component locator strategy for correct mathematical constraint (6 DOF check)
- Integration of effective fixture feature adjustment to accommodate in service calibration

Cp and Cpk predictions and measurement analysis: In support of the DMU product 3D synthetic tolerance analysis activity outlined above, the manufacturing and assembly business centres need to identify domestic and outsourced capability against target product specification. An example interface is given in the figure below

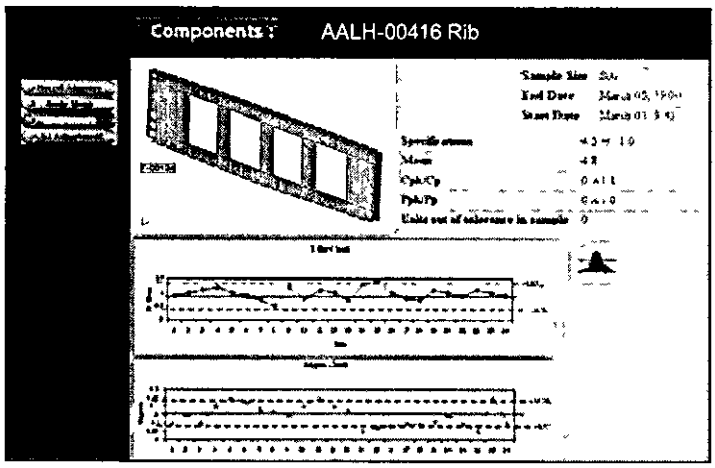


Figure 20 Component SPC database including Cp and Cpk

The synthetic tolerance analysis is undertaken initially with design tolerances based on normal distributions and target specification limits. These then become the input to the Monte Carlo simulation engine which processes this information to determine the synthetic stack outputs

Analytical model correlation: The next stage is to convert the tolerance analysis model into a synthesis model which combines all available manufacturing, assembly, and fixture tooling process capability data to the nominal model The synthesis model, where data is available, can then simulate the build characteristics based on correlated actual measurement data providing a more accurate prediction It is therefore very important to build and maintain a measurement knowledge database (as highlighted later) of all domestic, and where possible, supplier manufacturing and assembly process capability Where this information is not at all available, it is possible to acquire it from 3rd party software and production capability standards, ISO for example. It is imperative that organisations build and retain knowledge of their own process capabilities to be used in future development programs. Failing to do this will result in knowledge waste – one of the key wastes of the lean production philosophy

Measurement process plans: During the last stages, all KC and GD&T definition were defined and validated through the CAD/CAE/DMU synthetic tolerance model These steps will validate the high level design specification KCs' in a critical parameters brochure, against manufacturing, assembly, and inspection process capability metrics When all the tolerance analysis criteria are met, measurement process plan can be developed. The core information will be available form the last stages such as KCs and GD&T. Where appropriate, off line measurement programming may commence based out of the 3D CAD/CAE/DMU environments and these can later be proved out when prototype parts become available During this phase, the management of development and series production quality data should be considered Issues such as who will be the future customers for this data, what data will they require, and in what format will they need it needs to be addressed The planning of a central quality database for all measurement data types plus the type of customer interface will need to be considered

Gauge R&R: Gauge repeatability and reproducibility (R&R) specification is required to establish the appropriate media for inspection plans defined in the last stage. The gauge R&R technique assesses the process capability of a system to perform measurements defined by an inspection plan. Repeatability is an evaluation of how capable a measuring instrument may be to in terms of consistent accuracy. Reproducibility is an evaluation of the measurement system process including the man/equipment interface. When KC and GD&T information is available for component or assembly inspection, then gauge R&R techniques are used to define which

measuring systems are the most appropriate. This may be based on existing gauge R&R information from scheduled calibration routines.

Statistical process control: At the D7 final article definition (FAI) development stage, preparation for statistical process control (SPC) during series production should commence Product and process SPC undertaken at various levels of product maturity provides a constant indication of process capability and stability. It can also act as an early warning system flagging when a process parameter has becomes unacceptably out of control and in need of attention Again, the key information such as KC and GD&T is available and due to the gauge R&R information, the appropriate measuring systems have been defined. So the 'what' and 'how' is defined, all that remains is to specify the 'when' There are a number of SPC standards to calculate the appropriate sample size and measurement frequency After evaluation, the most appropriate standard should be adopted An example interface is given in the figure below.

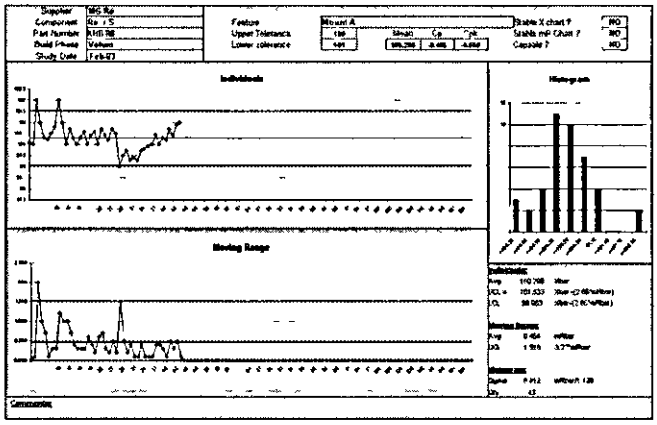


Figure 21 Post FAI SPC data definition and collection

Prototype and production gauge design: During the prototype and series production phases there will be a requirement to validate the different airframe components and sub assemblies for geometric compliance This is traditionally undertaken by physically comparing the component or assembly to a high specification master tooling gauge (MTG) and other master media hardware. This means that multiple MTGs' are required for the many stages of assembly build to validate component and assembly resultant geometry Due to their high specification MTGs' are expensive to both produce (manufacturing cost) and maintain (environmental specific storage). These costs could be radically reduced through the introduction of precision and flexible measuring systems. One such system is based on laser interferometer technology, i e , SMART 310, which has very high gauge R&R capability over large volumes These measuring systems can be used in conjunction with master digital models created within the organisation's CAD/CAE/DMU environments These digital masters act as a virtual MTG and the requirement

for physical MTGs' can be dramatically reduced or even eliminated Organisations need to move away from gauging and towards a measuring philosophy.

Dimensional validation: The final stage is to repeat the update the tolerance synthesis model again with series production measurement data and analyse the correlation between the virtual and the physical product. This synthesis model may now be used to predict overall product performance based on uploaded actual data This is useful if there is a long lead time associated with major assemblies from a supplier If the outsource organisation has actual data on the assembly they are about to ship, this data can be uploaded into the synthesis model to validate the variation effect on build specification If there is a problem, it can be highlighted before the assembly is shipped and a collaborative review could take place to resolve

5.3 Methodology architecture

The top level PARES architecture, developed by the author, is illustrated in the figure below The architecture is made up of six main chunks each being linked to the remaining. An explanation of each chunk and how it relates to the activities in the PARES process is given below

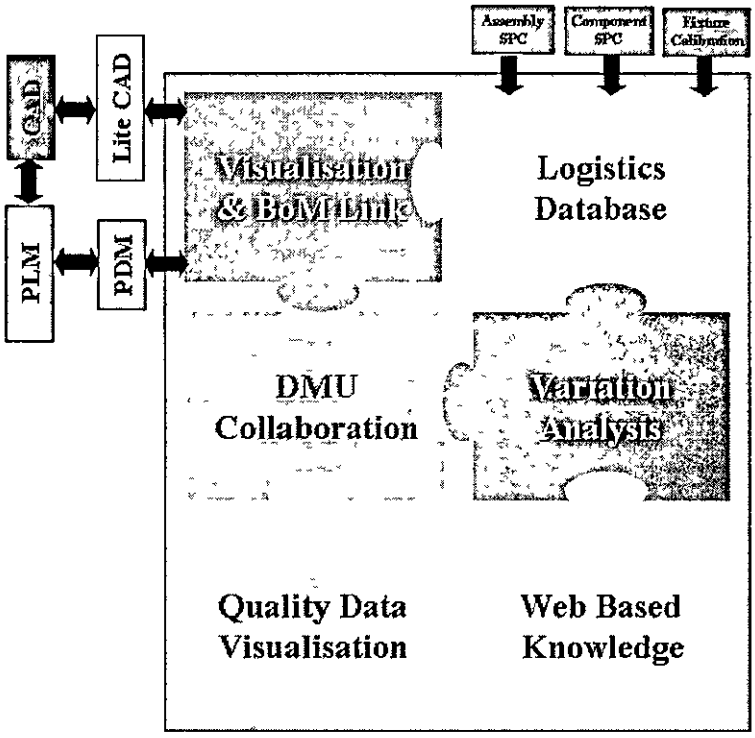


Figure 22. PARES top level architecture chunks

CAD and BoM links: Is responsible for the link to product and process digital information. Any DM analysis will be undertaken based on a digital data snapshot of the overall development

schedule Updates and changes to digital data will need to be flagged to the IPD/DM analysis engineers who my then manage the analysis model The CAD and BoM links include:

- CAD definition of product dimensional control zones for external surface controls, steps, gaps, waviness, surface finish
- Product definition assembly sequence, product variant data, fixture tool interaction, and inspection process stages
- CAD feature definition: fully defined KC and critical parameters brochure features, datum's', tolerances, GD&T Required for both product and assembly fixture systems.
- Supplier CAD data for evaluation of major interfaces for landing gear, engine equipping, weapon systems, etc.

Logistics database: The logistics database is a central quality data depository which should include all hardware dimensional information The PARES activities relating to this chunk are

- Quality information cache: all CMM measurements including laser tracker, mobile arm (Faro, Romer), high level product specifications such as steps, gaps, waviness metrics.
- Recording and storing of component or assembly point cloud format data to record detailed form measurements.
- Manufacturing and assembly process SPC· manufacturing and assembly inspection data, fixture calibration and dimensional maintenance records
- Manufacturing group or set knowledge capture Record Cp and Cpk values for manufacturing process sets based on group technology.
- Interface to off line CMM inspection process and generate base programs
- Message alerting of product non conformance based on aircraft zone ownership

DMU collaboration: The tolerance synthesis model may be used to evaluate resultant product characteristics based on real measurement data input from internal and external 3rd parties. In addition, contributor reports may be run to aid root cause analysis where specifications are predicted as not being met

- Use of closed loop tolerance synthesis models updated with actual measurement information supplied from a 3rd party SPC database to predict effects on overall product specifications.
- Development of digital MTG model to evaluate component or assembly prior to supplier sign off.

- Use of digital MTG to evaluate batch SPC on long lead time supplier component and assemblies

Tolerance analysis and synthesis: The tolerance analysis model may be used to validate manufacturing and assembly process capability against high level product specification.

- Create 1D/2D PVA studies to evaluate early structure concepts for dimensional capability.
- Creating full 3D synthetic tolerance analysis based on detailed CAD of product and process Analysis to be validated against product dimensional specifications
- Specific risk assessment on suspect design areas Use and integration of kinematic, FEA, and custom models to perform risk mitigation
- Enable root cause analysis where dimensional specifications are not being met through the detailed contributor reports

Quality data visualisation: The ability to integrate and mine all available quality data, then recover it in a consistent and useful format to support engineering design. Currently organisations hold quality data in multiple raw formats with no consistent reporting interfaces making this activity time consuming and inefficient Product high level quality data should be web published and made accessible to all engineering functions The publication of quality data should be undertaken and released to a strict schedule Specific items are

- The development and deployment of a web based quality reporting system made available to the organisation This is to outline product high level scores through the use of a dimensional quality dashboard.
- Advanced interactive quality viewing for GD&T and point cloud specific domestic and supplier data trends on components and assemblies This should be available to all IPD/DM analysis engineers and personnel responsible for quality management.

Web based knowledge: Review supplier hardware quality performance through interactive collaboration When quality data is received and it is subject to issue, a detailed review may be undertaken to present the overall effect on product specification using the root cause analysis tolerance model. Main issues are:

- Store and manage all measurement data types
- Portal to quality communication pipeline between domestic and third party suppliers and customers.

- Storage of all supplied actual measurement data for an SPC database.
- Collaboration to review supplied quality data, and resolve issues

The operational structure of the PARES process has been modelled using the IDEF0 (Integrated Definition) modelling methodology. An overall representation and a first level decomposition of the PARES process can be seen respectively in figure 23 and figure 24.

Five main process blocks have been identified to in the IDEF0 first level representation, these are:

- Create PVA model.
- Create GVA model.
- Create inspection plan
- Gauge R&R.
- Inspection process

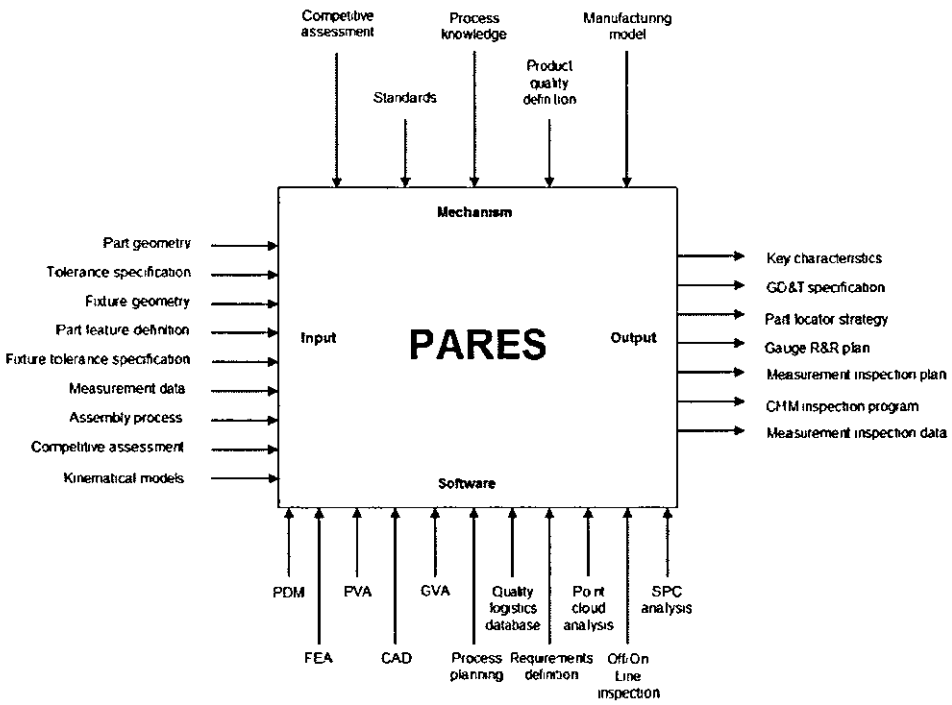


Figure 23 Overall IDEF0 representation of the PARES process

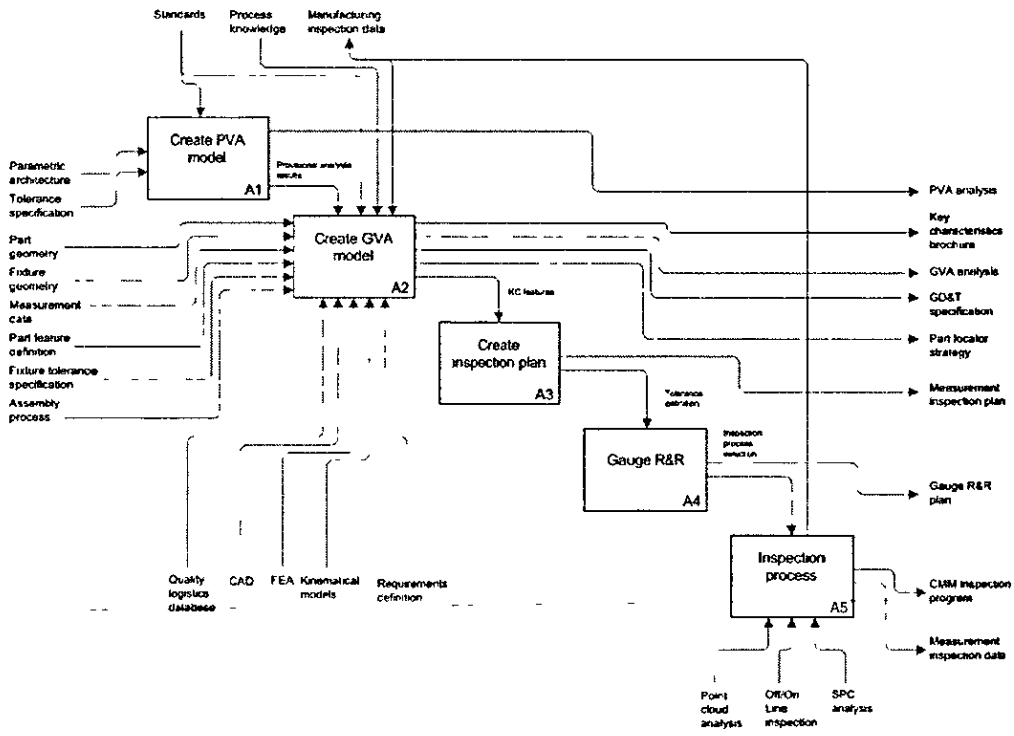


Figure 24 First level IDEF0 represenation of the PARES process

5.4 PARES benefits

The PARES methodology will potentially bring the following benefits

- Lead to a more structured approach to product lifecycle DM, the PARES will need to be integrated into an existing product lifecycle management process clearly defining each process element and it's maturity gate
- Produce a more robust product, PARES drives product and process design validation to ensure variation is identified, quantified, and managed through out the design and development stages..
- Promotes the idea of designing quality into the product and not inspecting it out, the process guides as organisation to consider the effects of variation at all stages of the design and development process It particularly promotes product and process design evaluation at the early digital mock-up stage and not waiting until tooling and prototype product hardware are available for quality check
- Promotes a measurement culture, not a gauging culture; promotes the use of a closed loop measurement strategy based on dynamic process checking to ensure manufacturing and assembly activity stays within required control limits

- Reduce production defects, improving scrap and rework rates, scheduling flow, and delivery times; improved product and process control ensures a more predictable and controllable manufacturing environment.
- Makes effective use of design, manufacturing, assembly, and inspection process knowledge from legacy programs or credible 3rd party organisations. Ensure all relevant current production process data is recorded as reusable knowledge Reduces knowledge waste resulting from quality data being either not available, or in an unusable format.

The proposed PARES methodology, the process activities, and top level architecture have been presented in this chapter. Two significant sections of the methodology have been identified for further investigation as part of this research project, these being

- **Develop a PVA tool for wing box assembly analysis:** Design and develop a specific PVA tool to analyse the key parameters of an aircraft wing box structure. The wing box assembly analysis tool will be designed to perform 1D/2D tolerance analysis to validate the target concept design for capability. The PVA will be developed based on a number of requirements identified by Airbus together with wing structure information The PVA development process is presented in chapter 6 of this thesis
- **Digital mock-up (DMU) to geometric variation analysis (GVA):** Three case studies were identified and undertaken on an Airbus wing box structure investigating the assembly fit of ribs, spars, skins, and D nose parts This involved the use of a 3D CAD/CAE/DMU environment to make use of product information such as identified KCs' and associated GD&T tolerance metrics. The three case studies of 3D synthetic tolerance analysis are presented in chapter 7

The two sections identified from the PARES methodology for further work will be investigated in the following chapters

Chapter 6

6 Development of a parametric variation analysis (PVA) tool for wing box assembly

Objectives: This chapter outlines the design and development of a PVA wing box assembly analysis tool in response to a specific need identified in chapter 4. This is reinforced in Chapter 5 which positions the requirement for a number of PVA tools within the proposed DM process PARES This specific PVA tool is designed to evaluate assembly process against parametric target capability, for example, wing box structure steps and gaps. The approach embodies the requirements established at Airbus taking into account the analysis needs, working practices, and wing structure information The PVA tool is presented under the following sections:

- PVA tool development background.
- Requirements specification and scope.
- Design and development methodology
- PVA tool functional overview
- Benefits and limitations of the PVA tool.
- Potential further development work

6.1 PVA tool development background

A number of PVA analysis projects were identified in support of this research The requirements for these projects were based on specific assembly scenarios identified by the composite wing development unit at Airbus, Filton An initial search into suitable PVA analysis tools capable of performing early parametric studies with sufficient flexibility failed to identify a suitable candidate It was therefore agreed that a suitable PVA tool be developed to support the planned analysis work The development of the PVA tools was to be undertaken by the author and submitted as part of this research project

The PVA analysis projects were managed under a single project initiative entitled the 'Variation analysis of aircraft carbon fibre composite wing box structure assembly' (Jeffreys 1998a) which included.

- **Design and development of a PVA tool to analysis wing box assembly:** the PVA tool for wing box analysis is presented in this chapter
- **Conduct case studies to review DMU 3D geometric variation analysis on wing box structures:** the case studies are presented in chapter 7.

Airbus defined the requirement for the PVA utility as being capable of identifying baseline estimates of parametric dimensional variation within aircraft wing box features during the early stages of design. The requirement was documented and an agreement was set in place for the author to design and develop a demonstration PVA tool

A wing box provides the primary and core structural elements of a wing system It is physically located in the central part of the wing and facilitates the base platform for other wing elements to be assembled, such as leading and trailing edges, engine mounting pylons, main landing gear, and so on Further more, a large portion of the wing box structure in many large military and commercial aircraft also functions as the main fuel cell In basic terms, the wing box is generically made up from a number of ribs set periodically across the length of the structure, a front and rear spare typically of I, C, or Z configuration, and an upper and lower skin to complete the closed box structure (see figure below) Traditionally, these structures have been designed and manufactured from metallic materials and associated processes Recently, both military and commercial aircraft companies are investigating the further incorporation of composite materials, CFC for example, within wing box primary structure design Driving this requirement is the desire to produce a lighter wing structure which will result in an improvement for in-service affordability.

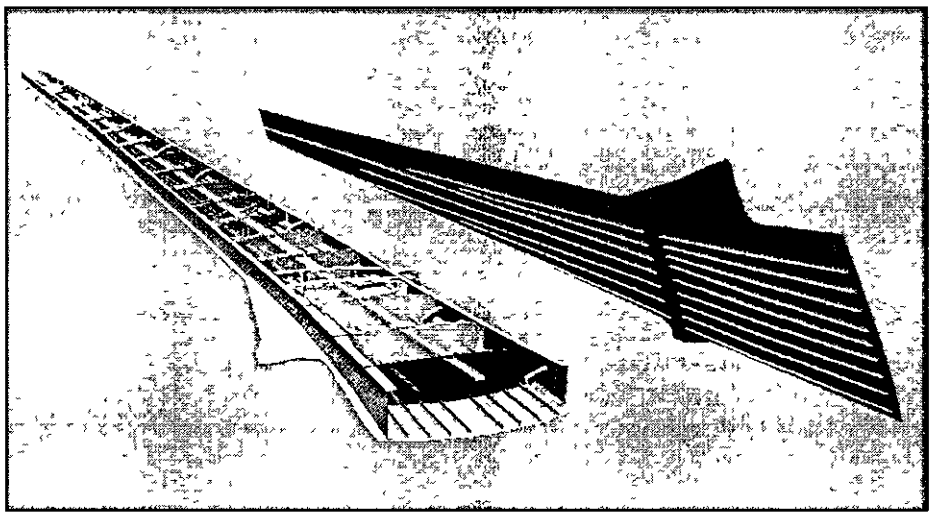


Figure 25 Example wing box structure with top skin removed, courtesy of Airbus

6.2 Requirements specification and scope

The requirement was to design and develop a parametric dimensional variation analysis application capable of modelling a number of identified key features within the aircraft wing box structure. The main requirements were developed and validated with Airbus, these were primarily.

- Variation analysis for 1 and 1.5D configuration
- Perform analysis on a generic wing box structure to include rib, front/rear C spars, top/bottom skins, D nose, and A frame components.
- Identify key parameters for analysis, for example, identified key characteristics such as steps and gaps
- Apply variation to each parameter based on selected distribution.
- Capable of worst case, root sum square (RSS), and statistical analysis
- Apply variation based on sample manufacturing measurement data
- Storing analysis results for recall.
- Print out simple analysis reports
- Operate on low specification PC

From the primary requirements a functional and technical specifications for the PVA tool was defined by the author in support of this research The scope of the PVA tool was limited to a single generic wing box structure configuration, based on a set assembly build philosophy (see figure 26) This was defined as·

i. Locate front and rear spar sub-assemblies, D nose to front spar and A frame to rear spar.
ii Locate rib; rib upper flange to be flush with upper front and rear spar flanges
iii Fettle/shim rib if out of tolerance on step control
iv Locate upper skin
v. Locate lower skin.

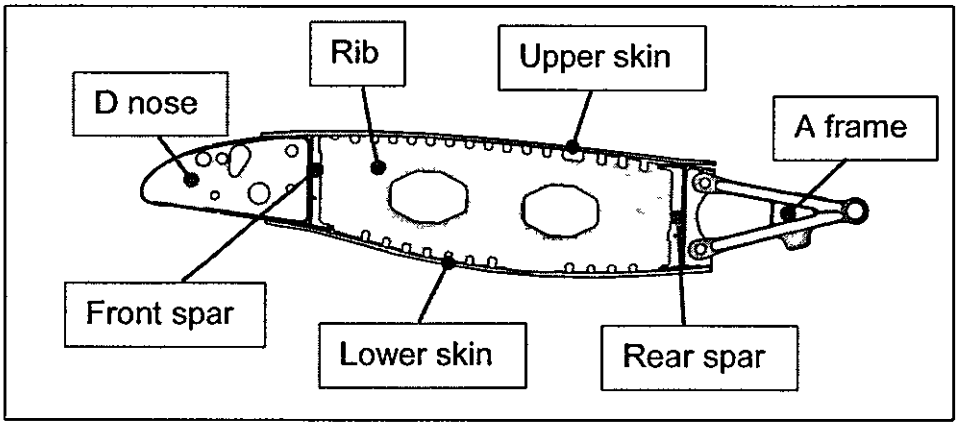


Figure 26 Components within the generic wing box

6.3 Design and development methodology

The core development was undertaken within the MS Excel application making use of available math and statistic functions and macro commands. In addition, the Decisioneering Crystal Ball Professional (Decisioneering 2000) software module was integrated to the MS Excel application. This has allowed the use of Monte Carlo simulation to be performed within the base PVA utility. The primary development blocks for the PVA tool were

- ***Review and define generic wing box structure components, parameters, assembly sequence to be include in development scope;*** define all wing box structure product details for inclusion in the analysis model and verify these with Airbus
- ***Define analysis model process flow;*** outline the blocks, structure and process flow of the analysis tool.
- ***Develop main wing box component gallery;*** define all component and parameter configuration back to central wing box gallery
- ***Generate component and feature parameter tolerance chains for each assembly stage;*** develop feature data tables for each component and define the tolerance stack chain
- ***Build the set viewing table;*** define the data set viewing table to enable storage and recovery of specific configurations including nominal data and parametric feature limits.
- ***Consolidate and test all the above activity and integrate Crystal Ball Pro software module;*** integrate all analysis blocks with Crystal Ball Pro software where appropriate and test.
- ***Perform analysis tool validation;*** generate test data and validate output against 3rd party analysis engine.
- ***Develop user instruction;*** generate instruction and help section

- ***Present the analysis tool back to Airbus;*** review analysis tools with Airbus.

The development blocks were generated and the resultant functional elements are presented in the next section.

6.4 PVA tool functional overview

The PVA functional process is defined in figure 27 below There are six steps in the PVA process, these are

i Analysis configuration
ii Parameter features definition
iii Tolerance specification
iv Simulation parameters definition
v Analysis of results
vi. Knowledge capture

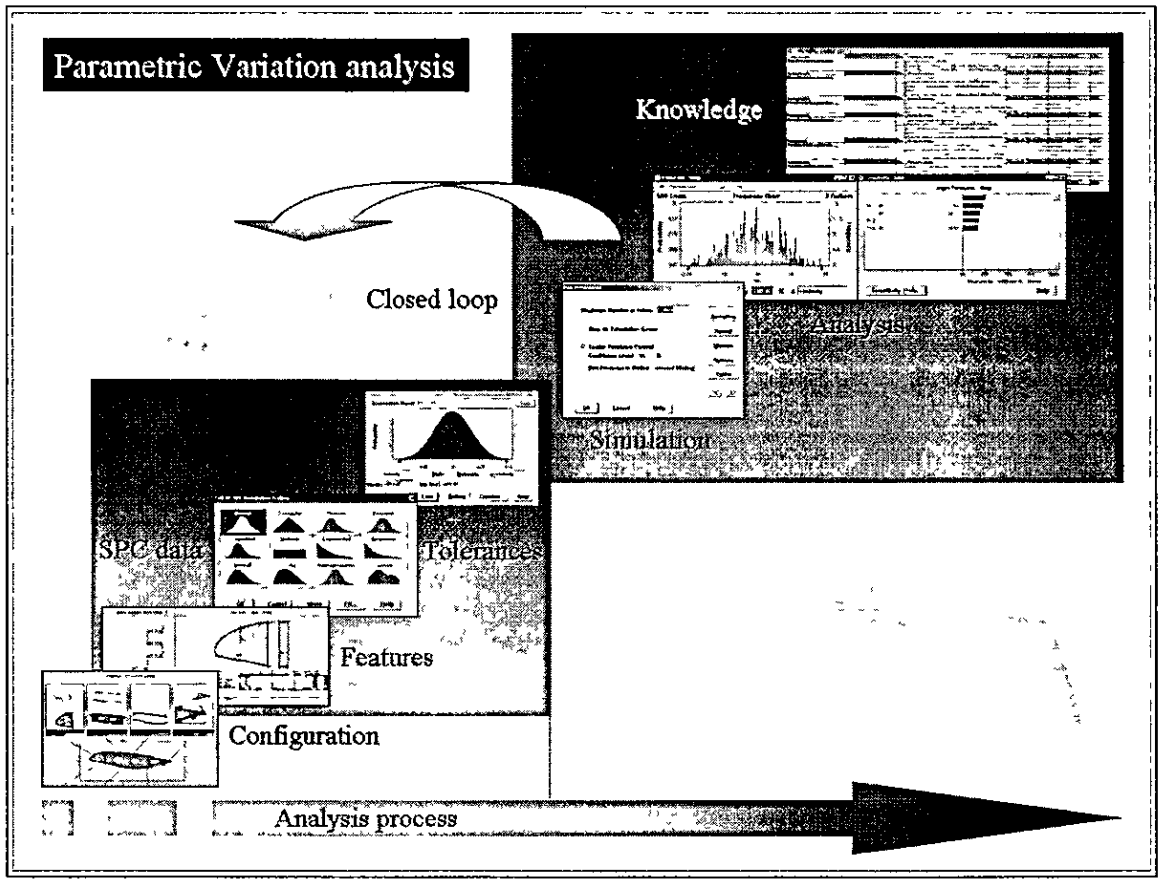


Figure 27. PVA process

The seventh optional step is to rerun the analysis with revised are previously saved parameter data An explanation of the six steps is given below in sections 6 4 1 to 6.4 6.

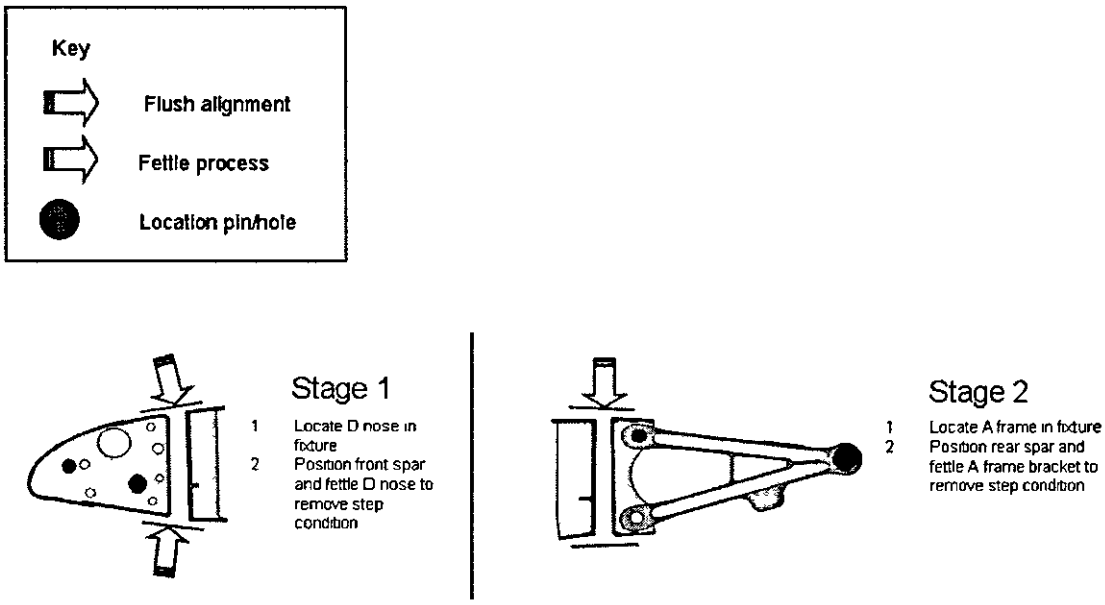
6.4.1 Analysis configuration

The wing box assembly configuration can be viewed in the 'Wing box component gallery'. The gallery is made up of eight sections, one for each major component. At the centre is a schematic of the complete assembly wing box with reference pointers to all individual components, these being:

- D nose configuration
- A frame configuration
- Front spar configuration
- Rear spar configuration
- Rib configuration
- Upper skin configuration.
- Lower skin configuration

To aid navigation, the images within the component gallery are hyperlinked and selection of a specific assembly area them would lead the user to the appropriate component analysis driver table.

The wing box assembly process, identified for this analysis, is illustrated in figure 28



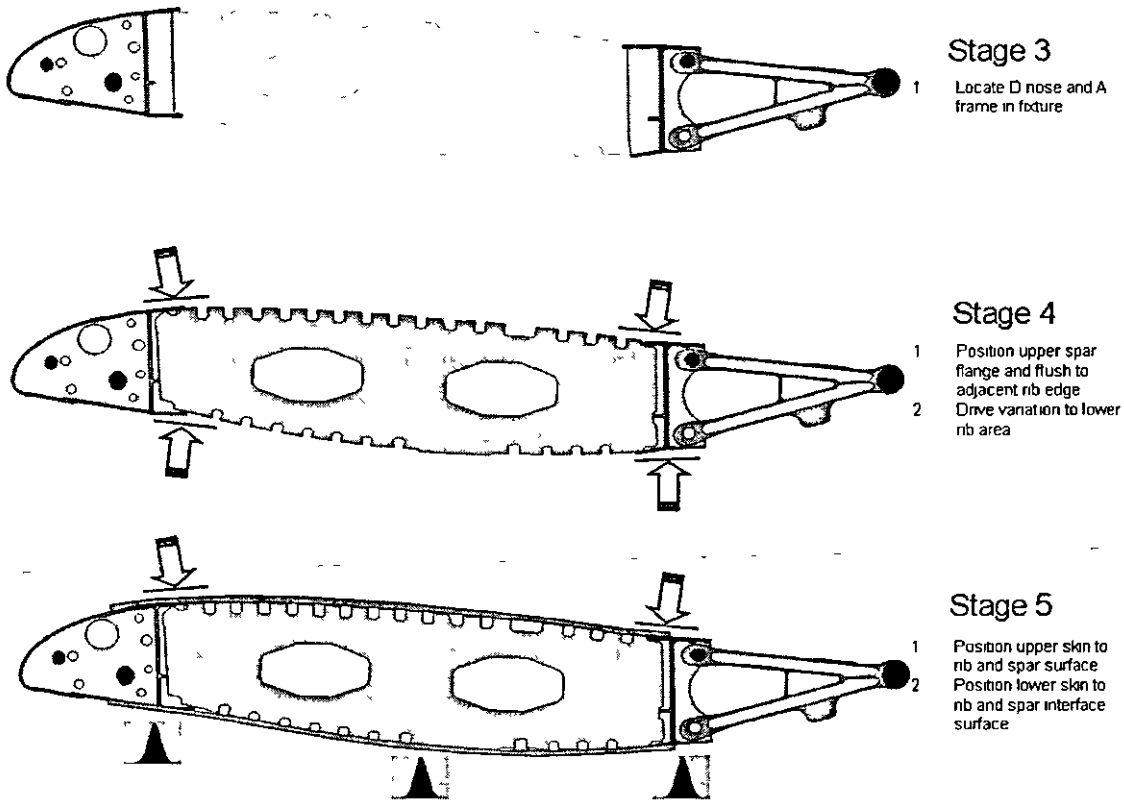


Figure 28 Wing box assembly process defined for this analysis

6.4.2 Parameter feature definition

For each assembly stage included within an analysis the parameter details for each component included will need to be defined. This is specified within the data driver tables which require nominal information on all parametric elements making up a dimensional chain. The component parameters represented in these studies are consistent with a standard aerospace methodology for a generic wing box assembly process.

6.4.3 Tolerance specification

At each assembly stage, component parameter tolerances need to be defined. This is again specified in the data driver tables The tables contain a number of available cells into which data relating to a tolerance chain feature may be input

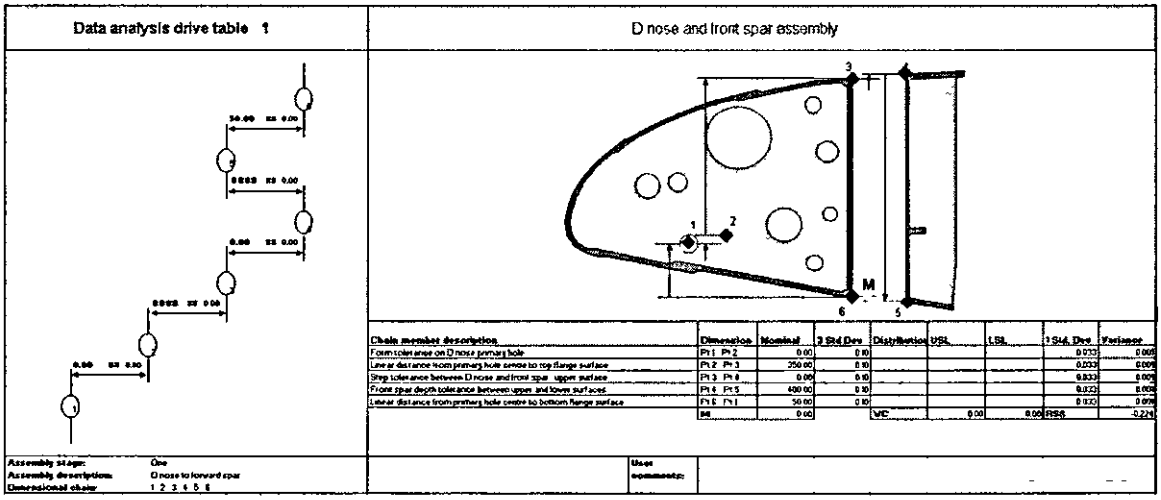


Figure 29 Data driver table, D nose to front spar assembly example

The required parameter tolerance data can be categorised as:

- ***3 Std. Dev.;*** the 3 standard deviation tolerance applied.
- ***Distribution;*** the parameter feature variation distribution type
- ***LSL;*** the lower specification limit of tolerance
- ***USL;*** the upper specification limit of tolerance

6.4.4 Simulation parameter definition

When all parameter feature nominal and tolerance information has been completed the simulation criterion must be defined The analysis tool can perform three types of simulation, these are

- Worst-case simulation
- Root sum square simulation
- Statistical simulation; Monte Carlo and Latin Hypercube simulation

Worst-case simulation: Worst-case (WC) simulation technique represents a conservative approach for assembly analysis It assumes that all variation levels will be at their maximum (or minimum) levels. WC variation levels are calculated by the simple linear addition of all individual values. WC simulation does not take into account the distribution of feature size and they do not exceed their respective specifications.

$$\text{WC T total} = t1(+ \text{ or } -)\ t2(+ \text{ or } -)\ t3(+ \text{ or } -)\ .\ (+ \text{ or } -)t_n$$

The tolerance variables will take a value at one of its limits in such a way to yield an extreme condition at a point of analysis, i e. the maximum expected variation at that point WC does not take into account the laws of probability.

Root sum square simulation: Root sum square (RSS), or linear stack, predicts variation at a given point which is not expected to be exceeded more than 1 in 370 assemblies (99 73%) This analysis was developed as a more accurate representation of variance when considering a large number of tolerances One assumption made is that the analysis represents features that are manufactured about the mean point of the tolerance, i e an equal bilateral tolerance is assumed. The RSS method, is used when an assembly response function can be expressed as a linear function of the component parameters. The math function for RSS is

$$\text{RSS T total} = (t1^2 + t2^2 + t3^2 + \ldots + tn^2)^{0.5}$$

Where tn^n represents the individual tolerances and T total equals the total predicted assembly tolerance (equal bilateral variation) using the RSS model

Statistical simulation: Statistical analysis employs a statistical distribution which represents more accurately the expected process variation of each parameter dimension The analysis tool allows the use of actual manufacturing process data or an approximation of a distribution curve and limits to give a better representation of actual or calculated variation data This can be established by directly sampling available data and attaching it's characteristics to a specific parameter feature

Further explanation on techniques such as Monte Carlo simulation is available in the appendices of this thesis

Several standard distribution types are available to represent desired variation characteristics. The following statistical distributions are supported by the analysis tool:

- Normal distribution.
- Uniform distribution
- Triangular distribution.
- Binomial distribution
- Poisson distribution
- Geometric distribution.
- Hyper geometric distribution.
- Lognormal distribution
- Exponential distribution

- Waybill distribution.
- Beta distribution

These were all available via a drop down menu from each ***Distribution Type*** entry cell. Unique groups of manufacturing sample data established from development experimentation at Airbus were available under descriptive headings such as

- Specific cured CFC panel variance
- Specific debulked CFC panel variance

Other specific manufacturing process capability based on industrial best practice was also available for sampling These included

- Aluminium high speed machining.
- Resin film infusion
- Resin transfer moulding
- Specific Pre-pregnated CFC.

Once the parameter feature distributions are established, the simulation run is defined The simulation engine is a Monte Carlo random number generator For each simulation run the number of times the assembly is to be built will need to be defined. To ensure good confidence levels from the output, current best practice would typically specify a count of 3,000 simulations or more, but this has to be established during the analysis

6.4.5 Analysis output

The simulation outputs for WC and RSS could be established as soon as the parameter feature nominal and tolerance limits were specified These outputs were represented as a single metric output made available in the data driver table. The statistical based analysis results can be run as a secondary simulation utilising the Crystal Ball Pro utility. The analysis results are ultimately assessed against to line-of-flight wing specifications for the profile tolerance of moving surfaces, fixed surfaces, and closure surfaces These include specification for overall profile, surface flushness (steps), gaps and grooves, and surface waviness These specifications differ depending on which defined zone of the wing is being considered The simulation outputs are presented in the following charts

Frequency chart; simulation outputs are displayed in a histogram Information such as output distribution type and fit are reported, and certainty levels may be manipulated for further analysis An example of a frequency chart for the D nose analysis is given below

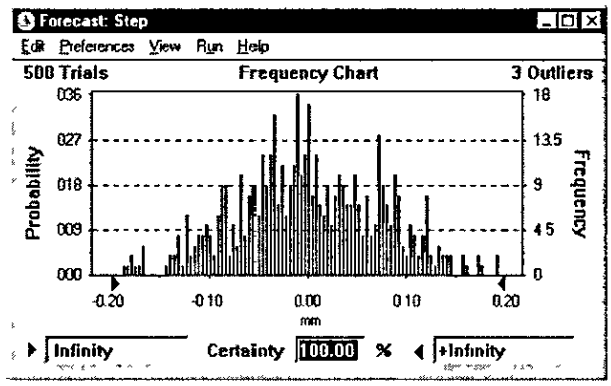


Figure 30 Example frequency chart for D nose

Sensitivity chart; evaluates the sources of variance and determines what contribution each element has made to the total measured variance The sensitivity chart displays how much each chain element affects the output the step measurement based on rank correlation An example chart is given below

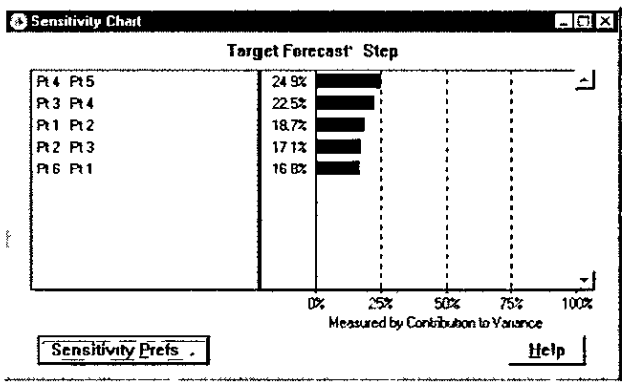


Figure 31 Example sensitivity chart for D nose

An example of a sensitivity chart for the D nose analysis is given below. It this example, the Pt4-Pt5 parameter feature is the biggest contributor to variation output

Statistical chart; reports standard statistical measures including the mean, median, mode, standard deviation, variance, skewness, kurtosis, and so on. An example of a statistical chart for the D nose analysis is given in figure 32 on the next page

Forecast: Step

Edit Preferences View Run Help

Cell BK252 Statistics

Statistic	Value
Trials	500
Mean	-0.00
Median	0.00
Mode	---
Standard Deviation	0.08
Variance	0.01
Skewness	-0.06
Kurtosis	3.54
Coeff. of Variability	349.63
Range Minimum	-0.27
Range Maximum	0.27
Range Width	0.54
Mean Std. Error	0.00

Figure 32 Example statistical chart for D nose

6.4.6 Knowledge capture

An analysis session can be captured in two steps. The assembly instance information such as feature nominal, USL and LSL, distribution, etc could be saved to the set data table held within the application. This could then be saved and reused for future analysis. The statistical simulation output could additionally be saved to a report file which may be printed

6.5 Evaluation of the PVA tool

The requirements for a PVA analysis tool were based on the literature survey, identified industrial requirements, and the PARES methodology together with inputs from Airbus and case studies to validate the research The PVA application was developed following the process outlined in the 'design and development methodology' section. The primary aim was to design and develop the PVA utility, to validate the main functions, and handover to Airbus

Following development, the PVA utility was validated by the author. This was undertaken through the following steps

- A simple 4 component 1D assembly stack was defined using MS Excel (see figure below).
- The model was then used to produce an analysis model using the PVA tool.
- In order to validate the Monte Carlo simulation outputs including the frequency, sensitivity, and statistical charts, a basic 1D model was generated in VisVSA to represent the same analysis conditions and outputs.
- Outputs form both the PVA and VisVSA models were analysed

The PVA and VisVSA analysis tools demonstrated the following correlation against the validation model (see figures 33-39)

	Nom	Tol	Dist	Tol/3	Nom + Tol	Nom - Tol
Part A	115 000	0 100	Uni	0 033	115 100	114 900
Part B	50.000	0 005	Nor	0 002	50 005	49 995
Part C	12.000	0 100	Uni	0 033	12 100	11 900
Part D	180.000	0 030	Nor	0 010	180 030	179 970
Gap	3.000					

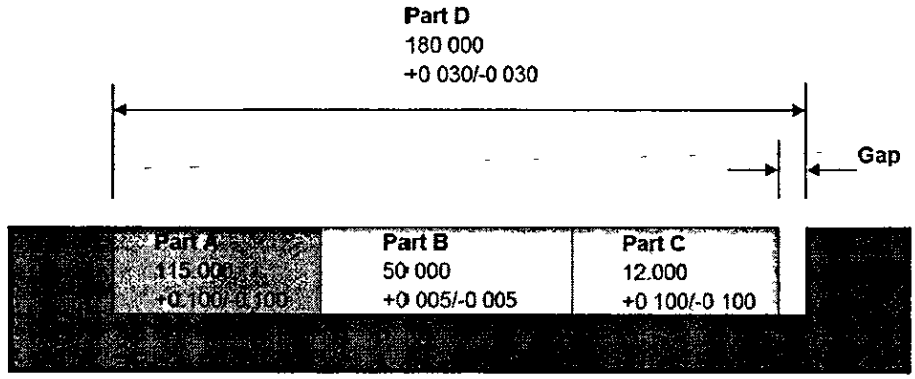


Figure 33 Simple 4 part assembly

VisVSA analysis results:

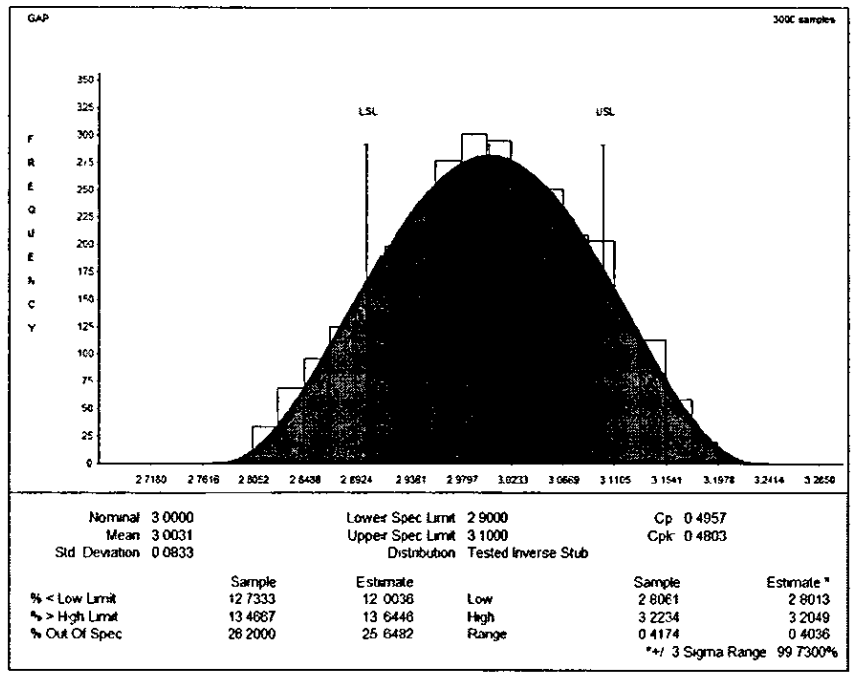


Figure 34. VisVSA process report

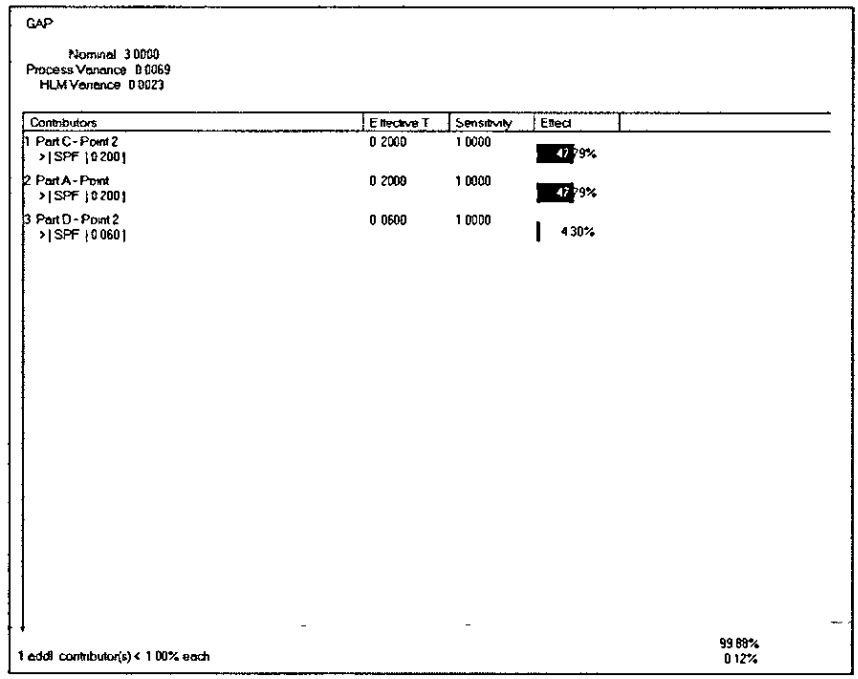


Figure 35. VisVSA contributor chart

Nominal	3 00	Mean	3 00
Std Dev	0 08	Lower Limit	2 90
Upper Limit	3 10	Distribution	Inv Stub
Cp	0 50	Cpk	0 48
% < Spec	12 73	% Out of Spec	26 20
Est % < Spec	12 00	Est % > Spec	13 64
Est % Out of Spec	25 65	Low	2 81
High	3 22	Range	0 42
Est Low	2 80	Est High	3 20
Est Range	0 40	Nom +/- Range	3 00 +/- 0 20
Nom +/- 3Sigma	3 00 +/- 0 25		

Figure 36 VisVSA statistics table

The PVA applicaton results

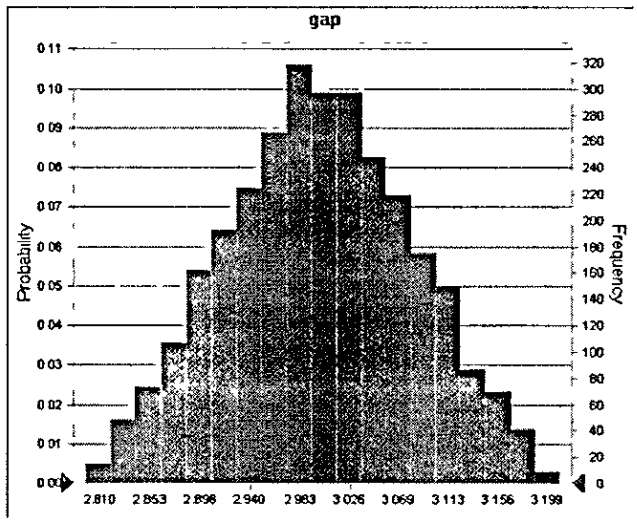


Figure 37 PVA process chart

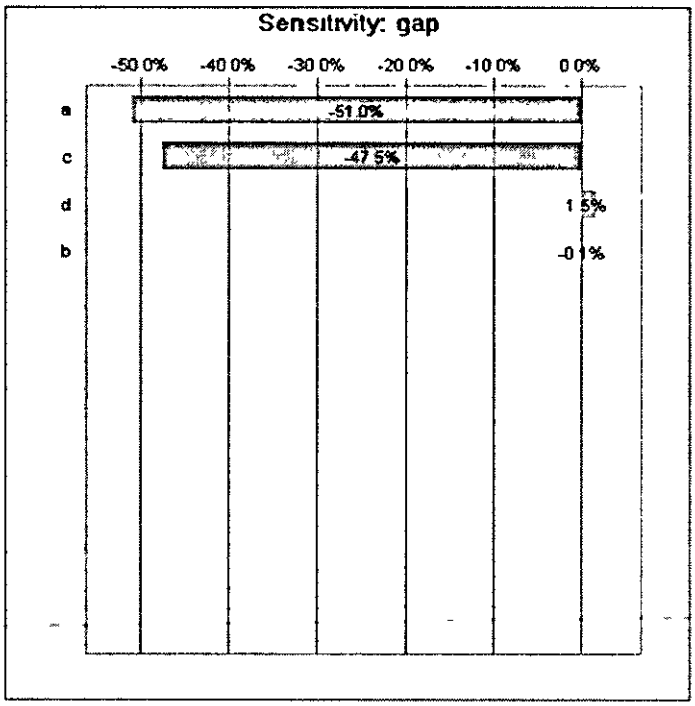


Figure 38 PVA sensitivity chart

Statistics	Forecast values
Trials	3,000
Mean	2 999
Median	2 999
Mode	---
Standard Deviation	0 081
Variance	0 007
Skewness	0 02269
Kurtosis	2 47
Coeff of Variability	0 02698
Minimum	2 797
Maximum	3 208
Range Width	0 412
Mean Std. Error	0 001

Figure 39 Statistical chart

From the results it can be seen that pridected gap range was 0 4174mm and 0 412mm from the VisVSA and PVA tools respectively. This represents a difference of only 0 0054mm. The contributor reports have some subtle differnecs (see figure below) The both analysis models rank the contributors in the same order with the exception that VisVSA ranks the first 2 parts, part A and part C, as joint first where as the PVA tools prodicts Part A as the first contributor followed by in second place by part C There is a further discrepency in that the amout both analysis models rank the third contributor VisVSA predicts that Part D contribution will be 4.30% where as the PVA tools proedicts 1.50%

Part	VisVSA	PVA
Part A	47 79%	51 00%
Part C	47 79%	47 50%
Part D	4.30%	1 50%

Figure 40 Contributor report comparison

The main elements for this comparison are the predicted range of varaiation, and the order and magnitude of the contributor elements. Although there are some minor discrepancies in the % contribution and their ranking, a comparison of the other statistical and variation range outputs suggest good correlation

6.6 Benefits and limitations of the PVA tool

The primary intention of the PVA tool was to demonstrate to Airbus how a limited, simple but fast tolerance analysis tool could be made available to all personnel at the early stages of design The benefits and limitations of the tool in its current from are described below.

Benefits:

- Fast and simple to use, no formal training required
- Does not require detailed geometry to be available, can be used on generic wing box assembly at early design stage An example of how this may be used for D nose to C spar assembly fit up is shown in figure 28.
- No software cost incurred. Only requires a common desk top application such as MS Excel to operate The Decisioneering Crystal Ball Professional software module is only required if statistical analysis is to be performed.
- Can incorporate actual manufacturing measurement data or available industrial process capability into model If actual sample data is available on individual features, the PVA tool can be configured to run a simulation using this data for each related model input replacing the standard distributions selected from the distribution gallery with Crystal Ball Pro Each individual sample data can also be represented by a simplified statistical model which includes values for mean shift, standard deviation, skewness and kurtosis

Limitations

- Only capable of 1D and 1 5D stack analysis
- Can only consider pre defined assembly sequence.
- Cannot readily accommodate all elements of GD&T tolerance criteria
- Limited to modelling of parameters and not individual features.

6.7 Further development work

The PVA tool is basic demonstrator but it could be significantly developed to perform much more complex tolerance analysis and synthesis tasks Areas for possible consolidation and development could include:

- **Material properties:** add material properties against each component
- **Model temperature variation:** allow the input of thermal expansion variation based on product working envelope versus material property
- **ISO limits and fits:** to be readily applied to hole and pin based features
- **Individual feature definition:** add definition to basic features such as holes, pins, and points, and not just assembly parameters
- **Individual features template:** to allow the definition of GD&T.
- **GD&T paper gauging techniques:** incorporate paper gauging techniques in order to accommodate GD&T material modifiers and bonus tolerances
- **Relational database integration:** set up to store all analysis configurations and results This could also be extended become a platform to store all domestic manufacturing measurement data, standard ISO process capability data, and where available supplier measurement data applicable to this type of study
- **Include other aircraft structure zones:** expand the analysis to other aircraft zones, for example, fuselage, horizontal and vertical stabilizers
- **Cylindrical 2D analysis to accommodate fuselage modelling:** provide capability to analyse cylindrical 2D geometry based assembly issues Model the potential effect of skin thickness, part-to-part hole position misalignment, fastener capability, and their effect on curved geometry
- **Limited 3D tolerance analysis:** produce limited 3D analysis by incorporating matrix transformation to component to component assemblies This could be done by using a number of point based 321 moves to each component in sequence until a measurement point coordinate on the last component is resolved to an x, y, and z co-ordinate. This type of development would be complex but is technically possible

6.8 Concluding remarks

The development of the PVA utility has demonstrated the benefits and limitations of performing simple 1D/2D tolerance analysis at the early design stage This type of analysis is essentially based on a generic structure configuration and will provide an early insight to assembly parameter capability and can influence design decisions before detailed 3D geometry is generated. The analysis can also help in the product design selection process

However, later in the design development cycle when detailed 3D design geometry is available a second degree of tolerance analysis and synthesis is required In order to meet these demanding analysis requirements a different approach is required. Such as approach is outlined in chapter 7 and is demonstrated on three Airbus wing structure case studies. The case studies provide the core effort behind the consolidated Airbus project entitled 'Variation analysis of aircraft carbon fibre composite wing box structure assembly' (Jeffreys 1998a).

Chapter 7

7 Geometric variation analysis (GVA) on proposed Airbus wing box assembly

Objectives: This chapter outlines a number of geometric variation analysis case studies performed on a development wing box structure The case studies have been undertaken in response to the need outlined in chapter 4 for synthetic geometric variation analysis to be undertaken when detailed 3D CAD geometry is available Furthermore, the proposed PARES DM process outlined in Chapter 5 requires that the 1D/2D PVA analysis is extended to a more detailed 3D geometric analysis models The approach accommodates a number of specific analysis needs for the Airbus A3XX wing box assembly. The case studies are presented under the following sections

- Background to Airbus A3XX case studies
- Case study analysis methodology.
- Dimensional analysis for simple rib to skin assembly case study
- Dimensional analysis for rib to complex skin assembly case study
- Dimensional analysis for spar equipping assembly case study
- Highlight results and conclusions

7.1 Background to Airbus A3XX case studies

During the wing development phase of the Airbus A3XX commercial aircraft there was a requirement to investigate how capable the current manufacturing and assembly tooling would be to facilitate an enhanced wing assembly joining process. This enhanced process involved the use of film and paste bonding technologies for the sealing and joining of CFC interfacing surfaces to be used in conjunction with conventional mechanical fastening methods A diagram of a generic wing box with D nose and A frame brackets attached is given in figure 41.

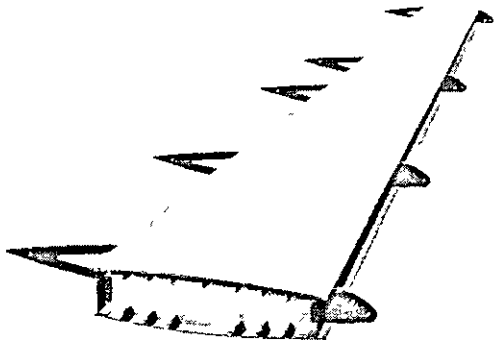


Figure 41 Example wing box assembly with D nose and A frame, courtesy of Airbus

The requirement was partly addressed by the identification of a number of analysis tasks by Airbus These tasks have been addressed through a number of case studies undertaken by the author

These case studies represent the work undertaken in addressing the 'Variation analysis of aircraft carbon fibre composite wing box structure assembly' (Jeffreys 1998a) project. The primary aim of the project was to simulate the propagation of wing components into assembly fixture in order to predicted key interface conditions which in turn may be analysed to establish if the conditions will meet defined assembly specifications. These specifications include the maximum and minimum gap conditions permitted between components for mechanical fastener, film bonding and paste bonding assembly processes The following three case studies were identified A description of the analysis methodology for each is given in the next section

- **Case 1:** Dimensional analysis for rib to complex skin assembly
- **Case 2:** Dimensional analysis for C spar equipping assembly

7.2 Case study analysis methodology

Essentially, the case studies were undertaken following the same analysis methodology. The methodology consisted of the following stages·

a Define study aims and objectives

b. List assumptions

c Design assembly components and tooling features

d. Identify key features on components and tooling

e Define tolerances from process capability data for all key features

f Create assembly model.

g. Define assembly sequence.

h Identify assembly moves

i. Define analysis measurements

j Perform assembly simulations

k. Assess results

Each of the above stages will be demonstrated through the presentation of a single case study. The example case study will be the 'Dimensional analysis for rib to complex skin assembly. case 2' The core aims and objectives, and conclusions for Case 1 and case 3 are also presented.

7.3 Dimensional analysis for rib to complex skin assembly

This case study represents part of the work undertaken in support of the 'Variation analysis of aircraft carbon fibre composite wing box structure assembly' project (Jeffreys 1998a). The study aims and objectives are given below

7.3.1 Analysis aims

The aim of this task is to simulate the assembly of complex skin and rib components into a setting fixture (see figure below) so that a critical interface gap may be analysed The gap specification includes the maximum and minimum condition permitted between components at identified points for the mechanical fastener, film bonding, and paste bonding assembly processes

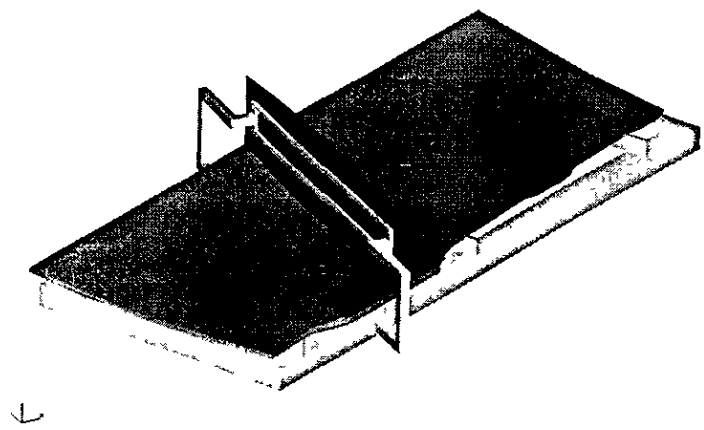


Figure 42 Rib, complex lower skin and assembly fixture

The analysis model will represent the resultant assembly complex interface gap condition between the lower rib surface and lower skin upper surface. This interface condition within a generic wing box is shown in the diagram below

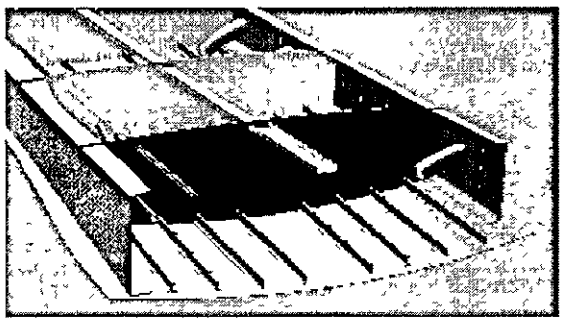


Figure 43 Complex rib (dark shaded) to lower skin in generic wing box

7.3.2 Analysis objectives

The aims of the analysis will be addressed through the following objectives.

- **Create CAD solid geometry models for complex rib, skin, and fixture:** a base geometric 3D surface model of the complex skin (supplied by Airbus) will be converted into a solid model Generated rib model using an offset surface 'splash' from the interface area of the skin upper surface When skin and rib models are completed the fixture solid model can be generated All additional features for assembly can then be added All geometry was created using the Dassault Systemes CATIA V4 1 8 CAD software.
- **Create the assembly analysis model:** the Variation Simulation Analysis software VSA-3D, integrated into CATIA, will be used to create the assembly model The FD&T tolerance specification module with CATIA will be used generate feature and datum information.
- **Perform a number of 'what-if' scenarios:** to explore the effect of different key feature tolerances and designed nominal gap conditions for the following specifications
    - Assembly through use of mechanical fasteners.
    - Film bonding assembly techniques.
    - Paste bonding assembly techniques
- **Document conclusions and recommendations:** document findings and draw conclusions.

7.3.3 List assumptions

The analysis assumptions are as follows:

- All component and tooling features in the analysis are absolute rigid entities, i e, mechanical conditions such as mass deflection or component deformation (caused by the resulting assembly configuration) will not be taken into account.
- Tooling geometry will be minimized to key assembly features and structures for simplicity
- The complex rib and skin components tolerance specifications will be based on a CFC manufacturing process capability.
- The fixture tolerance specifications will be based on steel fabrication process capability

7.3.4 Design of assembly components and fixture

The design of the rib and fixture tooling can be seen in the following figures The design details for the complex skin are not shown for confidentiality reasons The nominal geometry and dimensions for the rib and fixture were based on the complex skin model.

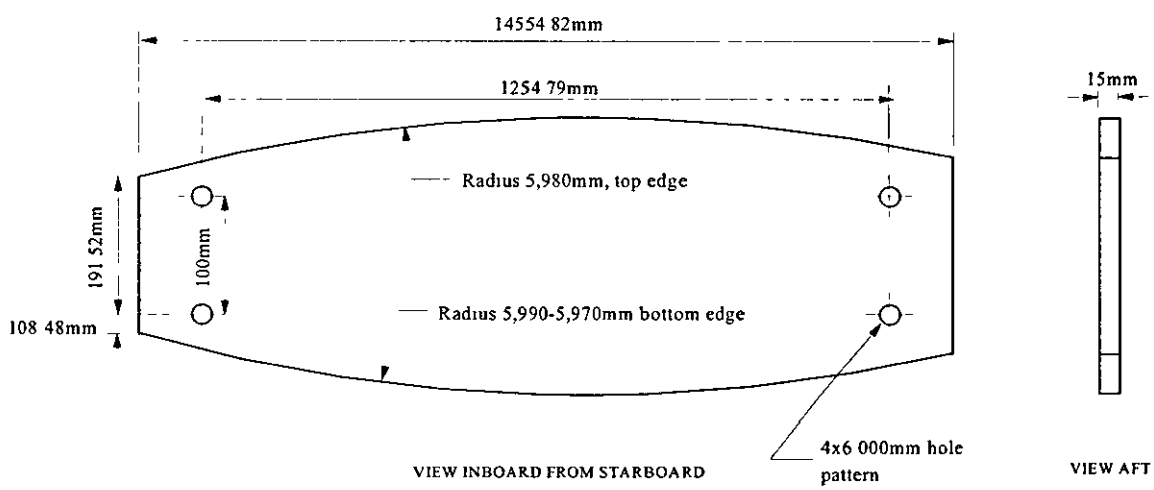


Figure 44 Rib design schematic

The fixture features will be represented through basic location and pickup entities required to orientate and secure the rib and complex skin components for assembly. Components and tooling for this analysis have been considered for the starboard side wing section, i.e. hole (4 DOF) at wing structure root

The nominal design for the fixture can be seen below.

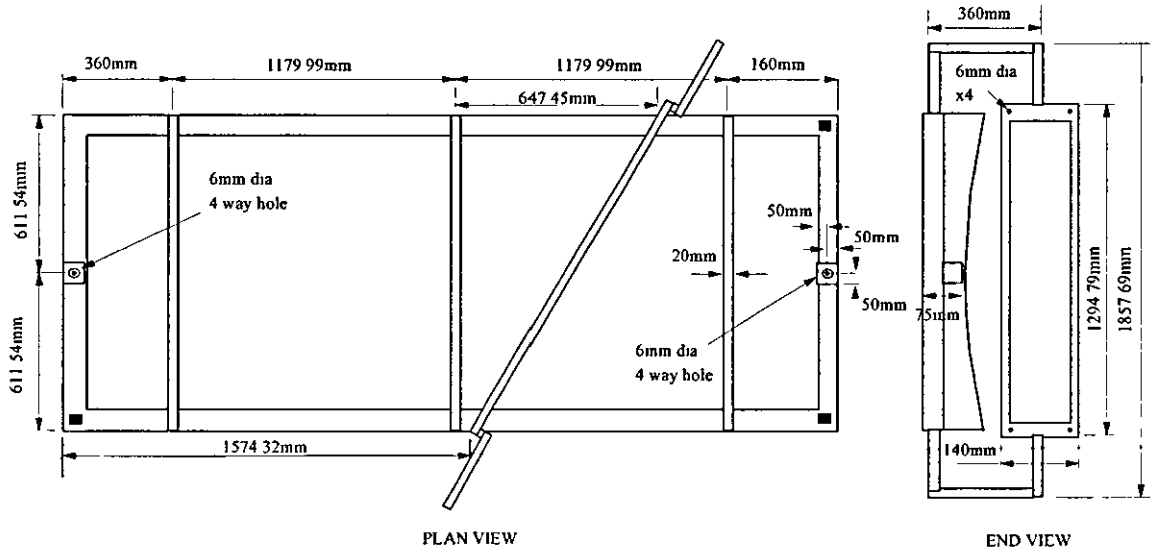


Figure 45 Fixture design schematic

7.3.5 Identify key features and tolerances

Rib critical features and tolerances (see figure 45 below)

Primary datum A	Flatness of form of +/-0 125mm
Secondary datum B	Hole perpendicularly of dia. +/-0 080mm on 4 way hole at MMC to datum A, diametric tolerance of H9 (+0.030/-0 000mm)
Tertiary datum C.	Hole position accuracy of dia +/-0 080mm on 2 way hole at MMC to datum A, datum B at MMC, and diametric tolerance of H9 (+0 030/-0 000mm)
Bottom edge feature	Surface profile of +/-0 100mm to datum A, datum B at MMC and datum C at MMC
Hole 1 and 2:	Hole position accuracy of dia +/-0 080mm at MMC to datum A, datum B at MMC, datum C at MMC, and diametric tolerance of H11 (+0.075/-0 000mm) on 6 000mm dia

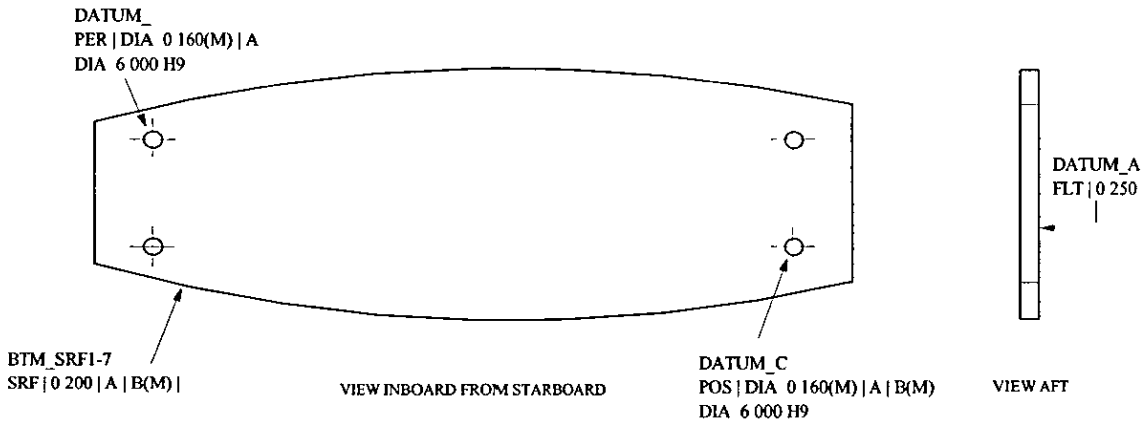


Figure 46 Rib critical features and tolerances schematic

Complex skin critical features and tolerances (See figure below)

Primary datum A:	Planar theoretical datum projected from bottom skin surface
Secondary datum B·	Hole perpendicularly of dia +/-0 180mm on 4 way hole at MMC to datum A, diametric tolerance of H9 (+0 030/-0.000mm)
Tertiary datum C	Hole position accuracy of dia +/-0.180mm on 2 way hole at MMC to datum A, datum B at MMC, and diametric tolerance of H9 (+0 030/-0 000mm).
IML surface features:	Initial surface profile of +/-0 500 to datum A, datum B at MMC and datum C at MMC (Bottom surface features).
OML surface features	Surface profile of +/-0 500 to datum A, datum B at MMC and datum C at MMC (Top surface features)

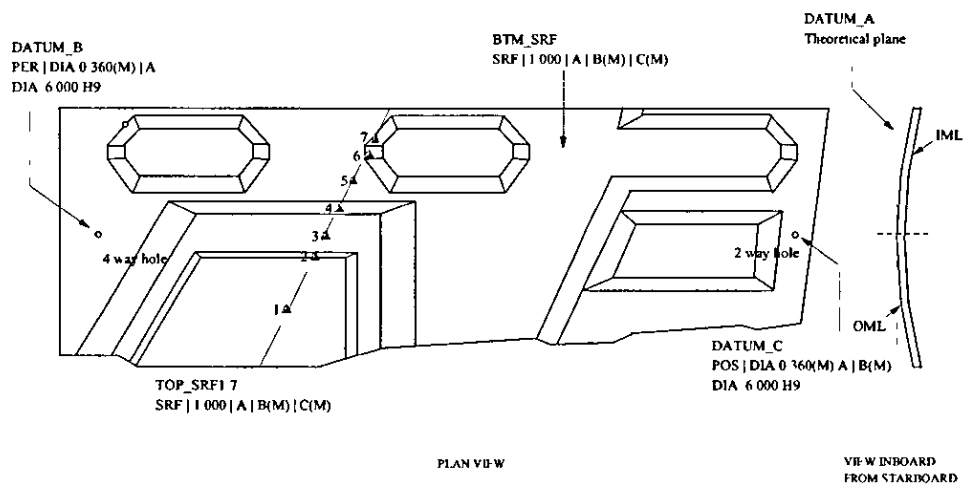


Figure 47 Complex skin critical features and tolerances schematic

Fixture critical features and tolerances

Rib associated:

Primary feature.	Position accuracy of +/-0 080mm to tooling datum A, datum B at MMC and Datum C at MMC.
Secondary feature	Hole perpendicularly of dia +/-0 180mm on 4 way hole at MMC to tooling datum A, datum B at MMC, datum C at MMC, and diametric tolerance of H9 (+0 030/-0 000mm)
Tertiary feature·	Hole position accuracy of dia +/-0.180mm on 4 way hole at MMC to tooling datum A, datum B at MMC, datum C at MMC, and diametric tolerance of H9 (+0.030/-0 000mm)

Assembly tooling pins to be used with assembly hole features are dia. 5 996mm nominal *

Complex skin associated:

Primary datum A:	Pick-up surface on top of main tooling structure forming a planar datum feature This feature has a flatness of form tolerance of +/-0.180mm
Secondary datum B	Hole perpendicularly of dia +/-0 180mm on 4 way hole at MMC to datum A, diametric tolerance of H9 (+0 030/-0 000mm)
Tertiary datum C	Hole position accuracy of dia +/-0 400mm on 2 way hole at MMC to datum A, datum B at MMC, and diametric tolerance of H9 (+0 030/-0 000mm)
Surface pick-up 1-3·	Surface profile of +/-0 180mm to datum A, datum B at MMC and datum C at MMC

Assembly tooling pins used to secure rib and skin components into the fixtures are dia. 5 996mm nominal, see below

Pin/hole tolerance

The standard assembly fixture tolerance with regard to pins and holes are

Pin = 5.990mm dia at h7 (+0 000/-0 012) for assembly fixtures

Hole = 6 000mm dia at H7 (+0 012/-0 000) for assembly fixtures and components.

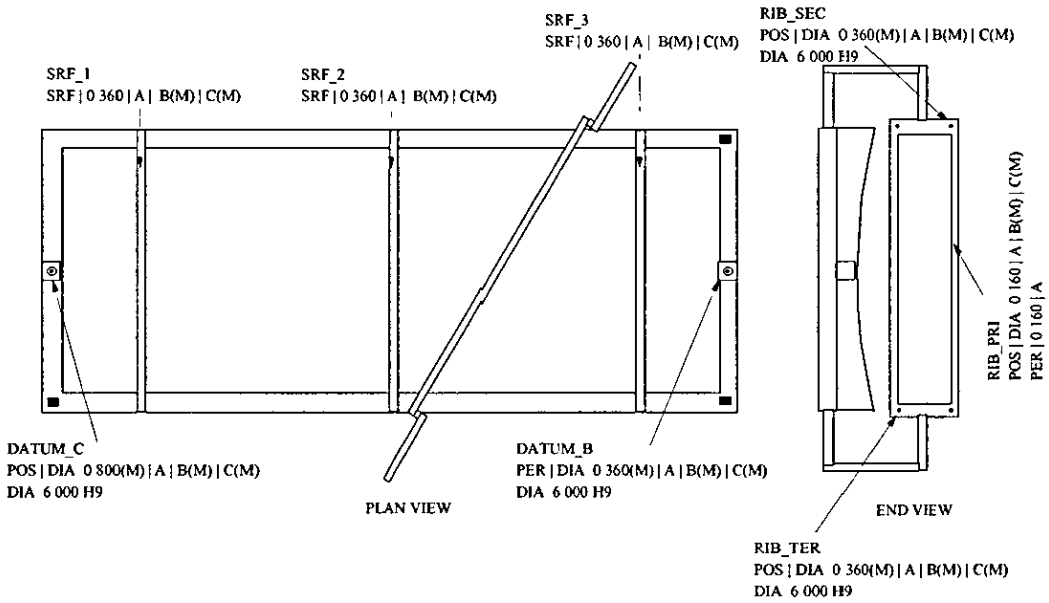


Figure 48 Fixture critical features and tolerances schematic

There is no facility with the VSA software to model the hole/pin/hole tolerance relationship Therefore, for this simulation the pin has been specified as a nominal diameter and its tolerance (float) has been added to the fixture hole tolerance Therefore:

Pin nominal & tolerance 5 990mm (+0 000/-0 012)	Hole nominal & tolerance 6 000mm (+0 012/-0 000)	CLEARANCE
Max condition = 5 990mm	Min condition = 6 000mm	0 010mm
Min condition = 5 978mm	Max condition = 6 012mm	0 034mm

Total clearance (float) is 0 034mm - 0 010mm = 0 024mm

It is not possible to specify unilateral tolerance conditions in Catha's functional & dimensional tolerancing (FD&T) module other than the use of ISO limits and fits. Therefore to satisfy the above specification make the component and fixture holes H9 (+0 030/-0.000) and make the fixture pin a nominal 5 996mm diameter. This creates a float specification on hole/pin/hole of +0 024/-0 000mm as required

The tolerances specified in the above section represent the initial design specification The complex skin OML and IML feature tolerances were changed as part of the "what-if" scenarios in order to represent different panel thickness variation. In addition the designed nominal gap condition for the different assembly processes were also revised to suite certain "what-if"

scenarios. These tolerance and nominal gap revisions are clearly stated on each of the different simulation results

7.3.6 Create CAD assembly model

The components and fixtures will been generated from the skin demonstration panel surface model. The complex skin and rib geometry will been constructed as sets of arcs, surfaces and faces in the CATIA CAE system. The fixture model will be constructed using exact solid geometry All critical features and tolerances have been generated within the CATIA functional dimensioning and tolerancing (FD&T) application This data can then imported in the VSA-3D tolerance analysis module and will be used to create the necessary feature and tolerance information required for the simulation system

7.3.7 Define assembly sequence

The assembly sequence will be as indicated in figure 49 below. The complex skin will first be installed to the assembly tooling followed by the rib section

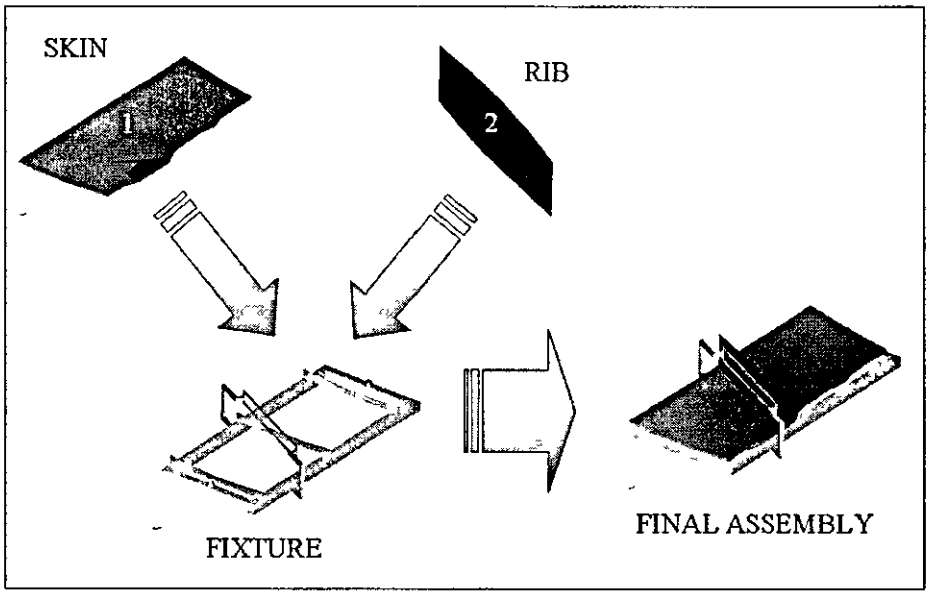


Figure 49 Assembly sequence diagram.

7.3.8 Identify assembly moves

The first and second moves are to locate the complex skin component the rib component into the fixture respectively.

Complex skin to fixture move

The skin component is located in three steps

- The first step is to orientate the skin such that its calculated profile line (BTM_SRF), is laying approximately in the x and y planar with the OML facing in the -z direction It is then placed onto the corresponding fixture pickup faces (SRF_1, 2 & 3) of the assembly tooling and approximately aligned in the x and y orientation against the secondary and tertiary tooling location hole features.
- The secondary hole feature of the skin (DATUM_B) and secondary hole feature of the tooling (DATUM_B) are to be aligned and the pin inserted
- The tertiary hole features of the skin (DATUM_C) and tertiary hole feature of the tooling (DATUM_C) are to be aligned and the pin inserted

The above move will be simulated in VSA-3D through a feature based 321 operation

Rib to fixture move

The rib is also located in three steps

- Datum A planar (DATUM_A) of the rib is orientated in the x and z planar and offered up to the corresponding flat pickup planar feature (RIB_PRI) of the assembly tooling.
- Hole datum B (DATUM_B) on the rib is aligned with the corresponding tooling hole (RIB_SEC) and an assembly pin is inserted
- Hole datum C (DATUM_C) on the rib is aligned with the corresponding tooling hole (RIB_TER) and an assembly pin is inserted

The above move will be simulated in VSA-3D through a feature based operation.

7.3.9 Define analysis measurements

Measurement strategy for gap condition

For the simulation analysis the objective is to measure the variation at a gap condition using a normal vector between the bottom edge of rib 6 and the complex skin IML surface. Simulation measurement will be facilitated at 17 points between the corresponding surfaces of each component (see figure below) The point to point measurements will be performed using criteria of the shortest distance between surfaces through a normal vector The measurement points are located at the complex skin's surface/surface interface, midway between these and at the skin edges. The VSA gap measurement template will be used to perform the analysis.

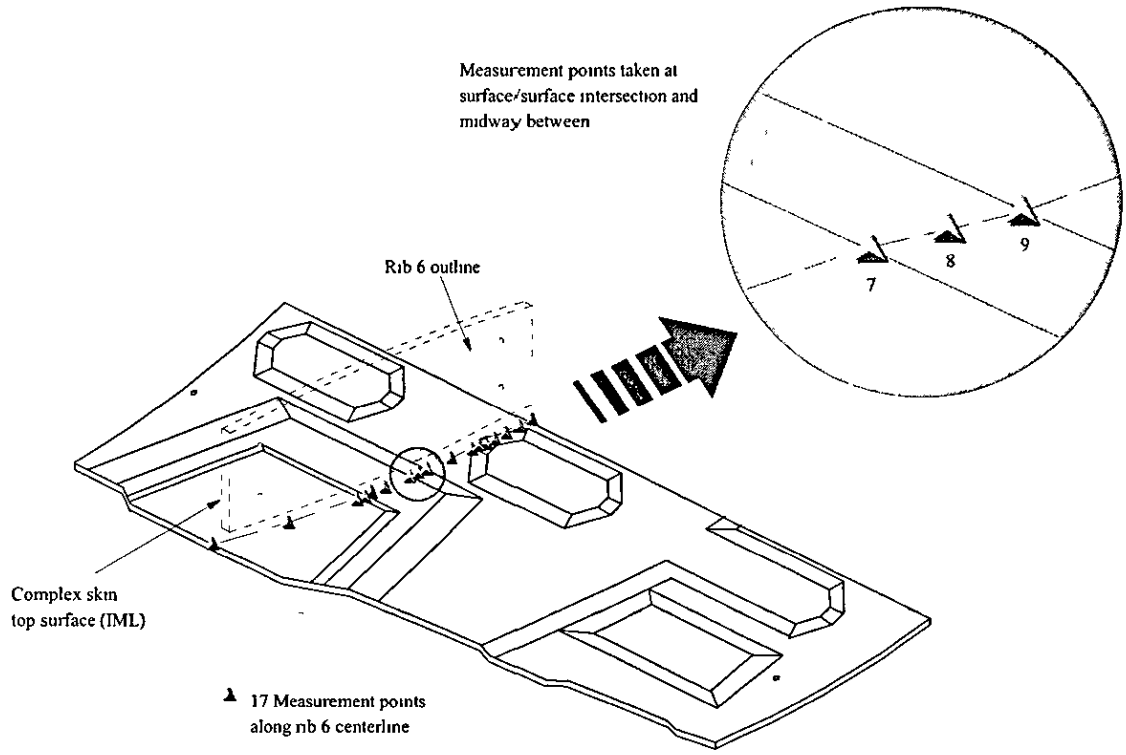


Figure 50 Measurement strategy for gap condition

7.3.10 Perform assembly simulations

Each simulation will be performed using 2,000 assembly builds This number of builds will be used to ensure a statistically stable set of results. All variation simulation will be of a normal distribution type

The simulation will be undertaken in two stages

- Monte Carlo simulation
- High-Low-Median (HLM) simulation

An explanation of the above simulation techniques can be fond in the appendix of this thesis

7.3.11 Simulation results and analysis conclusions

Some of the conclusions from this work are listed on the next page.

- It is evident that each of the three assembly processes will require a different nominal gap condition to ensure Cp and Cpk process capability outputs are optimised
- The complex skin out of assembly tolerance cases were of a magnitude greater than those associated with the simple skin profile (i e Case 1).
- For the simple skin (Case 1) tightening the surface tolerances had a much greater impact on out of assembly specification cases than for the complex skin
- For the film assembly process the optimum gap condition has changed for both the simple skin and the complex skin
- The tolerance specification for a paste joint is sufficiently large to ensure that virtually all assemblies, even with the complex skin, can meet the assembly gap specification
- With regard to the complex skin, top surface profile and the secondary datum were by far the most significant contributors to assembly variation.
- The simulation results suggest that a reduction could be accommodated by the paste bonding assembly process with little or no effect on Cp or Cpk process capability

7.4 Dimensional analysis for simple rib to skin assembly

The overview of the simple rib to skin assembly is presented below.

7.4.1 Analysis aims

The aim of this task is to simulate the assembly of skin and a rib components into a fixture so that a predicted interface gap condition may be analysed in order to establish if the condition will meet defined specifications These specifications include the maximum and minimum gap conditions permitted between components for mechanical fastener, film bonding and paste bonding assembly processes. The resultant virtual hole condition between components to facilitate mechanical fasteners will also be simulated

7.4.2 Analysis objectives

The aims of the analysis will be addressed through the following objectives

- Create nominal component and tooling feature geometry in CATIA V4 1 8 software The geometric models of the components and fixture will be cylindrical in nature and will not directly represent any actual Airbus wing design,

- Undertake analysis in the Variation Simulation Analysis VSA-3D software;
- Perform a number of 'what-if' scenarios to explore the effect of different key feature tolerances and designed nominal gap conditions for the following specifications
    - Assembly through use of mechanical fasteners.
    - Film bonding assembly techniques
    - Paste bonding assembly techniques
- From the results document conclusions and recommendations

7.4.3 Define assembly sequence

The assembly sequence will be as indicated in figure 51 below The skin will first be installed to the assembly tooling followed by the rib section.

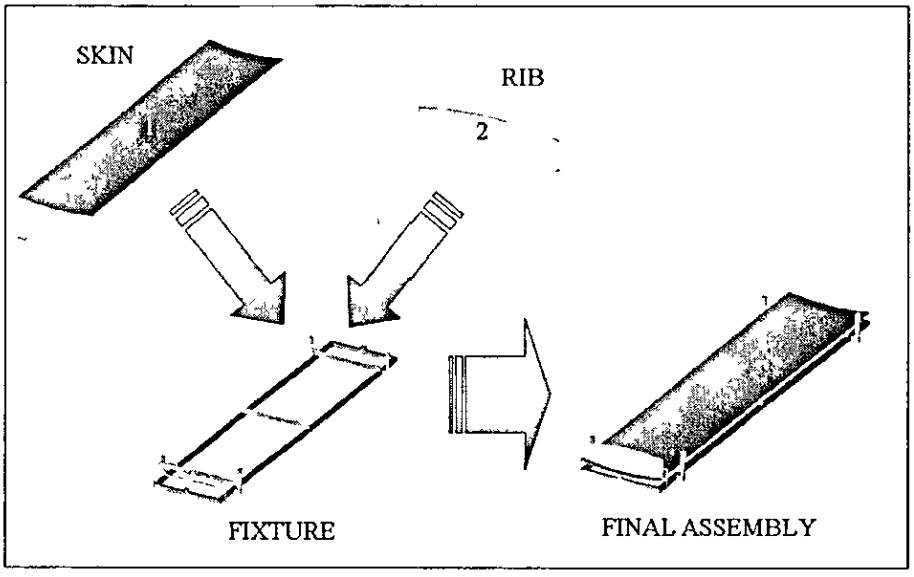


Figure 51 Assembly sequence diagram

7.4.4 Simulation results and analysis conclusions

Some of the conclusions from this work are.

- Skin thickness variation (surface profile) in the majority of cases has proven to be the biggest contributor to out of specification conditions in assemblies simulated.
- Improvements in skin surface (thickness) control will significantly improve assembly dimensional quality.

- Revision of the nominal gap condition for a given joint assembly process can contribute to the improvement or deterioration of their Cp and Cpk
- Where nominal gap conditions are revised at joint interfaces, the adhesive manufacturing companies should be challenged to improve their process specifications
- With regard to the fixture and its tolerance, some improvements could be made but in general these would have little effect with regard to improving the dimensional quality of the assembly given the current tolerance specification.
- There is an opportunity with machine finished CFC component features to improve their surface control with reference to their datum system This would result in better component and therefore assembly quality control

7.5 Dimensional analysis for C spar equipping assembly

An overview of the C spar equipping assembly is presented below

7.5.1 Analysis aim

The aim of this task is to simulate the assembly of complex skin and spar components into a fixture so that a predicted interface gap condition may be analysed in order to establish if the condition will meet defined specifications These specifications include the maximum and minimum gap conditions permitted between components for mechanical fastener, film bonding and paste bonding assembly processes.

7.5.2 Analysis objectives

The aims of the analysis will be addressed through the following objectives:

- Define analysis methodology
- Create nominal front spar component and tooling feature geometry in CATIA V4 1 8 software The model of the complex skin will be reused and from the base geometry for the C spar design.
- Undertake analysis in the Variation Systems Analysis VSA-3D software
- Perform a number of 'what-if' scenarios to explore the effect of different key feature tolerances and designed nominal gap conditions for the following specifications
    - Assembly through use of mechanical fasteners

- Film bonding assembly techniques
- Paste bonding assembly techniques

- From the results document conclusions and recommendations

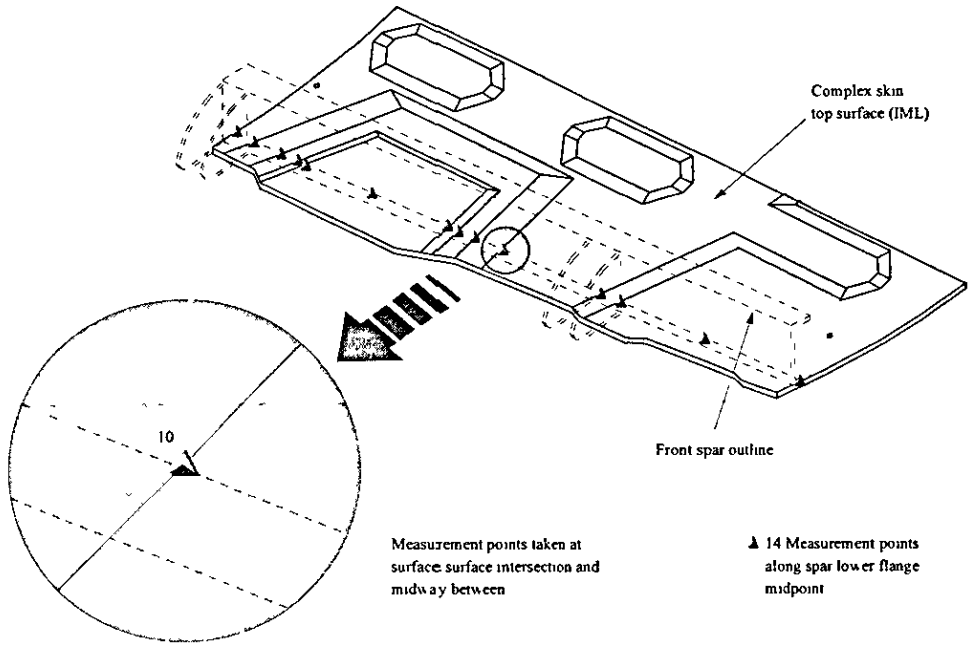


Figure 52 Measurement points for C spar equipping.

7.5.3 Define assembly sequence

The assembly sequence will be as indicated in figure 53 below. The complex skin will first be installed to the assembly tooling followed by the C spar section

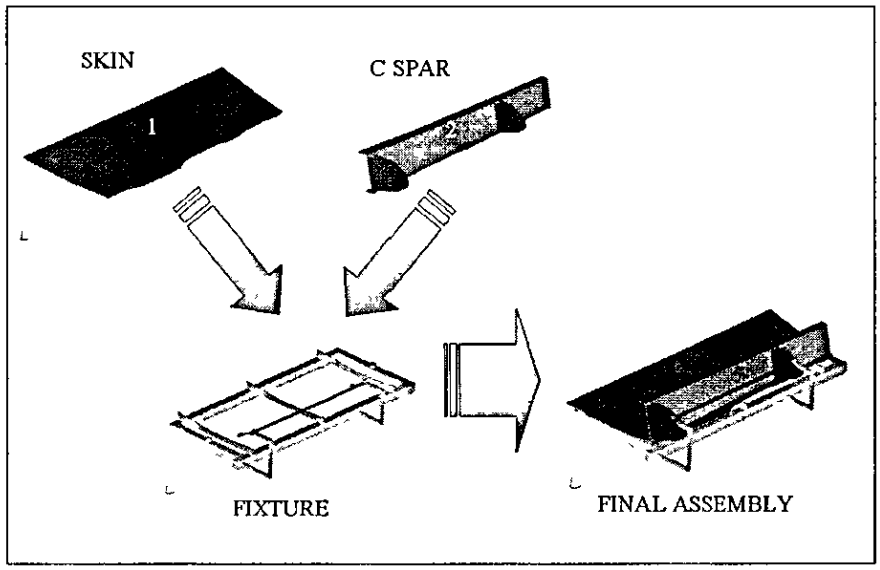


Figure 53 Assembly sequence diagram

7.5.4 Simulation results and analysis conclusions

Some of the conclusions from this work are

- Improvements in assembly capability would be achieved through setting a unique nominal gap condition for each of the assembly process.
- From the assembly simulation results it can be seen that the most difficult option to control is the mechanical fastener process, followed by film bonding and finally the most controlled was the paste bonding assembly processes.
- For the paste bonding assembly process, the simulation results suggest that a HL specification reduction could be tolerated with little or no effect on assembly capability
- The predominate variation contributors for this assembly when the skin top and bottom surfaces were set at non optimum tolerance were the actual skin surfaces themselves
- The tolerance range for the paste bonding assembly gap condition appears to be sufficiently large to accommodate all assemblies However, even with a revised nominal gap condition the process mean lies to the left of centre of the LL and HL specifications causing a number of assemblies to remain below the LL.
- The film bonding assembly process with skin surface tolerances set to an optimum and a specified nominal gap condition resulted in the smallest number of out of specification assemblies

7.6 Overall conclusions

The two case studies performed on the proposed composite wing box assembly structure have been presented in this chapter The defined analysis methodology has demonstrated the benefits of performing assembly tolerance analysis at a maturing design stage where some or all detailed 3D CAD product geometry is available This type of analysis should overlap the early ongoing PVA tool analysis, examples of which are outlined in chapter 6 This later stage 3D analysis will provide a more powerful validation of proposed manufacturing and assembly capability and will challenge design for production decisions before it reaches the design freeze maturity gate. The methodology used in the analysis forms a critical component of the proposed PARES methodology outlined in chapter 5. It also directly addresses the need identified in chapter 4 for the comprehensive 3D geometric tolerance analysis of structures to be performed when detailed geometry and key feature definition is available.

An additional need identified in chapter 4 is to develop new, or revise existing, manufacturing and assembly business processes Some airframe manufacturers are incorporating components made from composite materials such as CFC and GRP in addition to the traditional metallic materials such as Al/Ti related processes Both composite and metallic components may be geometrically complex and will need to be dimensionally robust to ensure both their assembly and achieving final product quality key characteristics

In order to gain an understanding of the issues a number of practical experiments were designed. These experiments explore the design, manufacture, assembly, and inspection of composite and metallic fuselage components for different geometric form The key issues for investigation are·

- Possible effect on overall assembly characteristics at different operating temperatures when using components made from materials with different thermal properties, for example, aluminium and carbon fibre composite
- The potential effect of advanced and complex manufacturing process on piece part dimensional stability, for example, the manufacture of carbon fibre composite.
- The effect of geometric shape complexity on overall assembly characteristics

These conclusions have been formed from extensive case study material which are confidential from Airbus and due to a none disclosure agreement between the author and the company they cannot be exposed

The experimentation is presented in chapter 8

Chapter 8

8 Assembly of carbon fibre composite panels to aluminium substructures

Objectives: This chapter outlines a number of experimental tasks designed in response to the need identified in chapter 4, section 4.3 for the development of new, or revise existing, manufacturing and assembly business processes. This need arise due to future commercial and military aerostructure designs incorporating a mix of composite and metallic materials and associated advanced manufacturing processes. The wing box assembly PVA tool and geometric analysis case material presented in chapters 6 and 7 respectively outline the type of analysis that may be conducted. These types of analysis however will only be effective if the geometric variability of targeted materials and manufacturing processes, CFC for example, is well understood This experimentation explores some of these issues first hand by conducting a number of practical design, manufacture, assembly, and inspection tasks of CFC panels to aluminium substructures. The experimentation is presented under the following sections:

- Aims of the experiment
- Objectives designed to meet the aims
- Define the experimental method
- Highlight the results and conclusions
- Identify possible future experimental work

8.1 Aims of the experiment

The experimentation presented in this chapter has been developed in response to some of the needs identified in chapter 4 These needs translate to the requirement for a better understanding of geometric variation characteristics on advanced materials and associated manufacturing process currently being considered for some established and future aerostructure development programs The investigation will generate material and process knowledge which may be incorporated into assembly analysis such as the PVA tool and later within a full synthetic geometric study using advanced tolerance analysis tools.

The aim of this experiment is to investigate geometric dimensional variation and its effect on the ability of CFC panels to be assembled to aluminium substructures Panel and substructure assemblies are sometimes designed with the functional requirement of interchaneability, i e , capable of being installed, removed and replaced without adjustment or alteration to panel or mating structure This functional requirement can become impeded by various forms of geometric variation and this impedance is anticipated to increase as panel and substructure geometric form becomes more complex The main aim of this work is to address these issues directly through a series of practical experiments including the manufacture, assembly and inspection of representative panel and substructure entities. In addition, the experiment will investigate into techniques designed to compensate for variability leading to a higher certainty of part to part interchangeability.

8.2 Objectives of the experimentation

The objectives of the experiment will address the aims through the investigation of two geometric types of panel and substructure assembly, these being·

Stage I - Planar geometric profile: Stage I involved the design, manufacture, assembly and investigation of two similar CFC panels onto a single aluminium substructure.

Stage II - Cylindrical geometric profile: Stage II will involve the detail design, manufacture, assembly and investigation of a number of CFC panels onto an aluminium substructure. The concept design of the panel and substructure will be of cylindrical profile

The experimentation was designed to investigate the individual component, assembly, and interchangeability elements of a planar and cylindrical form of CFC panel to a corresponding aluminium substructure The following activities were performed in support of stage I and stage II of the investigation

- Design of the experiment
- Design of panel and substructure.
- Identification of material and manufacturing process
- Design of assembly process
- Determination of assembly key characteristics
- Define design tolerances
- Design of assembly process

- Identify the quality measures to be investigated
- Design of experimental methods
- Perform measurement analysis using a range of metrology equipment, the Brown & Sharpe Micro Measure IV and VALISYS software.
- Perform a tolerance analysis study on the panel and substructure assembly using the VSA and VALISYS analysis software
- Experimental results and discussion.

8.3 Design of the experiment

The experimentation is centred on the design, manufacture, assembly, and inspection of planar and cylindrical CFC panels to corresponding aluminium substructures. Panel and substructure were designed and modelled in the Dassault Systemes CATIA system and a number of special features were constructed and used in the analysis These component datum reference frame, features, and tolerances were also generated in CATIA's advanced 3D functional dimensioning and tolerancing (FD&T) module This features based information would be used for inspection and assembly simulation analysis

Both panels are assembled to the substructure via the 20 dowel pins representing a close tolerance fastener similar to those used in advanced composite aerostructures For experimental purposes the panel and substructure assembly investigation is cantered about its ability to demonstrate interchangeability, one of the key functions of advanced structures. To demonstrate interchangeability in this experiment the panel and substructure needed to:

- Assemble unitizing all 20 dowel pins
- Demonstrate panel/substructure gap specification
- Demonstrate panel/substructure step specification

The experiment investigated the panel and substructure entities in a controlled environment using a Brown and Sharpe co-ordinate measuring machine (CMM) and the Micro Measure IV software These investigations outlined design and manufacture process variation such as hole position and form, surface and edge form of both panel and substructure

The panel and substructure assembly was investigated using precision hard gauges over a range of temperatures This was to demonstrate the effects of thermal expansion on the different material used for the panel and substructure

The CFC panel has a coefficient of expansion of 0 004mm/metre/^{0} C and the aluminium substructure of 0 026mm/metre/^{0} C This different coefficient values will have an effect on certain panel and substructure feature requirements for assembly such as hole/hole alignment, and step/gap conditions

These initial results will then be used as a basis for further investigation using Tecnomatix VALISYS software imbedded within the CATIA system This will demonstrate automated inspection programs generated off-line directly within the CATIA CAE environment The inspection data can be investigated using different analysis modes which will demonstrate different result conditions The VALISYS software also utilizes functional inspection analysis which allows the use of a bonus tolerance system making use of the specified material condition modifiers associated with some tolerances The use of the different inspection modes will demonstrate different result conditions.

The panel and substructure will also be subject to an assembly simulation This will be undertaken by the variation simulation analysis (VSA-3D) software also integrated into CATIA The simulation will be undertaken to investigate predicted variation results against known measured inspection data

8.4 Design of panel and substructure

The geometry design for stage I and stage II panel and substructure can be seen in figure 54 and 55 respectively The panels and substructures were created as solid model entities allowing the designation of detailed component features which are central to analysis

All features were modelled in solid geometry to provide a platform for the attachment of datum reference frames and tolerance metrics These will be utilised for assembly and the measurement inspection processes.

The design of the substructure primary face was lowered by a nominal 1mm This was to allow a controlled gap between the panel and substructure in their assembled state in case shimming techniques were required Shimming in this way in order to control the relationship between panel outer surface steps and gaps is common in the aerospace industry

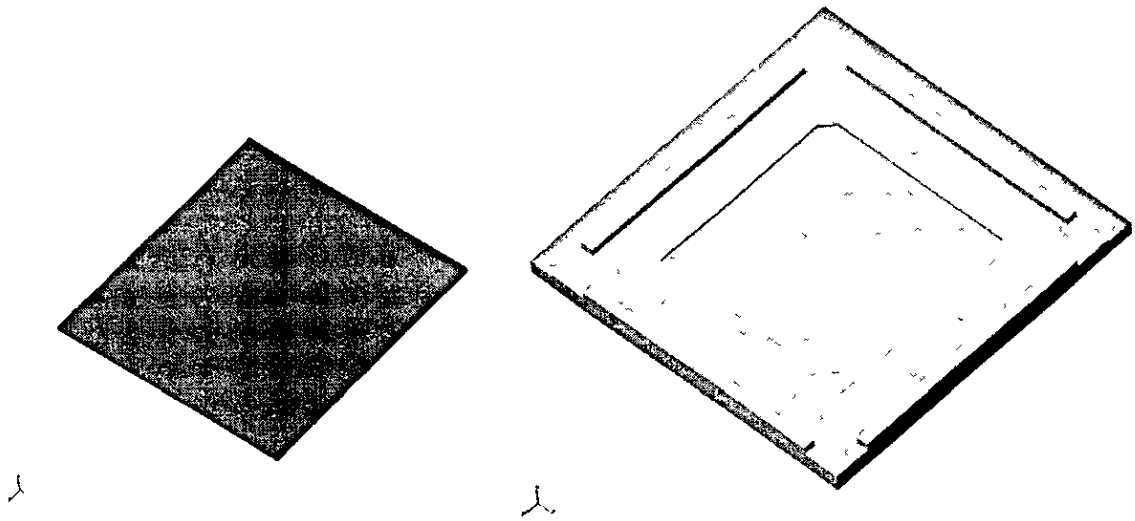


Figure 54 Panel and substructure design – Stage I.

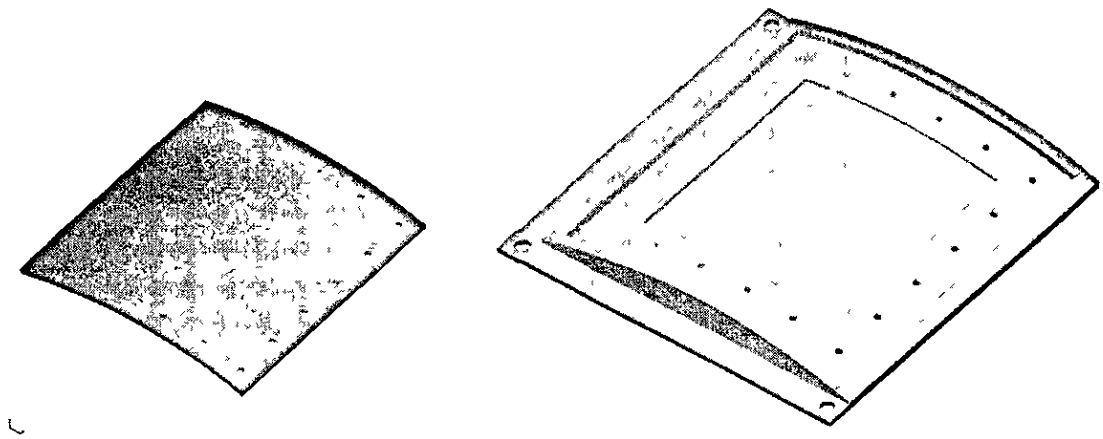


Figure 55 Panel and substructure design - Stage II

The panel and substructure 3D geometry is available for detailed interrogation, i e , dimensions, angles, etc.

8.5 Identification of materials and manufacturing process

The materials identified for this experiment were chosen to represent the characteristics and properties of materials currently used for this application in the aerospace industry. The same material specification, where ever possible, was used throughout this experiment to aid consistency. The panel material was a resin pre-pregnated (prepreg) CFC. The resin is a type 8552 epoxy matrix and the carbon fibre is an IM7 grade continuous weave designed for the prepreg process The carbon fibre is prepregnated with resin before delivery to the customer

These material grades are currently being used in the aerospace industry for the manufacture of interchangeable panels Data sheets for resin and CFC materials are available from the author upon request The production of CFC components from this type of material requires a complex lay-up and curing process The details of this process are considered to be beyond the scope of this thesis.

8.5.1 CFC panel manufacturing process

The stage I panels were laid up and cured at BAE SYSTEMS The stage II panels were laid up and cured at Airbus The production of net edges and holes was undertaken at Loughborough University using the Wadkin V4-6 CNC and the Cincinnati Sabre 400H machining centres The substructures were machined from a solid billet of 608276 grade aluminium This is basic grade aluminium with similar characteristics to aircraft grade materials

Design and manufacture of tooling plates: to enable the stage I and stage II panel lay-up and cure purposes, EN3B steel tooling plates had to be manufactured for each stage The plates determine the form shape for each panel generating a CPL at the panel and tooling interface. The tooling plates are shown in the figure below with their respective panels The plates were designed and manufactured at Loughborough University in support of this experimentation.

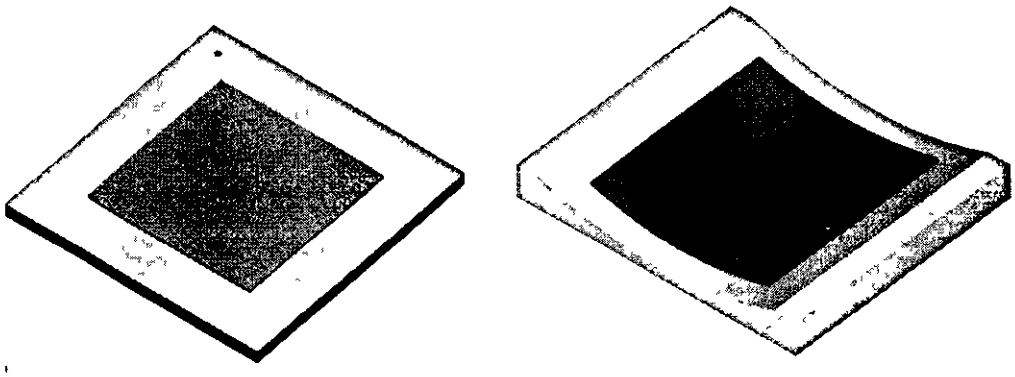


Figure 56 Lay-up and cure tooling plates - Stage I and satge II CFC panels

Lay-up and cure of CFC panels: this was undertaken following a BAE SYSTEMS process for lay-up and cure. This process was undertaken for stage I and stage II panels Data sheets for resin and CFC materials lay-up and cure are available from the author upon request

Routing of net panel edges and drilling of assembly holes: for stage I the production of holes and net panel edges required the adaptation of the tooling plate once the lay-up and cure process was completed In preparation of panel drilling and routing, 9x6mm tooling holes were drilled

into both stage I panels using the Wadkin machine tool in a manual operation These tooling holes were then used to secure both stage I panels onto a tooling plate via bolts The first panel (panel 2) was secured onto the tooling plate and then placed into the machining centre and clamped for operation. Panel 1 was prepared differently to panel 2 due to the resulting delaminating damage during the edge routing process To reduce this damage, panel 1 was sandwiched by a two layers of 4mm thick PVC plastic sheet, one on the top face and one on the bottom The plastic sheets were prepared by cutting a square profile to panel gross size and drilling 9x6 5mm holes in accordance with tooling plate hole pattern Panel 1 was then sandwiched between the plastic sheets An additional aluminium pressure plate produced to the same geometry as for the plastic sheets was placed on top of the CFC/PVC sheet sandwich The whole assembly was then bolted together producing a compressed sandwich which included the tooling plate, the CFC/PVC sandwich, and the aluminium pressure plate. This was then secured onto the machine centre via clamps and the holes and net edges were machined The main purpose of the plastic sheets was to ensure the cutter moved through solid sacrificial material above and below the panel edge surface to reduce the risk of delimitation of the CFC panel The edges of panel 2 were routed in one pass using an 8mm diameter solid carbide routing tool running at 8,000rpm and feed rate of 1 5 m/min

The holes were drilled normal to the surface profile in a single operation at 8 000 rpm and a 0 314 m/min feed rate The edges of panel 1 were routed in one pass using a 12mm diameter solid carbide routing tool running at 8,000rpm and a feed rate of 0 4m/min. Holes were drilled in a single operation at 8,000rpm and a feed rate of 0 314m/min A two flute solid carbide drill was used for producing the holes in both panels. An off-line CNC program was written to undertake the drilling and routing operations Stage II panel manufacture was undertaken on the Sabre 400H machine to accommodate the offset edges and hole axis. Essentially the same feeds, speeds and cutter details were used at each stage. The main difference is that the panels were routed using cibatool sacrificial tooling material and no PVC sandwich technique was incorporated This, as for stage I panel production, lead to some delaminating damage during the edge routing process

8.5.2 Aluminium substructure manufacturing process

Preparation of billet: the substructures were machined from two solid pieces of 608276 grade aluminium The initial billets was reduced to the required net base and edge dimensions through a manual milling operation using a 120mm diameter face cutter.

Figure 57. Sabre 400H and Wadkin V4-6 machine centres.

Machining of net substructure shape and drilling of holes: stage I final planar and hole geometry was then produced by the writing and executing of an off line CNC program. All features were produced on the Wadkin V4-6 machine centre (see figure 57 above). A 25mm diameter milling tool was used to great all planar geometry and initially holes were drilled with a 5.5mm diameter drill and finished with an adjustable radius boring tool. The final hole diameter was determined by offering the dowel pin to the hole until a fit condition was established. Stage II was undertaken on the Cincinnati Sabre 400H (see figure 57 above). The process was similar for stage I except but a 4 axis machine was required to generate the cylindrical geometry section and hole axis offsets. A 14mm diameter radial nose tool was used on the cylindrical surfaces finishing with a 6mm diameter ball nose cutter.

8.6 Design of the assembly process

The assembly process involved the fit of stage I and stage II panels to their respective substructures. In both phases the panels will be secured via 20 steel dowel pins which are used to represent a close tolerance fastener fit typically used in the aerospace industry. The panels were secured in all 6 degrees of freedom (DOF) in the following way:

i. Panel plane 6 > substructure plane 3 = 3 DOF in Tz, Rx, Ry.
ii. Panel hole 1 > substructure hole 1 = 2 DOF in Tx, Ty.
iii. Panel hole 11 > substructure hole 11 = 1 DOF in Rz.

Only two dowel pins are required to secure an orientation and a repeatable assembly. However, an additional 18 dowel pins have been used in this experiment to represent current military aircraft design which includes many panel to substructure assemblies with multiple fastener to cage alignments.

Assembly definitions have mostly been derived by the variation simulation software companies such as UGS PLM Solutions and Tecnomatix Technologies The action of taking one component to another is known as an assembly move The component being moved is referred to as the object entity and the receiving component is known as the target entity.

8.7 Determination of assembly key characteristics

The critical features of any assembly are initially determined from a detailed target product specification. The specification for this assembly is generic and represents a typical military aircraft weapon systems specification It includes.

Panels need to be fully interchangeable: this means being capable of being installed, removed or replaced without adjustment Traditionally, military aircraft removable flying surfaces are not manufactured to an interchangeability specification and are therefore geometrically unique This result in high maintenance costs associated with component replacement Current and future aircraft design will demand more components of an interchangeable specification in order to drive down maintenance costs All fasteners (20 dowel pins) must be used in the assembly operation

Panel to substructure assembly must be achieved through a range of environmental conditions: assembly need to be achievable in a range of conditions, i.e panel removal for maintenance of flying systems at different world locations and temperatures Military and commercial aircraft have extensive temperature envelopes in which they must function. Aircraft design now incorporated a greater mixture of material types with widely varying thermal stability and coefficients of expansion

The resultant external surface profile of the panel must be within an overall calculated profile line (CPL): all external flying surfaces are subject to a relatively close tolerance profile tolerance Currently this is not well understood by aerospace manufacturing companies due to the complexity of measuring a physical entity and then making a comparison to master digital data (MDD)

The resultant step and gap conditions between the panel and substructure: the assembled panel must lie within an in to, and out of, wind condition specification. Into wind condition refers to geometry with an orientation across laminar airflow and if uncontrolled will inter fear with laminar airflow Out of wind condition refers to geometry of orientation coplanar to laminar airflow and therefore has a reduced effect on airflow over flying surfaces. Different

specifications are generated for into and out of wind component geometry's with respect to step and gap condition These are important for two main reasons. The first relates to military aircraft whose design requirements demand low radar cross section specification to minimise observability The second related to both military and commercial who require low drag coefficients relating to flying surfaces in order to max dynamic performance, i e, lower fuel consumption, higher cruse speeds, and higher maximum speeds for example

The experiment will allow the above to be explored Aspects of interchangeability will be investigated through the fit and function tests at nominal and step ranges of temperature The fit condition of the 20 dowel pins will indicate the assembly capability at temperature and the measurement of step and gap conditions will also be recorded

There are a number of features on both the panel and substructure which are critical to the performance of the assembly with regard to the above. The key features of the panels and the substructures can be seen in the following figures

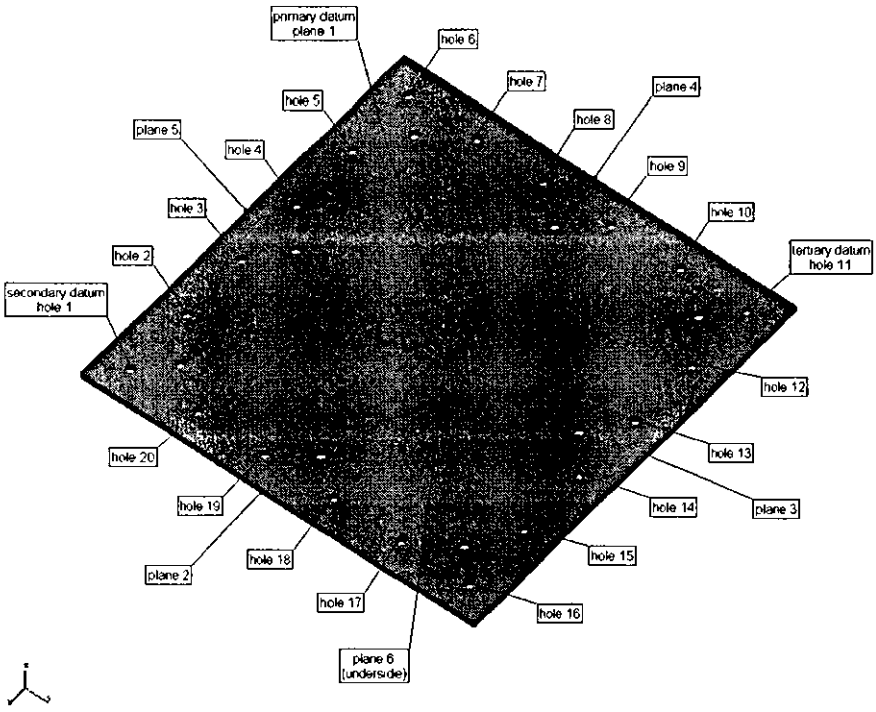


Figure 58 Panel critical features – Stage I

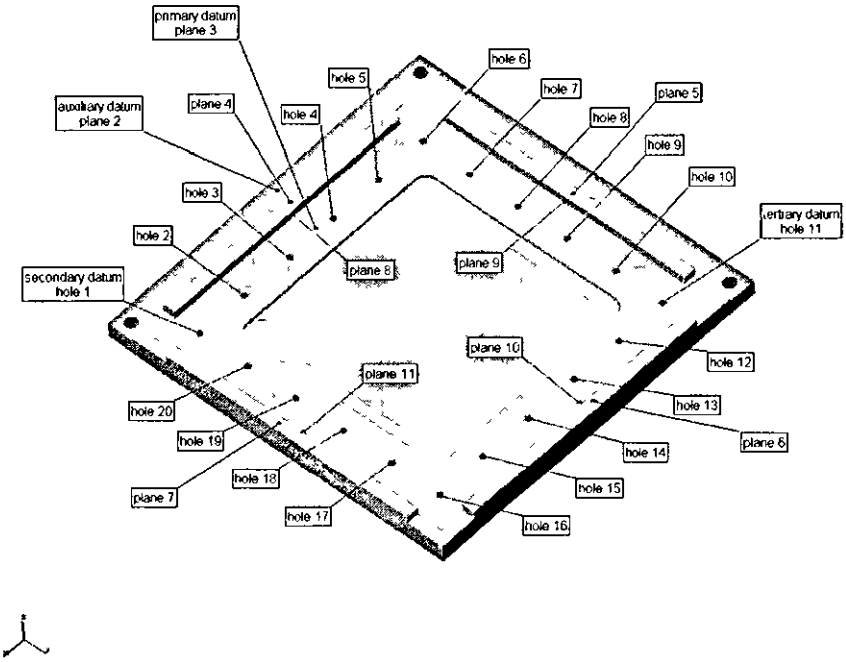


Figure 59 Substructure critical features – Stage I

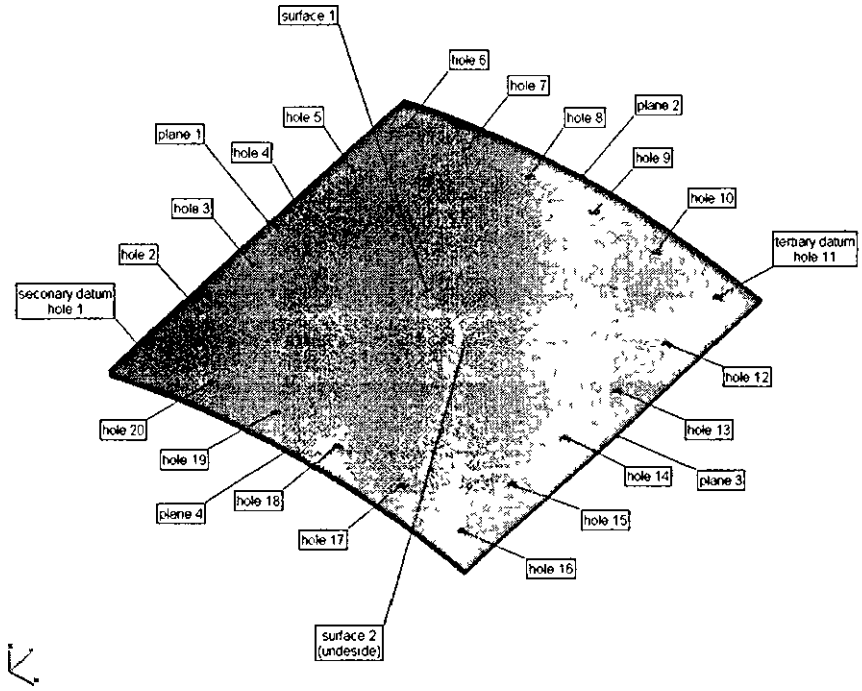


Figure 60. Panel critical features – Stage II.

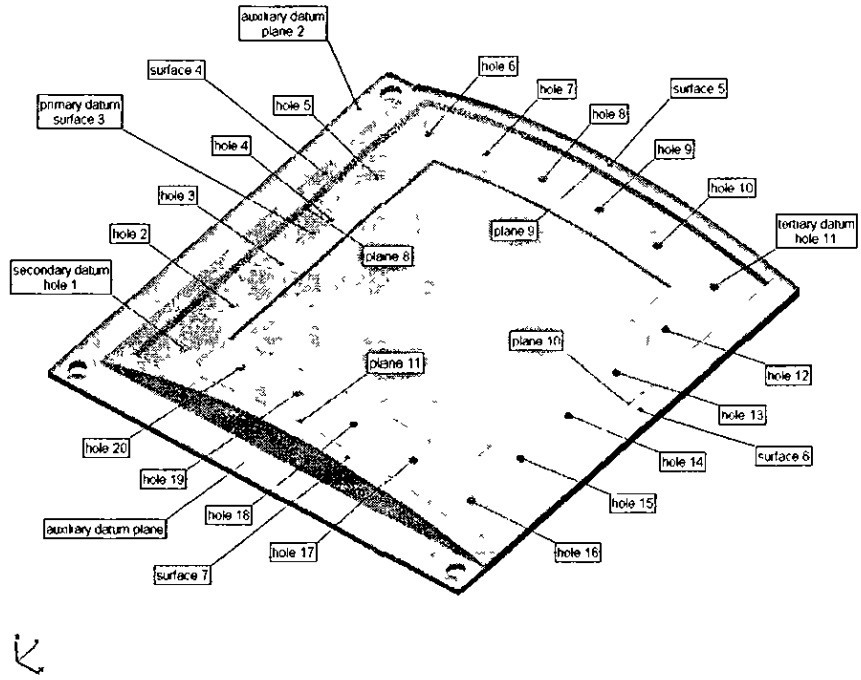


Figure 61 Substructure critical features – Stage II

8.8 Determination of component design tolerances

Part of the design process required the determination of a tolerance type and metric to control each of the critical features The tolerances were defined to the ASME GD&T Y14.5M 1994 standard. The determination of the type of tolerance call out was directly related to the type of control required of the geometric entities, i e., hole position for the fastener hole pattern and flatness of form for the interface landing surfaces The determination of appropriate designed tolerance metrics was achieved by extracting the process capabilities of the manufacturing equipment used for the production of the critical features, i e., the Wadkin V4-6 and the Sabre 400H This was achieved by investigating machine capability data from calibration and past process operations

The tolerance type and metric value for the manufacture of the panel and substructure are given below.

Component	Feature	Tolerance
Panel – stage I	Primary datum - plane 1	FLT|0 2
	Secondary datum – hole 1	PER|DIA 0 025|A, DIA +/-0 09
	Tertiary datum – hole 11	POS|DIA 0 025(M)|A|B(M), DIA +/-0.09
	Hole 2	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09

Component	Feature	Tolerance
	Hole 3	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 4	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 5	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 6	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 7	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 8	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 9	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 10	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 12	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 13	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 14	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 15	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 16	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 17	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 18	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Plane 2	PER|0 02|A
	Plane 3	PER|0 02|A
	Plane 4	PER|0 02|A
	Plane 5	PER|0 02|A
Substructure – stage I	Primary datum - plane 1	FLT|0 2
	Secondary datum – hole 1	PER|DIA 0 025|A, DIA +/-0 015
	Tertiary datum – hole 11	POS|DIA 0 025(M)|A|B(M), DIA +/-0 015
	Hole 2	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 3	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 4	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 5	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 6	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 7	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 8	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 9	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 10	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 12	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 13	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 14	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 15	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 16	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 17	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 18	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Plane 8	FLT|0 04

Component	Feature	Tolerance
	Plane 9	FLT|0 04
	Plane 10	FLT|0 04
	Plane 11	FLT|0 04
Panel – stage II	Primary datum – surface 1	N/A
	Secondary datum – hole 1	N/A
	Tertiary datum – hole 11	POS|DIA 0 025(M)|A|B(M), DIA +/-0 09
	Hole 2	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 3	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 4	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 5	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 6	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 7	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 8	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 9	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 10	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 12	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 13	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 14	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 15	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 16	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 17	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Hole 18	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 09
	Plane 2	SUR|0 02|A|B(M)|C(M)
	Plane 3	SUR|0 02|A|B(M)|C(M)
	Plane 4	SUR|0 02|A|B(M)|C(M)
	Plane 5	SUR|0 02|A|B(M)|C(M)
Substructure – stage II	Primary datum - plane 1	N/A
	Secondary datum – hole 1	N/A
	Tertiary datum – hole 11	POS|DIA 0 025(M)|A|B(M), DIA +/-0 09
	Hole 2	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 3	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 4	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 5	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 6	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 7	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 8	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 9	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 10	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 12	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015

Component	Feature	Tolerance
	Hole 13	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 14	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 15	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 16	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 17	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Hole 18	POS|DIA 0 025(M)|A|B(M)|C(M), DIA +/-0 015
	Plane 8	SUR|0 02|A|B(M)|C(M)
	Plane 9	SUR|0 02|A|B(M)|C(M)
	Plane 10	SUR|0 02|A|B(M)|C(M)
	Plane 11	SUR|0 02|A|B(M)|C(M)

Figure 62 Feature tolerance sepecification for stage I and stage II

8.9 Identify quality measures for investigation

The dimensional quality measures to be investigated for the panel to substructure assembly components are

- Interchangeable assembly capability in both controlled and uncontrolled environments
- Panel and substructure component detail inspection

Interchangeability, for the purpose of this experiment, was defined by the author as

> The ability of any of the manufactured CFC panels to be assembled onto, and removed from, its corresponding aluminium substructure utilizing all of the dowel pins, without modification to panel, pins or substructure, and without the use of 'undue' force

The ability of the panel and substructure assembly to demonstrate interchangeablity will be affected by a number of sources of dimensional variability, some of these are

Surface profile error: may lead to deviation from the nominal design surface known as the computer profile line (CPL). Deviation of the panel surface away from CPL may be the result of:

- Surface waviness.
- Surface form
- Surface roughness

Step and gap condition error: a step error can be described as any displacement between a surface designed to blend between an adjacent panel and substructure to form a discontinued condition The gap error can be described as any displacement from the nominal distance designed to exist across panel and substructure edge surfaces.

Hole and pin clearance error: hole and pin virtual clearance error between panel and substructure could result from:

- Vector (axial) error.
- Centre to centre (pitch) error
- Diametric error.

Environmental (temperature) variation: there is a considerable mismatch between the coefficients of expansion rates between the two materials used resulting in features being displaced in space as a result of the material involved moving at different rates

Dimensional inspection will take place using the following equipment.

- Brown and Sharpe Tessa 3D CMM using the MM4 software modules
- Brown and Sharpe Tessa 3D CMM using the VALISYS software modules
- Precision pin gauges
- Precision slip gauges
- Micrometer 25mm gauge
- Height gauge with dial indicator.

All dimensional inspection, except temperature related variation, take place in the metrology laboratory. This has a controlled environment with temperature at 20^0 C, +/-1^0 C, and humidity at $50^{\%}$, +/- 5%

8.10 Design of inspection methods

The experimental inspection methods were designed to address the quality measures defined in the previous section Detailed piece part inspection was carried out initially in a controlled environment Further inspection was undertaken at defined temperatures in order to investigate

the effects of thermal expansion and contraction on the assembly An outline of these processes is presented below

8.10.1 Controlled environment inspection methods

The following inspection methods were undertaken for the controlled environment investigation. The environment parameters were temperature 20° C, +/- 1° C, humidity at 50%, +/- 5%. All controlled environment analysis was undertaken in the metrology laboratory at the Wolfson School of Mechanical and Manufacturing Engineering

8.10.1.1 Surface profile error

Surface waviness error: detected through the use of surface finish and surface form inspection on CMM The surface finish detector was limited to a range of 5.5cm in a linear inspection. The CMM probed the entire panel surface recording data at 20-25 equally spaced points
Surface form error: detected by comprehensive CMM inspections for form error on each surface and edge entities Surface relationships were also investigated via the CMM for squareness and perpendicularity.
Surface roughness error: detected through the use of surface finish analysis
Thickness error (panel only): detected through the use of a standard 25mm micrometer. A panel thickness measurement was taken at the proximity of each assembly hole.

8.10.1.2 Step and gap error

Step condition: determined by using a dial gauge and square base The assembly and the dial gauge were placed onto a granite block surface, the stylus set on the panel upper surface and the gauge was set to zero. The stylus and gauge was then manoeuvred onto the step surface of the substructure and the value recorded Due to the form error of the panel a number of recordings were made for each of the four step conditions, from these a mean was calculated In addition the CMM was also used for an inspection using the MM4 and VALISYS software modules

Gap condition: determined by using slip gauges The investigation was undertaken by fitting the different slip block gauges in the gap condition at approximately four equal positions The largest slip gauge that could generally be pressed into largest gap was identified and recorded. The CMM was also used utilizing the MM4 and VALISYS software modules.

In order to simulate a larger number of panels to substructure assemblies each panel was rotated through 90 degrees four times and step and gap conditions were investigated The panels were then turned over and rotated through 90 degrees four times and investigated further Due to the 2 panels, this technique simulated the fit of 16 panels onto the substructure

8.10.1.3 Virtual hole condition error

The following methods were used to investigate panel and substructure hole form, hole pitch and hole diametric error. The hole errors for each component were determined from a single measurement routine on the CMM. Each component was given a datum as highlighted in figures 11 and 12 The MM4 routine incorporated an eight point inspection technique at each hole Four of the points were taken equidistant at the extreme top of the hole and the remaining 4 points equidistant at the extreme bottom of the hole. The VALISYS inspection software uses the same technique but includes a third set of four points midway between the first two giving a total of twelve measurements This was done to ensure the most accurate interpretation of hole geometry, especially about its axis Figure 16 below highlights the MM4 technique The routine included.

Panel and substructure hole form error: the form (cylindricity) error was recorded for each hole Cylindricity is calculated by the creation of two coaxial cylinders created about the initial best fit cylinder The coaxial cylinders are created at the widest and narrowest inspection points and the radial difference between the two is recorded as the cylindrical form error This is denoted as 'f' on an inspection output

Panel and substructure hole centre to centre (pitch) error: hole to hole (pitch) error is calculated by recording the x and y coordinates of each hole mid point position and resolving for distance. The centre of gravity position is derived from the best fit cylinder for the 8 inspection points undertaken for each hole inspected

Panel and substructure hole diametric error: hole diameter was taken form the best fit cylinder form the 8 point inspection technique The error was calculated by calculating the difference between the nominal and inspection diameter metrics

Inspection of assembly dowel pins: the assembly of the panel to the substructure was via 20 dowel pins These dowel pins were bought in and inspected on a CMM via a magnetic V block. The technique was similar to the above hole inspection using an 8 point process, four at each end

of the pins. The data from the 8 points was then used to calculate a best fit cylinder around the pin from which a diameter was recorded. The form of the pin was also recorded by the same process as for *Panel and substructure hole form error* given above. The dowel pin specification was diameter 6 mm, +0 004/+0 009 (based on supplier data)

8.10.1.4 Multiple temperature environment inspection method

The following inspection methods were undertaken for a range of environmental temperatures in order to demonstrate its effect on geometric variation There is a considerable mismatch between the panel and substructure materials with respect to their coefficients of thermal expansion rates These experiments were designed to investigate the effects of temperature chance on the assembly of panel to substructure and on some of its critical features The temperature range chosen for this experiment reflect a typical military and commercial aircraft operating requirements specification Military aircraft have particularly demanding environmental envelopes with not only a wide range of operating temperatures to endure but also a rapid transition from one end of a range to the other. Three parameters were investigated, these were;

- Step and gap conditions of panel to substructure.
- Panel and substructure hole diametric error
- Assembly performance of panel to substructure via dowel pins

The above investigations were undertaken in the same temperature batch session and in the order given The analysis was performed using a controlled oven booth for all temperatures above 0 degrees, and a controlled refrigerator unit for below 0 degrees. The environmental temperatures were monitored at all times during the inspections using digital readout thermocouples.

Step and gap conditions of panel 1 and substructure: the panel and substructure were 'soaked' in the appropriate temperature environment for a period of time in order to allow the components to stabilize at the required temperature Once the components had stabilized, they were removed from their environment and inspected rapidly in close proximity in order to reduce thermal change (rapid heating and cooling) error. After each investigation, the components were replaced for a period of time until they became thermally stable once again This process was repeated until all the relevant measurements had been completed.

Hole diametric error of panel 1 and substructure: the technique for inducing the correct thermal environment was the same as above for the step and gap inspection The hole diametric

error of the panel and substructure was determined independently through the use of precision pin gauges The gauges used were of 25 micron diametric steps

Assembly performance of panel to substructure via dowel pins: the technique for inducing the correct thermal environment was the same as above for the inspection criterion The assembly performance of the panel and substructure was determined by the fit of the 20 dowel pins This is essentially a hard gauge test It was conducted by placing the panel onto the substructure such that the primary holes of each were aligned i e , panel hole 1 to substructure hole 1, and a dowel pin inserted into both at hole 1. The assembly performance was then measured by inserting dowel pins equally in the x and y directions of the panel i e , hole 2, hole 20, hole 3, hole 19 etc until a no fit situation was encountered. The fit conditions at each hole were recorded.

8.10.1.5 CMM inspection using VALISYS V5.3.1 software

The VALISYS system is made up from a number of modules A detailed description of the VALISYS process and modules are available in the appendices of this thesis. The procedure listed below (figure 63) was used to undertake the CMM inspection using the VALISYS software.

Step No.	Activity	Function	Module
Step 1	Specify nominal dimensions of part	-	(CATIA)
Step 2	Create CAD model of part	-	"
Step 3	Define features to apply tolerances and datum's	FEATURES	Design
Step 4	Apply tolerances to features	GAUGE	"
Step 5	Verify and build tolerance schemes	CHECK	"
Step 6	Create inspection path and processes for features	PATH 1	Programming
Step 7	Define inspection probe (Renishaw PH9)	PROBE	"
Step 8	Verify/modify inspection process	PATH 2	"
Step 9	Create calibration process	PATH 3	"
Step 10	Export all Valisys data to system	VUTILITY	Design
Step 11	Import export files to CMM controller	FILES	Inspection
Step 12	Activate the part	FILES	"
Step 13	Establish link between the system and CMM	INSPECT	"
Step 14	Calibrate the probe	"	"
Step 15	Orientate the part	"	"
Step 16	Run inspection Process	"	"
Step 17	Disconnect the link	"	"
Step 18	Analyse the measured variation vs tolerance	QUALIFY	"
Step 19	Analyse the measured data	ANALYZE	Analyse

Figure 63 The VALISYS procedure

The structure of the reports produced from VALISYS is explained in the following section.

i. Analysis mode summary, briefly these are.

Cylinder axis method	LEAST SQUARES	(LS)
Limits of size	RMS AVERAGE	(AVE)
Axis extrapolation	YES	(YES)
Datum method	BEST FIT	(BF)
Degrees of freedom	All to GAUGE *N/A*	

ii List of feature variation and tolerance details and their post inspection status i e. PASSED or FAILED

iii Inspected part details and inspection process number

iv Summary of gauge analysis

8.11 VSA tolerance analysis

As part of the experiment a computer tolerance analysis study has been performed utilizing the VSA software The tolerance analysis study will analyse the effects of geometric variation on key features within the panel and substructure assemblies

The methodology used for this analysis will be similar to that outlined in chapter 7. It will include of the following stages

a Define study aims and objectives.

b List assumptions

c. Design assembly components and tooling features

d Identify key features on components and tooling.

e Define tolerances from process capability data for all key features.

f Create assembly model.

g Define assembly sequence.

h Identify assembly moves

i Define analysis measurements.

j Perform assembly simulations.

k Assess results.

The results of the tolerance analysis study are presented later in this chapter

8.12 Experimental results

The experimental methods described above produced the following results.

8.12.1 Geometric surface form error of panels and substructure

The following results were determined for geometric surface form error in the panels and substructures

Panel surface waviness - stage I

Panel surface waviness is the cyclic deviation of an external surface form from nominal. In panel 1 and panel 2, waviness is probably caused by the crossing of the carbon fibre bundles during the lay-up procedure and resultant deformation during curing processes Surface waviness is difficult to measure directly For this experiment waviness was identified using a Form Talysurf Series II. This equipment is designed to measure surface form and texture over a linear range of 120mm The panels were taken to Taylor Hobson at Leicester where they were measured The CMM data of the panels, taken on the Tessa 3D, also gives an indication of form error (see figure 64)

Panel 1	Panel 2
plane 1 - 0 0575mm	plane 1 - 0 0523mm
plane 6 - 0 2120mm	plane 6 - 0 1251mm

Figure 64 Stage I – panel 1 and panel 2 form error

Each panel plane was inspected with a cloud of 30 measurement points. Taking any measurements using a cloud of points philosophy basically involves taking as many points as deemed necessary (usually a high number) on a surface, evenly distributed over an area, in order to gain an understanding of its topographic definition

From the results plane 6 on both panels displayed a much greater error of form compared to plane 1 of each This is probably due to each plane 1 being on the side of the laid-up tooling. Plane 6 possibly inherit their form definition from plane 1 plus all the subsequent CFC layers placed on top during lay-up and cure.

The Talysurf Series II waviness and form inspection results are presented in figure 65 on the following page (all measurements in microns).

Surface inspected	Wa	Wv	Sm	Wp	Wt
Panel 1, plane 1 in x	5 62	16 04	4 73	15 93	31 97
Panel 1, plane 6 in x	14 76	45 36	4 81	61 2	106 56
Panel 2, plane 1 in x	14 34	42 37	5 64	54 55	96 92
Panel 2, plane 6 in x	6 5	16 03	3 32	15 69	31 72
Panel 2, plane 1 in y	4 91	12 24	4 1	15 76	28

Figure 65 Stage I - Talysurf Series II waviness inspection results.

Key·

Wa Corresponding parameters for waviness and primary profile; amplitude

Wv Corresponding parameters for waviness and primary profile; amplitude

Sm Corresponding parameters for waviness and primary profile; spacing

Wp Corresponding parameters for waviness and primary profile, amplitude

Wt Corresponding parameters for waviness and primary profile, amplitude

From the results it can be seen that the wave forms in the panel 1, plane 1 and panel 2, plane 1 are more uniform and of smaller magnitude when compared to panel 1, plane 6 and panel 2, plane 6 These results are consistent with those from the CMM form inspection data Both indicate a waviness error present with the lower panel faces (plane 6) demonstrating a greater magnitude than that of panel upper faces (plane 1). The last measurement on panel 2 was taken in the y direction, where all previous measurements were in the x direction. This resulted in a different pattern producing a bolder wave form output but with similar amplitude.

Surface waviness has the effect of increasing panel thickness and therefore introduces variation In a planar shape panel as used in stage I, the effects of panel waviness are minimal However, the effects of excessive waviness on a cylindrical or complex curve may present a bigger problem This may lead to hole misalignment and out of specification step and gap conditions

Panel thickness variation – Stage I and II

Panel thickness variation is mainly due to the CFC lay-up and cure process The process to lay-up and cure CFC panels is complex and includes a large manual input The panels manufactured in stage 1 and 2 are composed of more than 40 layers of prepreg weave material that has to be vacuumed down between approx. every 4 or 5 layers to expel any air inclusions. This type of lay-up process induces net panel thickness variation When this is combined with the variation caused by waviness, panel to panel and batch to batch thickness variation can vary as much as 5% The results of the panel thickness measurements can be seen in the figures below.

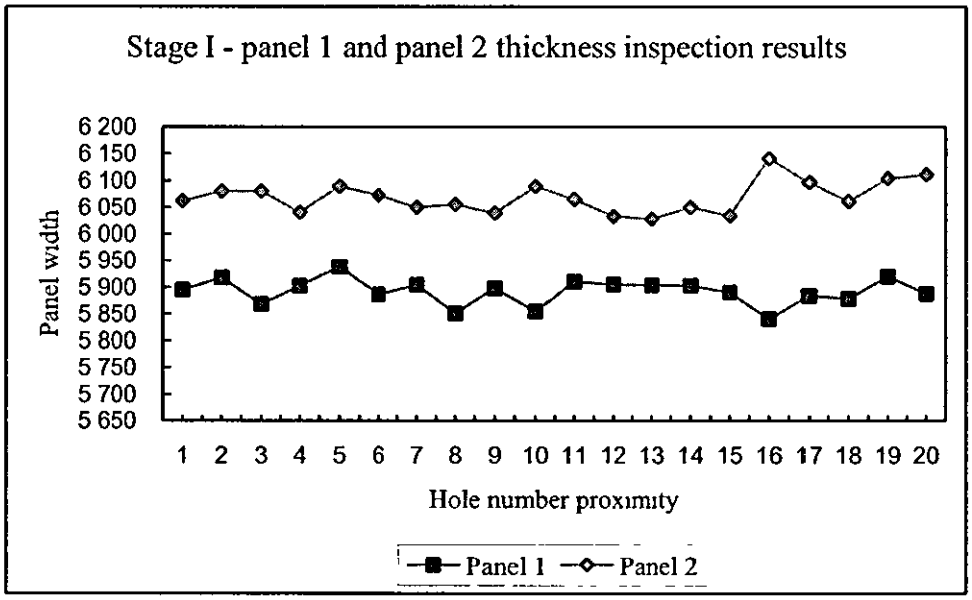


Figure 66. Stage I - panel 1 and panel 2 thickness inspection results

The results show that for Stage I there is an approximate mean width difference of 0 2mm for the nominal 6mm panels This variation will affect assembly performance in respect to the resultant step conditions between panel and substructure

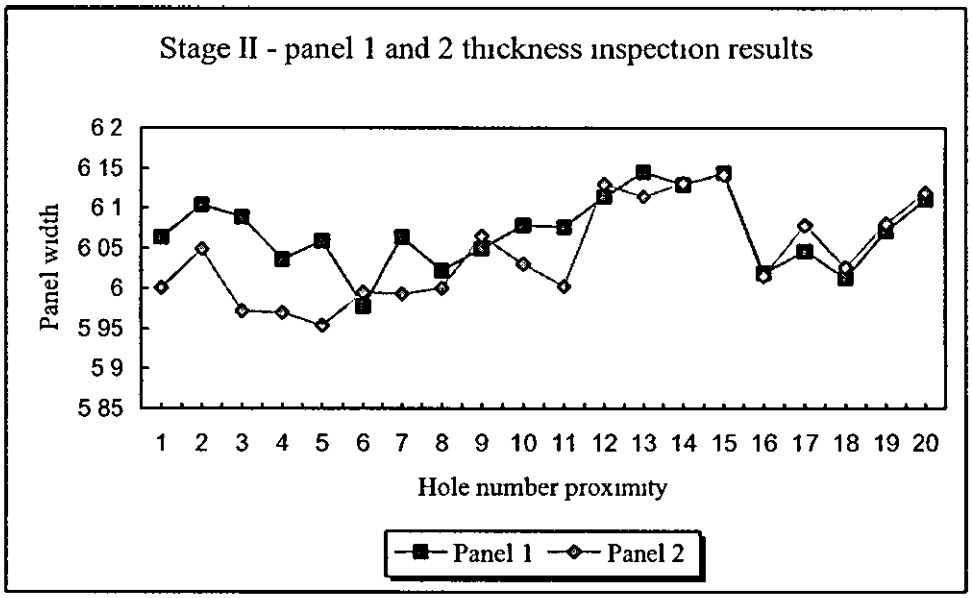


Figure 67 Stage II - panel 1 and panel 2 thickness inspection results

For Stage II the results are less stable. There is an approximate mean width difference ranging from 0mm to 0.15mm for the nominal 6mm panels As for stage I, this variation will affect assembly performance in respect to the resultant step conditions between panel and substructure for stage II

Panel geometric error – Stage I

The panel geometric error represents the overall error of each planar surface. Form errors are measured independently of any datum reference and present a fitted plane and deviations form that plane. Form error generally differs from waviness error. Form error describes deviation away from a nominal plane but it does not generally used to describe a type pattern It represents a gradual increase or decrees of form deviation such as a twist or a bow which could also be described as very long wavelength error. This may be cause by an element of the manufacturing process such as the distortion of a steel CFC cure mould tool The figure below graphically highlights the results.

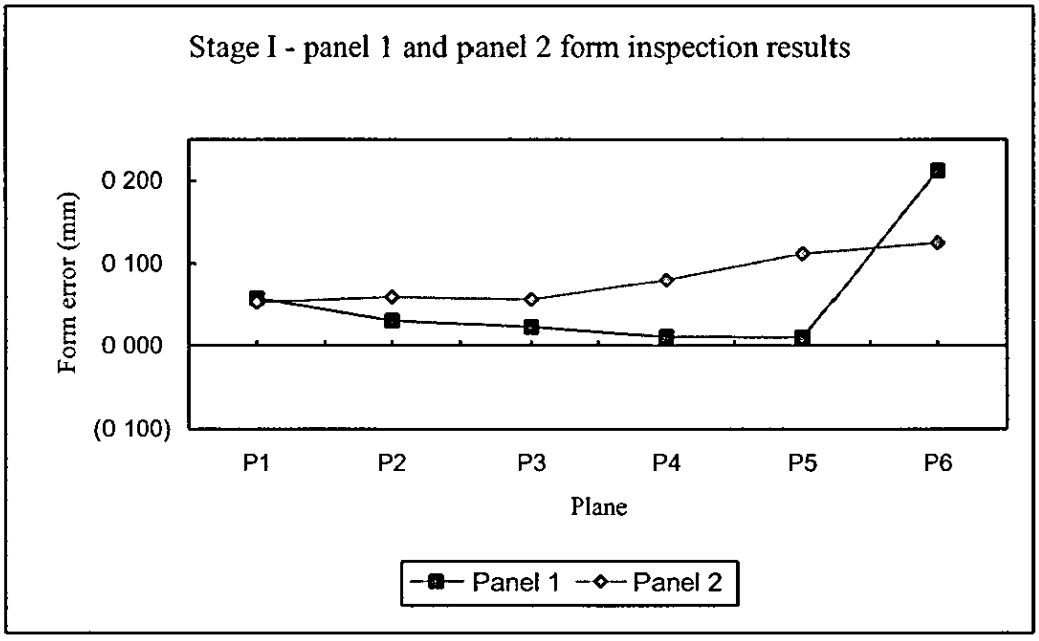


Figure 68 Stage I - panel 1 and panel 2 form inspection results

As can be seen from the results the form error on the top and bottom (planes 1 and 6) are of a different magnitude. In panel 1, plane 1 is of much smaller magnitude than plane 6. This is probably due to the orientation of the panel lay-up Plane 1 was probably the side in contact with the lay-up tool which accounts for its low form error. Plane 6 represents the final surface of the lay-up process and inherits from built up from each layer deposited

The form error of planes 2-5 represent the net panel edges. These were machined as part of the manufacturing process and it can be seen that their form error in considerably smaller when compared to planes 1 and 6. The error seen in panel 2 is generally larger than panel 1 This is due to a problem with the routing process that occurred on panel 2. The feed rate was to fast which resulted in the panel edge becoming delaminated and damaged. CFC is a demanding

material to cut and the correct cutting speed and feed rates are critical in order to gain a good net finish.

Substructure geometric error

Substructure geometric form variation will mainly be caused by machine process capability The form error can be seen in the figure below The main contributors to machine process capability are:

- Tool accuracy; effected by tool wear, tool damage
- Machine position accuracy, effected by inherent specification, machine wear
- Environmental conditions; effected by temperature and humidity.
- Efficient programming, effected by programming techniques, feed and speeds.

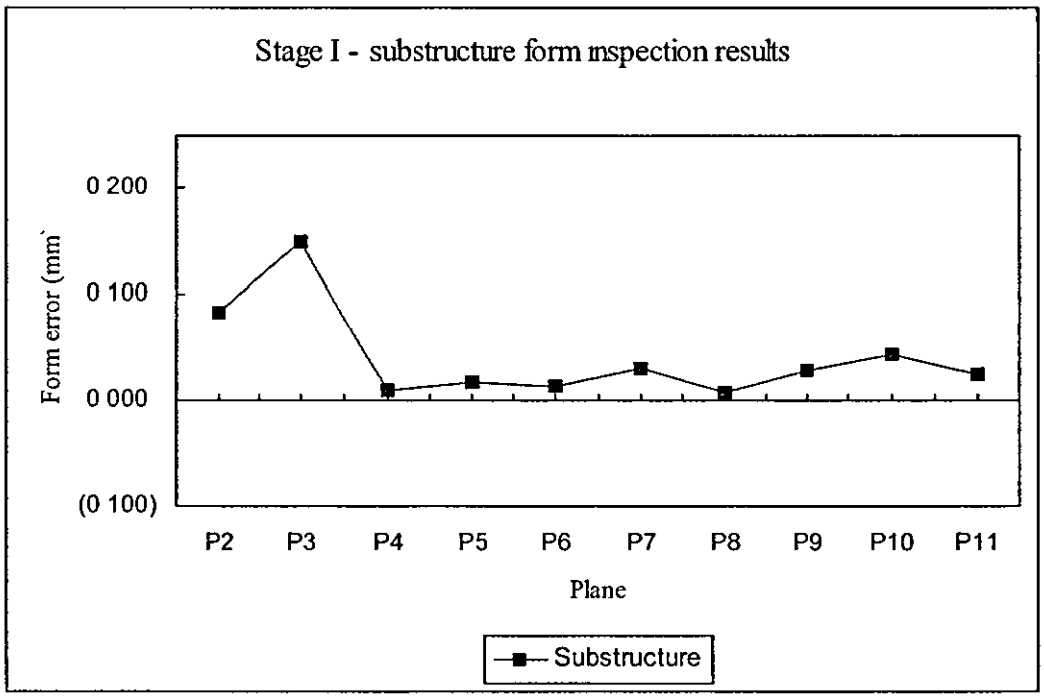


Figure 69 Stage I - substructure form inspection results

As can be seen from the results in the figure above, the largest form error is on the panel and substructure assembly interface, plane 3 This is due to the proportionally larger surface area of plane 3 in comparison to the other planes

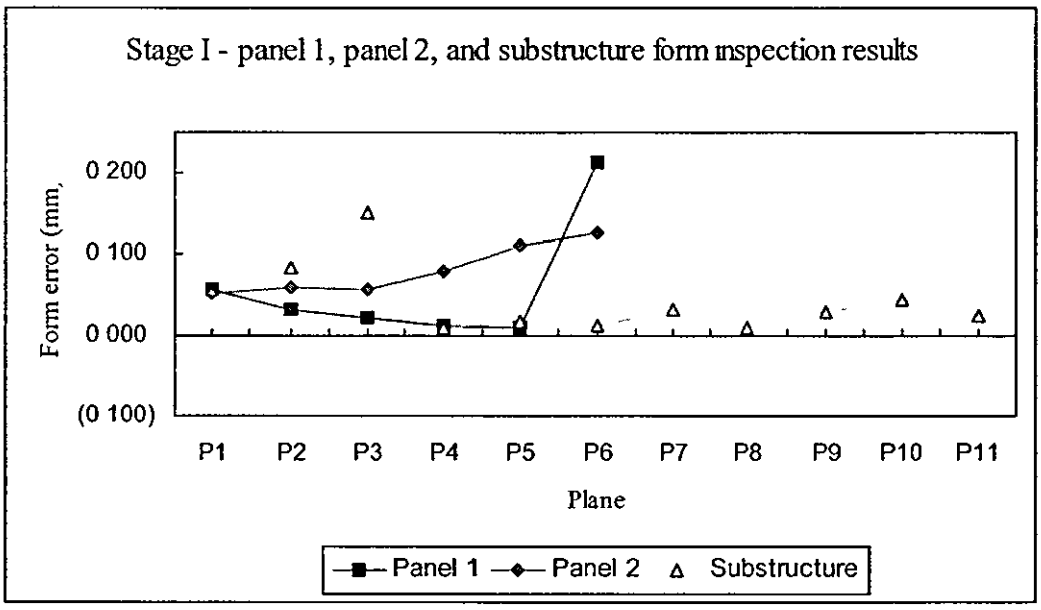


Figure 70 Stage I - panel 1, panel 2, and substructure form inspection results

There are no planar form measurements possible on stage II due to the geometry being cylindrical

8.13 Step and gap inspection results

The following results were determined for the step and gap conditions in panel and substructure assembly

Step condition of assembly – Stage I and II

The step conditions of the assembly represent the distance from the panel surface to the upper substructure step surface, measured normal to each. The step condition on an aircraft has an effect on the laminar airflow about the outside profile If allowed to drift out of specification it can affect an aircraft in two ways·

- Reduction of aerodynamic efficiency leading to loss of dynamic performance i e , top speed, cruse speed, range, etc.
- Increase of radar cross sectional area leading to potential increase of observability.

For the purpose of stage I experimentation, the step conditions were recorded and no comparison was made to a requirement specification The step condition results record a value for the difference from the substructure to the panel step height Therefore a positive step recording represents the panel surface being relatively higher than that of the substructure. The step condition results can be seen in figures 71, 72, and 73

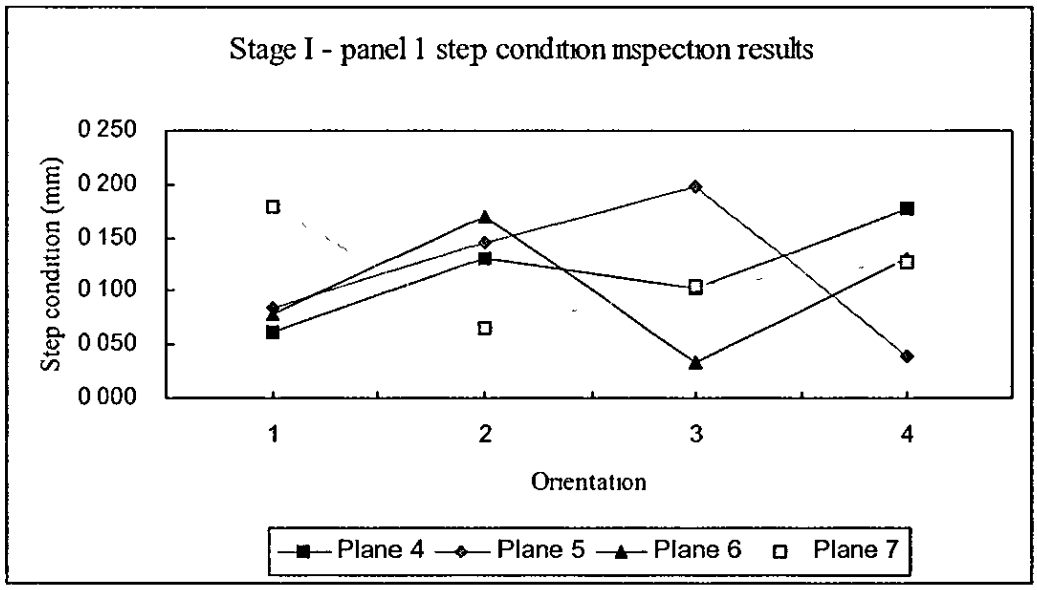


Figure 71 Stage I - panel 1 step condition inspection results

Due to the relative consistency of results, the error is probably due to the panel thickness variation in the region about plane 4 and 5, i e , the panel width at these regions are below nominal. The step condition of panel 2 could not be measured due to the damage resulting from the routing process required to produce the net edge.

For the stage II experimentation, the step conditions were recorded and no comparison was made to a requirement specification. The step condition results record a value for the difference from the substructure to the panel step height Therefore a positive step recording represents the panel surface being relatively higher than that of the substructure The results can be seen in the figures below.

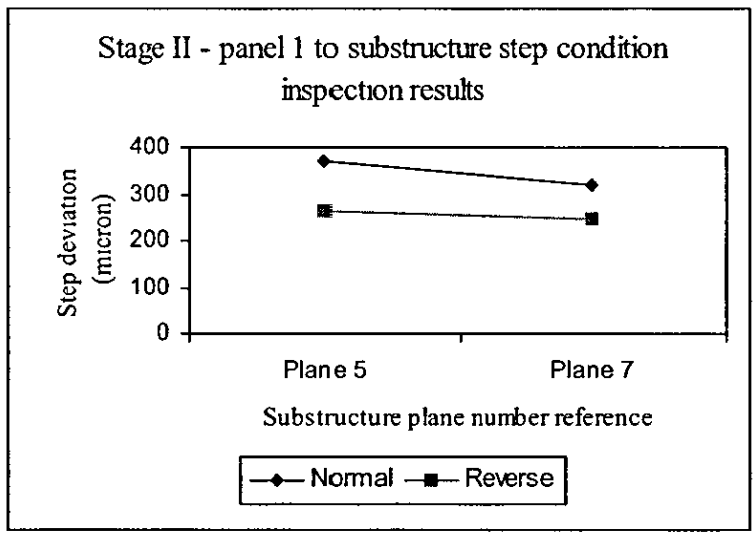


Figure 72 Stage II - panel 1 step condition inspection results

The step measurement error is again probably due to the panel thickness variation in the region about plane 5 and 7, i e, the panel width at these regions are below nominal The relative difference between the two orientations, which is approximately 0 1mm, suggests uneven panel thickness with some possible cylindrical form error. The same observations can be attributed to stage II, panel 2, step condition results

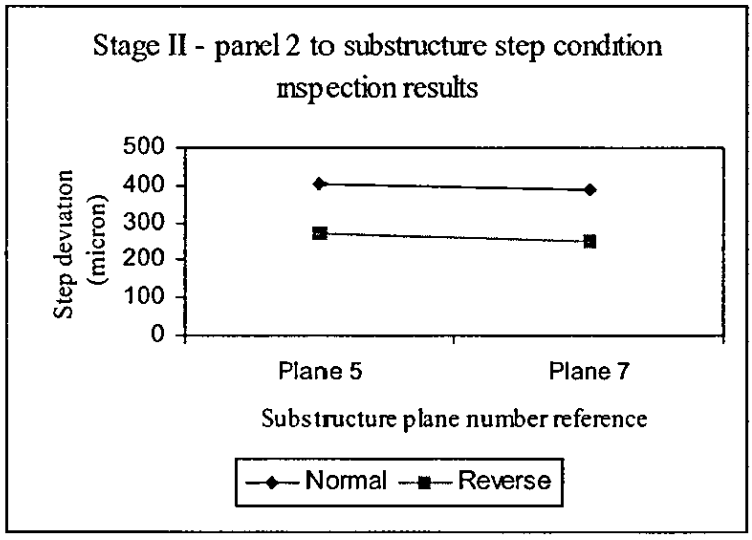


Figure 73 Stage II - panel 2 step condition inspection results

Gap condition of assembly – stage I and II

The gap conditions of the assembly represent the distance from the panel edge to the substructure internal planar edge, measured normal to each plane The gap condition on an aircraft can also have an effect on the laminar airflow about the outside profile. If allowed to drift out of specification it can effect aerodynamic efficiency leading to loss of dynamic performance i e, top speed, cruse speed, range, etc For the purpose of stage I experimentation, the gap conditions were recorded and no comparison was made to a generic requirement specification The gap condition results can be seen below

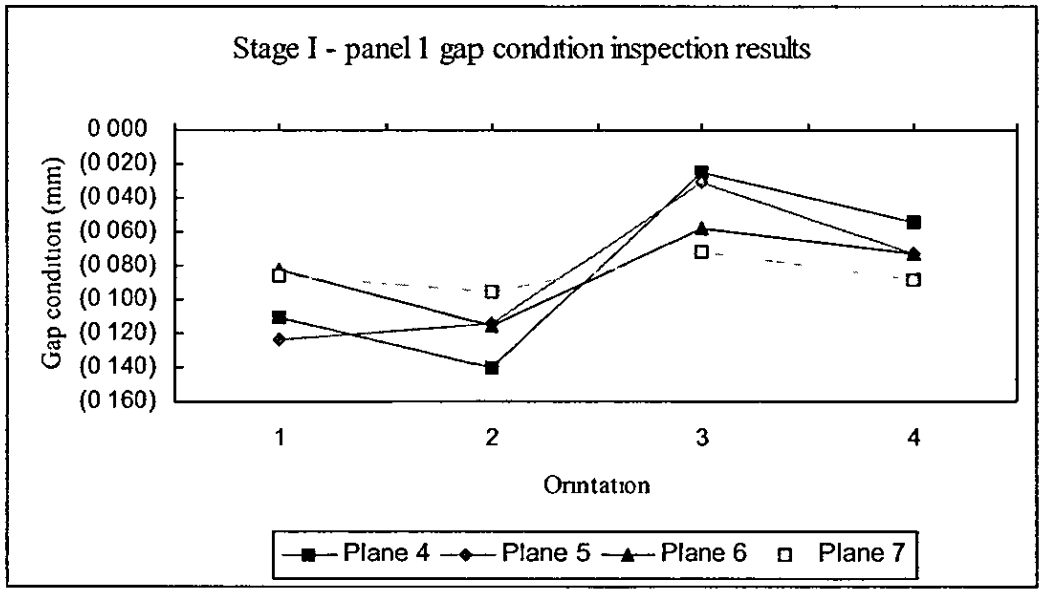


Figure 74 Stage I - panel 1 gap condition inspection results

As can be seen form the results the mean deviation of the gap condition is consistently below nominal, i e the gap condition is smaller than nominal This suggests that the manufacturing process used to produce either the substructure or the panel was cutting under size. This is consistent with a set of results measuring the distance between the datum hole and planar edge for each panel (see panel 1 and 2 datum to edge distance inspection results). These results demonstrate that the CFC panels machined consistently oversize which would result in a reduced gap condition after assembly to the substructure.

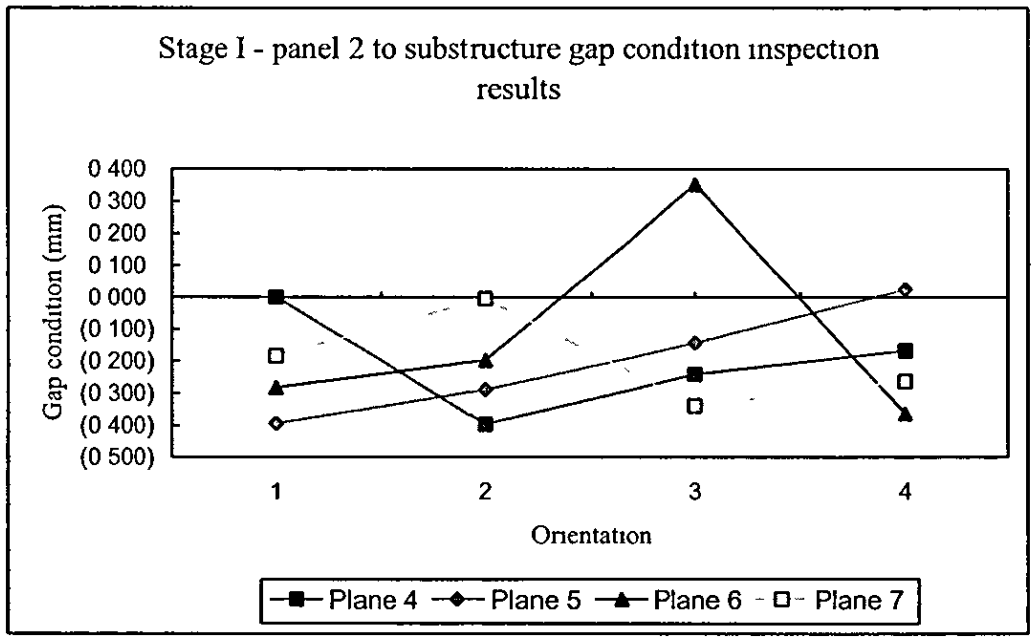


Figure 75 Stage I - panel 2 to substructure gap condition inspection results.

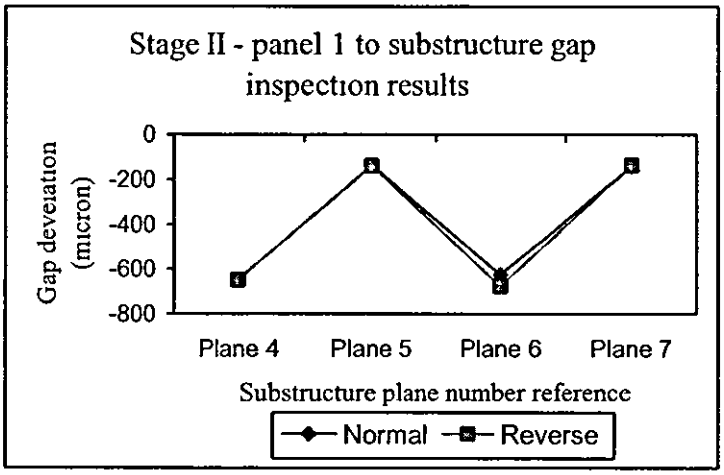


Figure 76 Stage II – panel 1 to substructure gap inspection results.

From the stage II panel 1 and panel 2 to substructure results it can be seen that the gap conditions were also undersize compared to nominal, see figures above and below

The magnitude of error changes with the edge type. Plane 4 and 6 for panel 1 and 2 were consistently measured as being approximately 0 6mm undersize, where as planes 5 and 7 were measured at only 0 2mm undersize This discrepancy may be attributable to a CNC machining program error on either the panel or substructure.

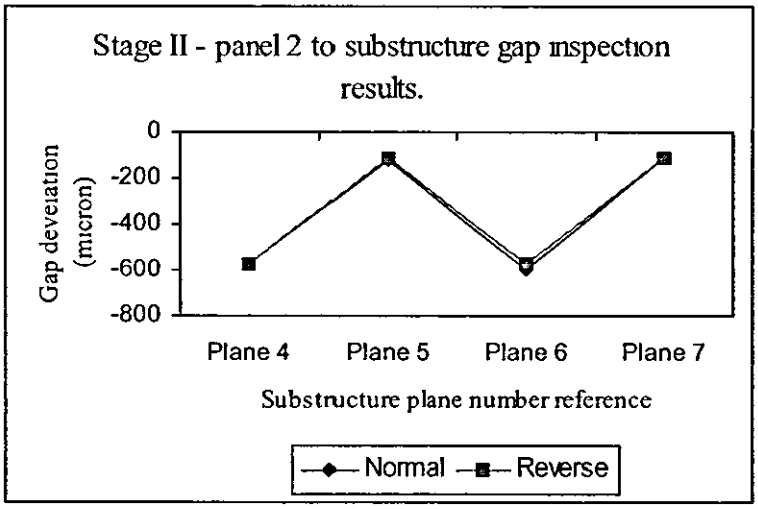


Figure 77. Stage II – panel 2 to substructure gap inspection results

8.14 Hole condition of panels and substructure

The following results were determined for the hole conditions in the panel and substructure components. The 20 hole patterns in panel 1, panel 2 and the substructure were inspected The measurements are divided into three categories, these being

- Hole form (cylindricity) error.
- Hole centre to centre (pitch) error.
- Hole diametric error

Stage I - panel 1, panel 2 and substructure hole form inspection results

The following results represent the measured hole form error in panel 1, panel 2 and the substructure for both stage I and stage II The hole form error of panel 1, panel 2 and substructure for stage I can be seen below

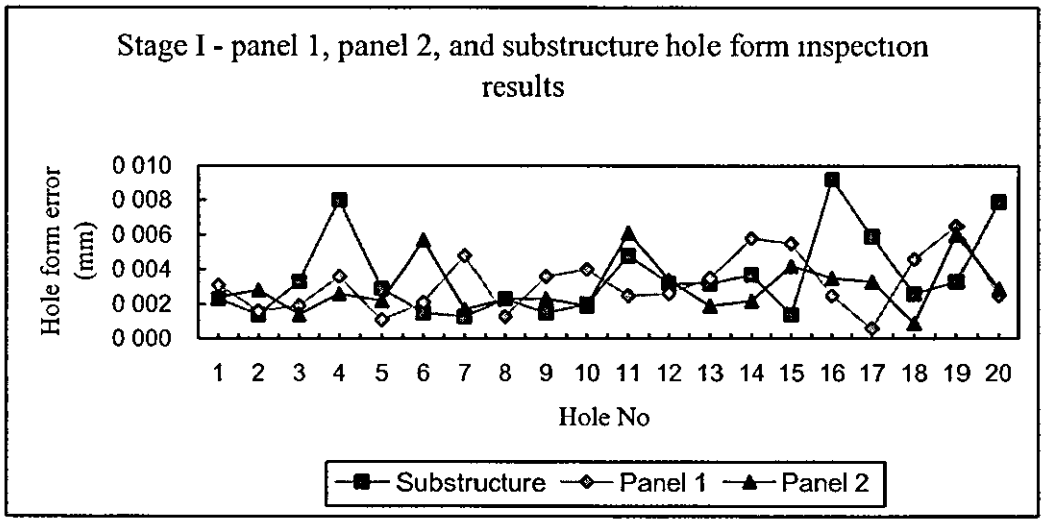


Figure 78 Stage I – panel 1, panel 2, and substructure hole form inspection results

As can be seen form the results for stage I the hole form varies relatively little Both panel 1 and 2 were in approximately the same range (between 0 007 and 0 001) with a mean of 0 003

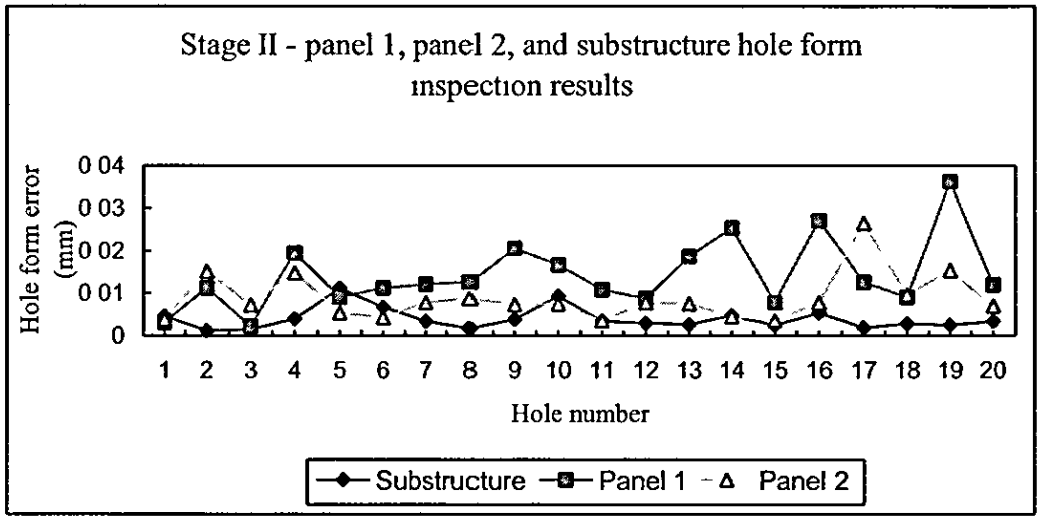


Figure 79 Stage II – panel 1, panel 2, and substructure hole form inspection results

For stage II, the results indicate that hole form varies relatively little. The average results for the substructure, panel 1, and panel 2 were 0.004mm, 0 014mm, and 0 009mm respectively. The results of stage II are less consistent with those from stage I due to an increase in geometric complexity The range for each of the outputs has also increase compared to the stage I results

For both stages I and II the substructure holes were finished with a boring bar where as the panels were drilled in a one hit cycle using a two flute twist drill. The form of the panel holes in stage I are generally better than that of the substructure, which was unexpected. This can be explained partly by the different depth of holes The depth of hole in the substructure is more than twice that of the panel This deeper hole in the substructure, although theoretically more accurate, recorded a bigger error in stage I This suggests that the depth at which an inspection process takes place is crucial to the output results, for example, if the substructure holes were to be inspected over the same depth range as that set for the panel, then the author would expect a better form result from the substructure holes.

Stage I and II - panel 1, panel 2 and substructure hole centre to centre inspection results

The following results represent the measured hole centre to centre error in panel 1, panel 2 and the substructure. Panel 1, panel 2 and substructure pith error results can be see in figures 81-85.

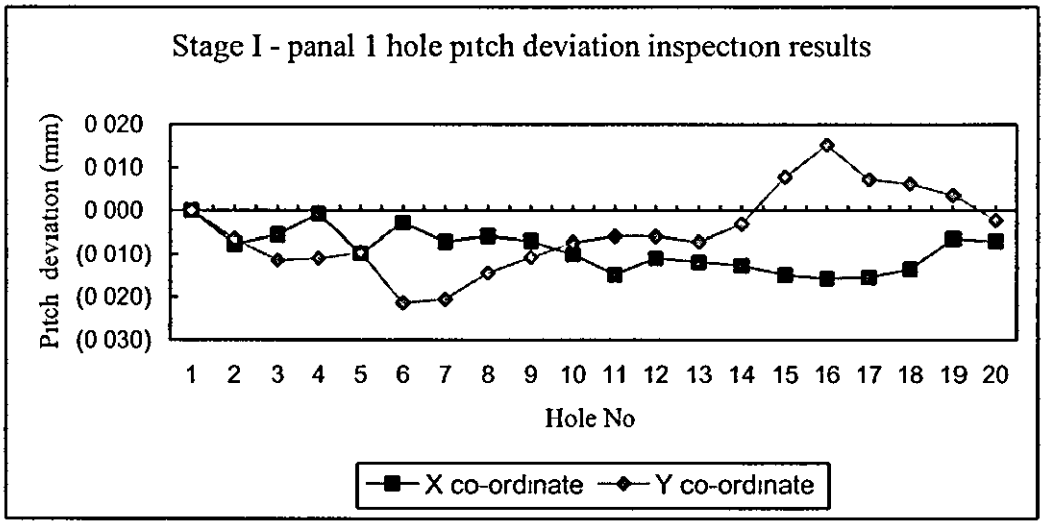


Figure 80 Stage I - panel 1 hole pitch deviation inspection results

As can be seen from the results panel 1, panel 2 and the substructure hole inspection demonstrates consistent and accurate hole position. Hole position accuracy is dependent upon machine tool accuracy All components were drilled on the Wadkin V4-6 which when last calibrated indicated a position accuracy of +/- 25micron over the full operating envelope. Due to the close proximity and the planar axial orientation of all the holes it can be seen from the results that all the hole positions are well within that specification

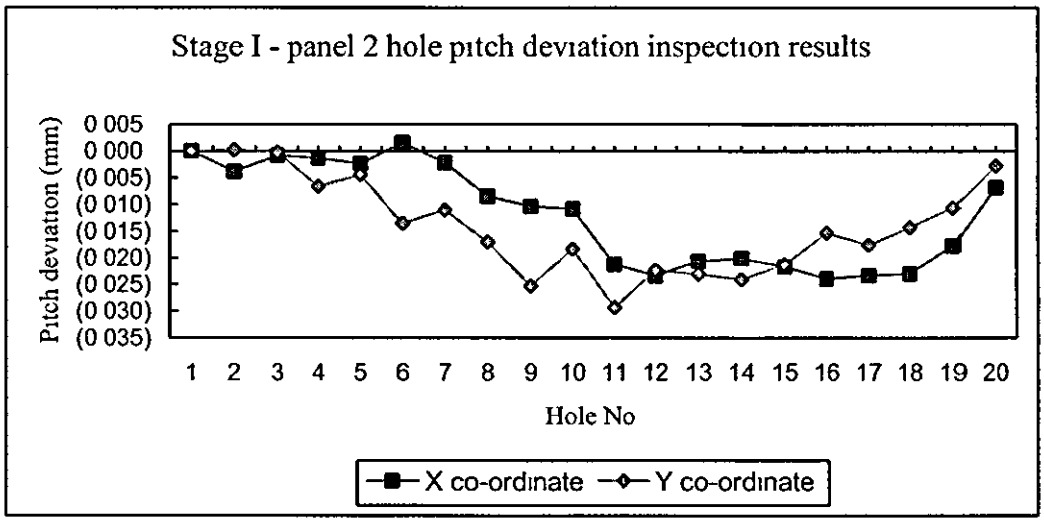


Figure 81. Stage I - panel 2 hole pitch deviation inspection results.

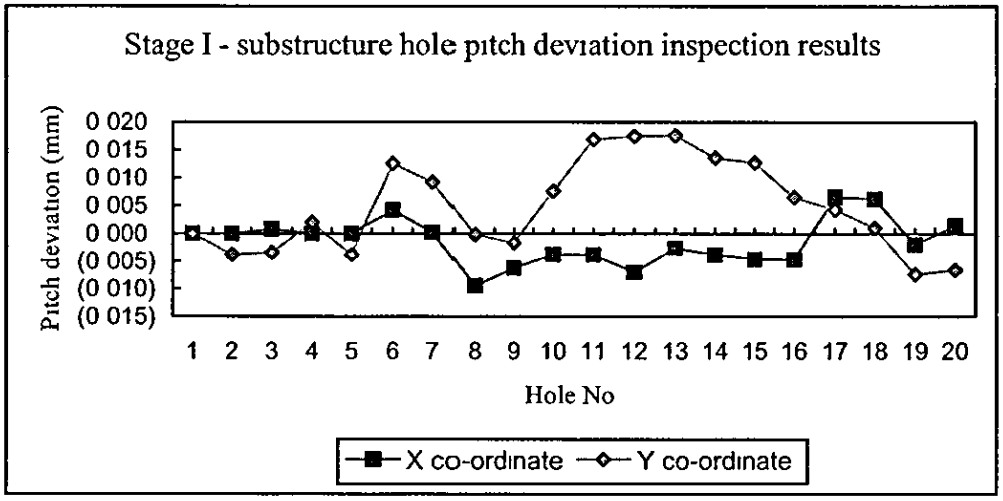


Figure 82 Stage I - substructure hole pitch deviation inspection results

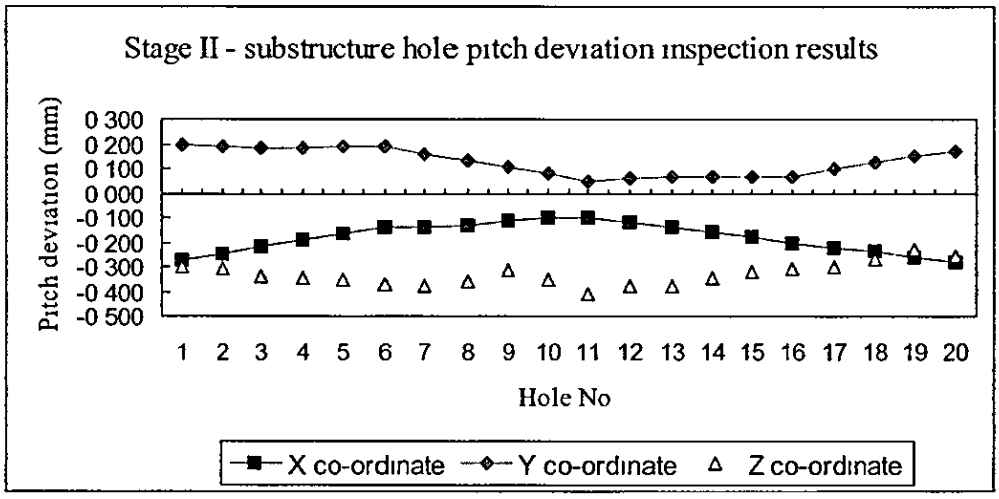


Figure 83 Stage II - substructure hole pitch deviation inspection results

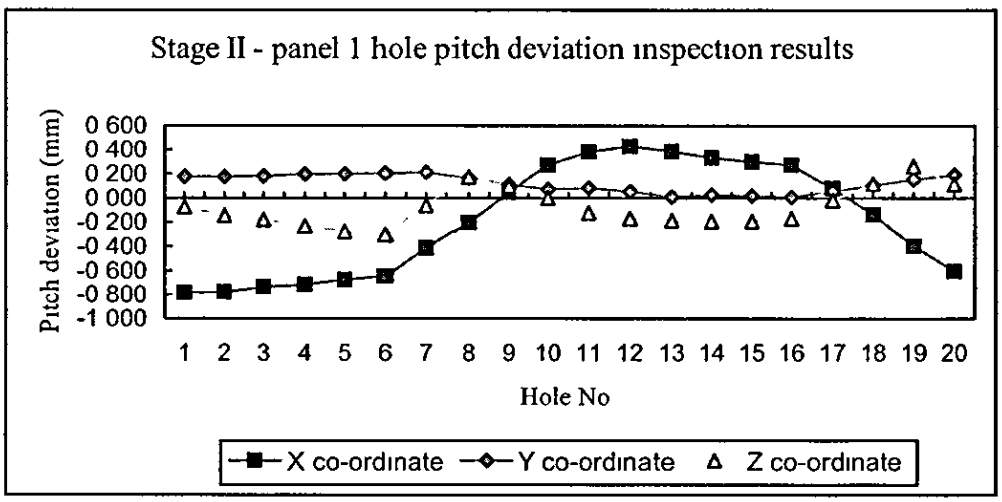


Figure 84 Stage II – panel 1 hole pitch deviation inspection results

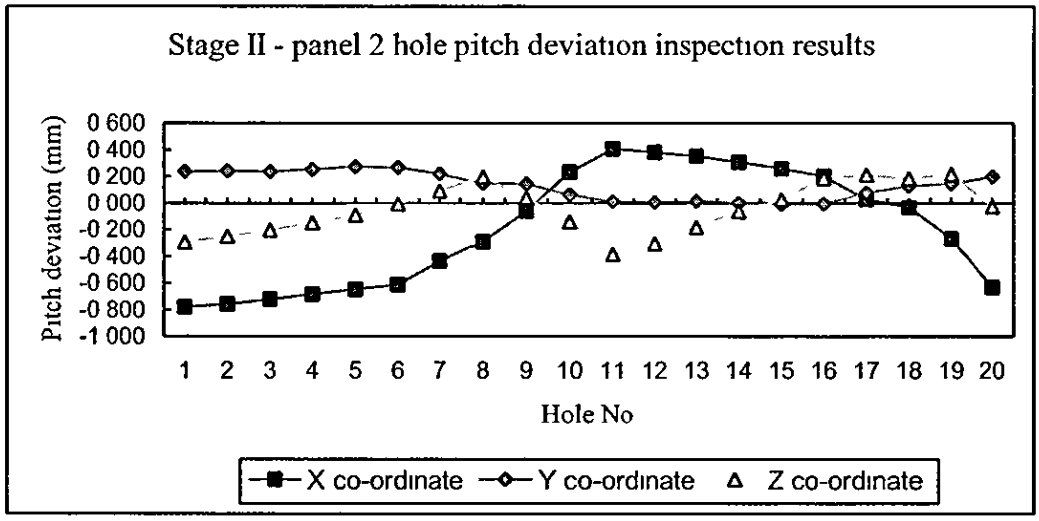


Figure 85. Stage II – panel 2 hole pitch deviation inspection results

Stage I - panel 1, panel 2 and substructure hole diametric inspection results

The following results represent the measured hole diametric error in panel 1, panel 2 and the substructure The results can be seen in the figures 86 and 87 below.

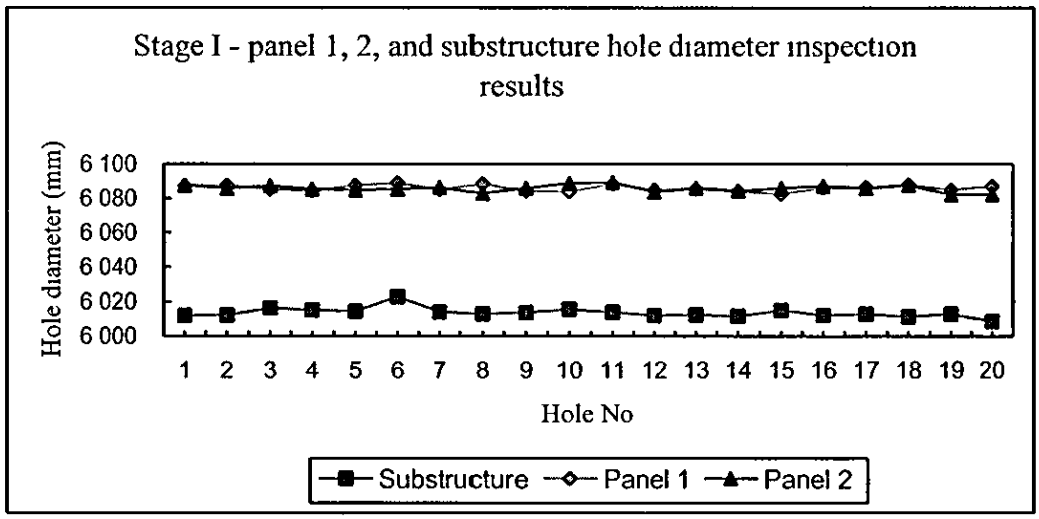


Figure 86 Stage I – panel 1, panel 2, and substructure hole diameter inspection results

The Panel holes were produced by a single cycle drilling operation with a solid carbide two flute twist drill of 6 1mm diameter. A suitable drill diameter was identified to compensate for the characteristics of CFC materials. These characteristics cause a resultant drilled hole diameter to shrink back to below the nominal cutter size This occurs because the fibre bundles become forced apart during the drilling operation which subsequently contract when the drill is withdrawn resulting in a diametric reduction

The substructure holes were drilled using a 6mm diameter twist drill and then finished with a boring bar. It can be seen from the results that the substructure hole diameters are smaller than those of the panels The panel holes demonstrate that they have consistently shrunk back below drill diameter by approximately 14 microns, less than anticipated The hole diameters were expected to shrink back to approximately 6 050mm or less but this did not occur Both panels gave a consistent measurement which suggests that the resulting shrink back from a CFC drilling operation may be predicted accurately.

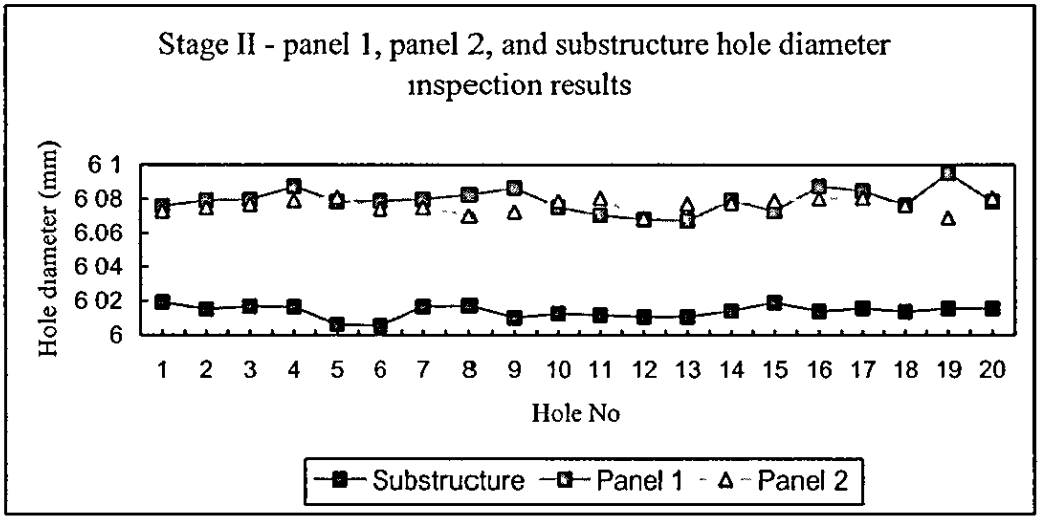


Figure 87 Stage II – panel 1, panel 2, and substructure hole diameter inspection results

8.15 Assembly dowel pin inspection results

The dowel pins used for the assembly of the panels to the substructure were inspected The inspection results can be seen below

Dowel No.	Diameter (mm)	Form (mm)	Pass/fail
1	6 009	0 003	Pass
2	6 007	0 002	Pass
3	6 009	0 003	Pass
4	6 010	0 002	Fail
5	6 009	0 001	Pass

Figure 88 Dowel pin inspection results

Twenty dowel pins (6mm diameter, +0 004/+0 009) were purchase for the assembly of the panels to the substructure A sample of 5 dowel pins (25% sample) was inspected on the CMM It can

be seen from the results that the dowel pin diameters were consistently on the upper limit of their tolerance. One dowel pin was recorded as being 1 micron over tolerance (25% failure rate), but due to the size of error being very small it was included in the assembly

The dowel pins were also inspected for form for information only

Gap condition of panel 1 to substructure

The gap condition inspection results are presented in the figure below

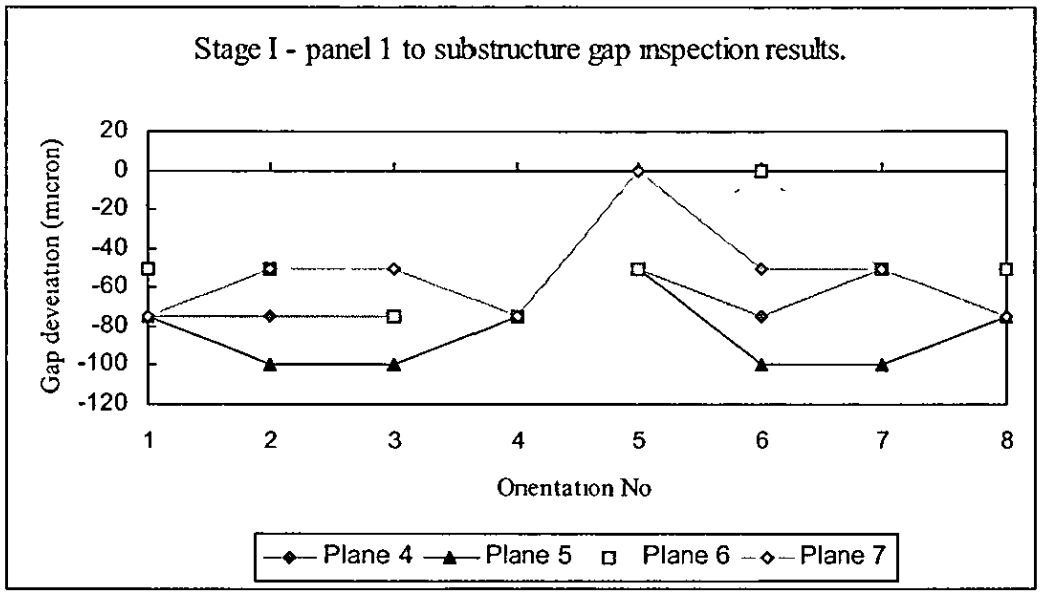


Figure 89 Stage I – panel 1 to substructure gap inspection condition

Step condition of panel 1 to substructure

The step condition inspection results are given in figure 90 The results indicate the poor surface condition following the delaminating problems during routing

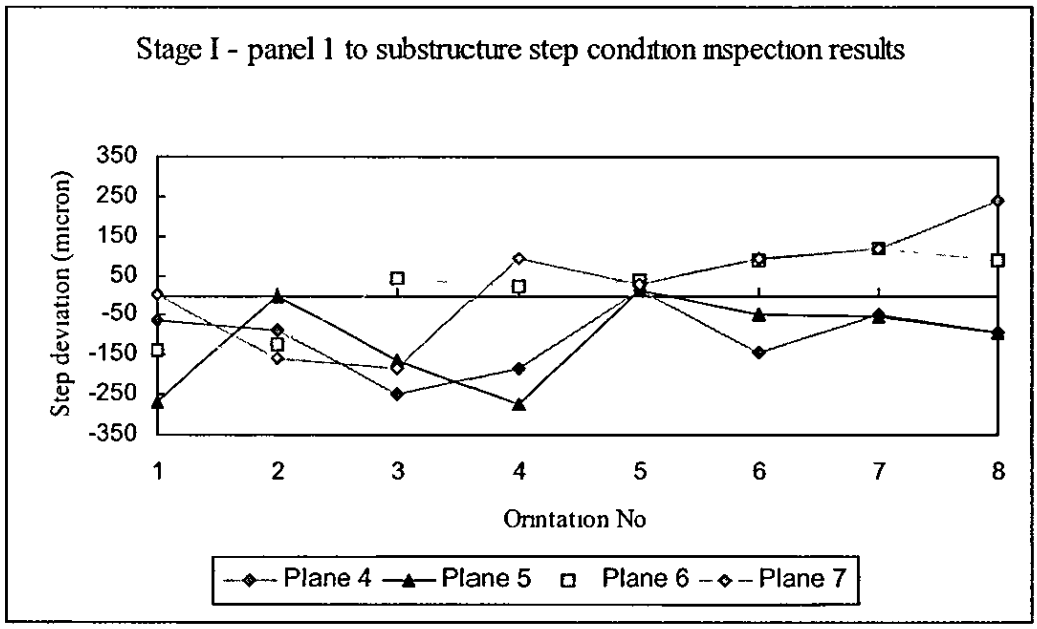


Figure 90. Stage I – panel 1 to substructure step condition inspection results

Gap condition of panel 2 to substructure

The gap condition inspection results are given in the figure below The results indicate the poor edge condition of the panel following the delaminating problems during routing

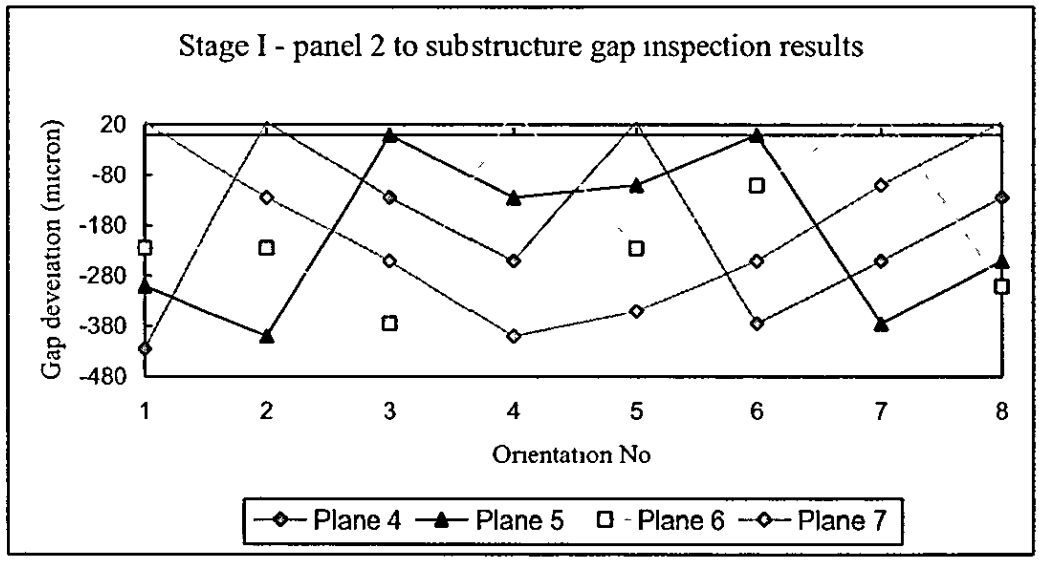


Figure 91 Stage I – panel 2 to substructure gap inspection results

NB. No step condition has been recorded for panel 2 due to delaminating damage during manufacture

8.15.1 Multiple temperature environment inspection results

Step condition of panel 1 to substructure

The step condition inspection results for a range of different temperatures are presented in the figure below.

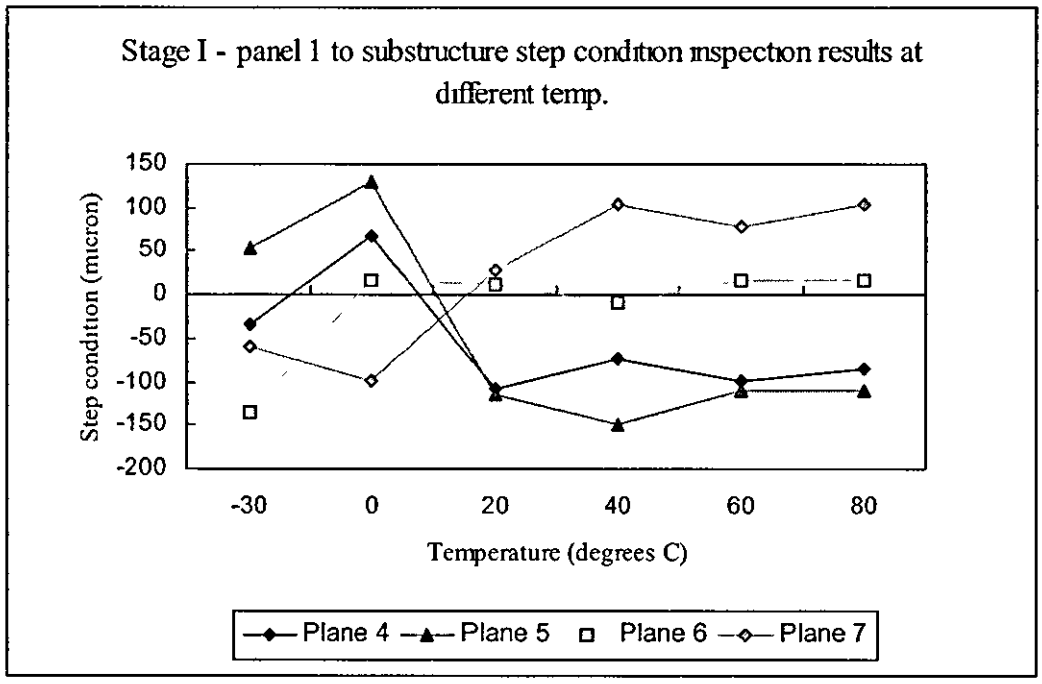


Figure 92 Stage I – panel 1 to substructure step condition results at different temperature

It can be seen from the results that through the range of temperature planes 6 and 7 are behaving as predicted, i e substructure material is expanding at a faster rate than the panel and therefore there is an increase in step size Step conditions at plane 4 and 5 however are behaving as if there is a twist or bow occurring during the changes in temperature

Gap condition of panel 1 to substructure

The gap condition inspection results for a range of different temperatures are presented in figure 93 below

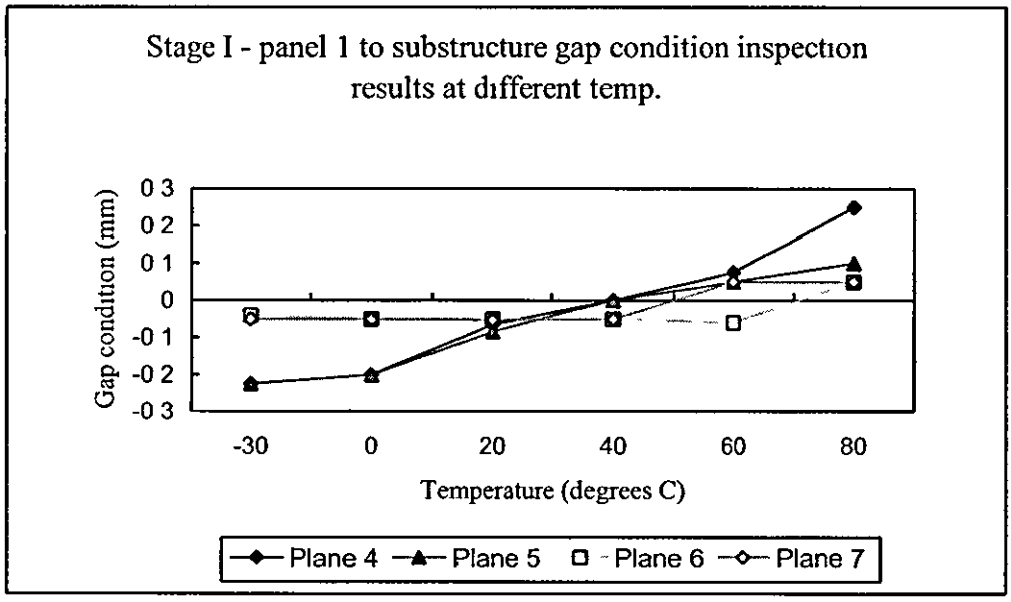


Figure 93 Stage I – panel 1 to substructure gap condition results at different temperature

As can be seen form the graphic results, plane 6 and 7 are relatively stable but as expected the gap condition widens as temperature increases but this is only evident at the higher temperatures This would also suggest that there may be some twisting or bending of the panel edges thought a large temperature range The gap condition of plane 4 and 5 also widens as temperature increases but with a more consistent rate of change

Stage I - panel plane-to-plane perpendicularity

The perpendicularity relation between the different planes is given below. The result suggests that there were no major errors to be noted (see below)

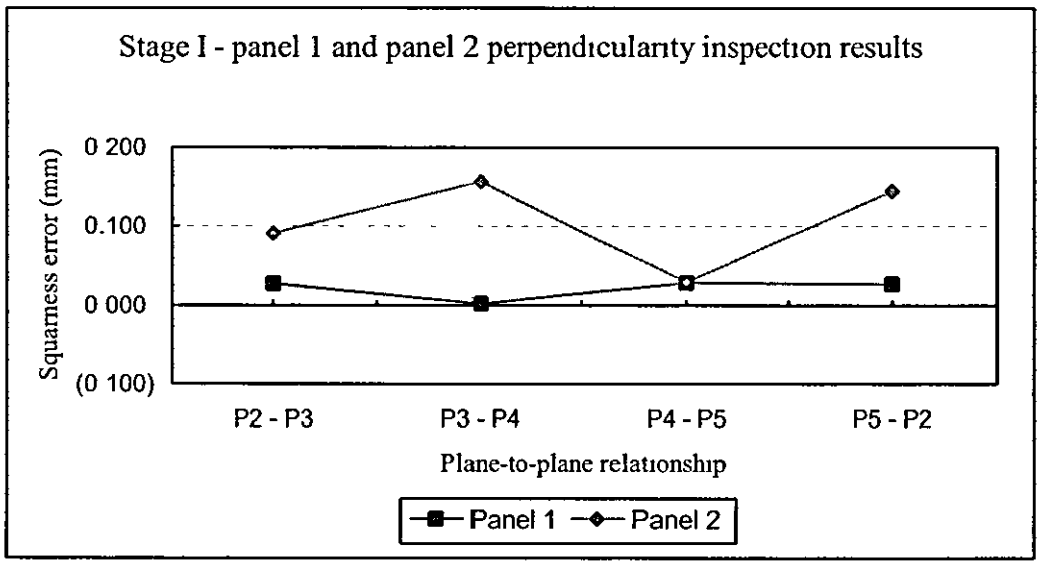


Figure 94 Stage I – panel 1 and panel 2 perpendicularity inspection results

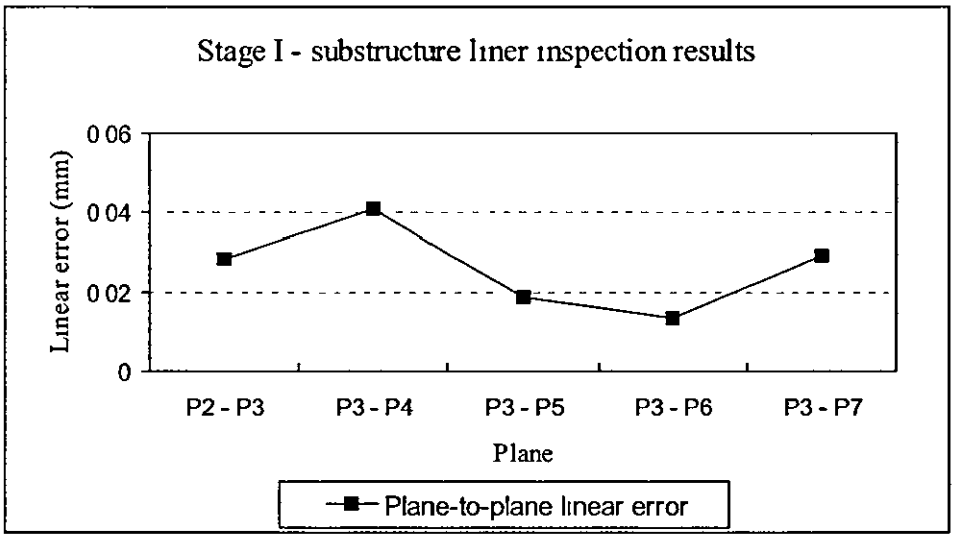


Figure 95 Stage I – substructure linear inspection results

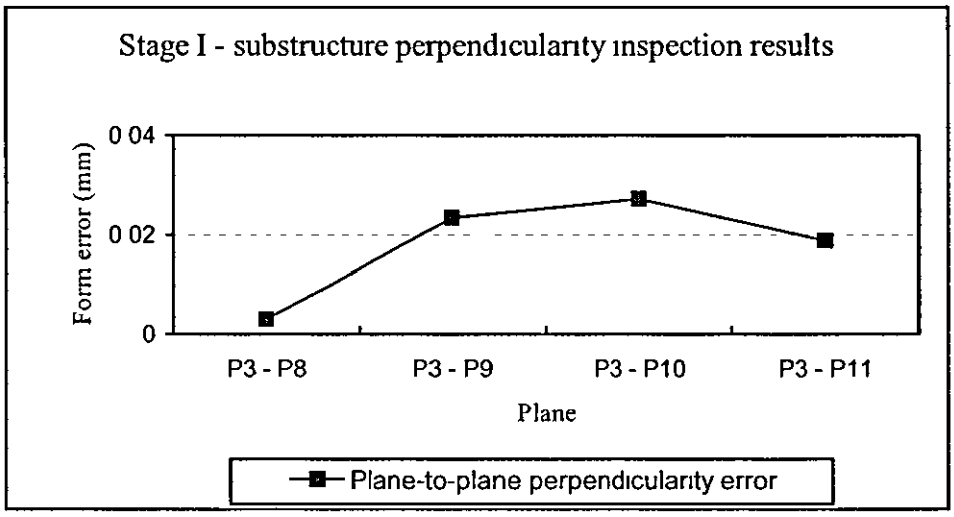


Figure 96 Stage I – substructure perpendicularity inspection results

Stage I - hole diametric error on panel 1 and substructure

The following results show hole diametric error for panel 1 on holes 1, 6, 11 and 16, which represent the condition at each corner of the panel All temperatures are ^{0} C and all measurements are in mm

Temp.	Hole 1	Hole 6	Hole 11	Hole 16
-30	6 095	6 095	6 095	6 095
0	6 095	6 095	6 095	6 095
20	6 095	6 095	6 095	6 095
40	6 095	6 095	6 095	6 095
60	6 095	6 095	6 095	6 095
80	6 095	6 095	6 095	6 095

Figure 97 Stage I - panel 1 hole diameter error at different temperature

It can be seen from the above table that hole diametric condition remained stable at all temperatures Due to the coefficient of expansion of CFC being relatively low (0 004mm/metre/^{0}C) these results were of no surprise

Hole diametric error on substructure

The following results show hole diametric error for panel 1 on holes 1, 6, 11 and 16. . All temperatures are ^{0} C and all measurements are in mm.

Temp.	Hole 1	Hole 6	Hole 11	Hole 16
-30	6 015	6 015	6 015	6 015
0	6 015	6 015	6 015	6 015
20	6 015	6 015	6 015	6 015
40	6 015	6 015	6 015	6 015
60	6 015	6 015	6 015	6 015
80	6 023	6 015	6 023	6 023

Figure 98 Stage I - substructure hole diameter error at different temperature

As can be seen from the table above, the substructure holes demonstrated good stability through a range of temperatures Due to the rate of coefficient of expansion of the aluminium (0 026mm/metre/^{0}C) it was expected that the hole diametric condition would increase Some evidence of the hole diameter increasing was evident at 80^0 C but this was only a small increase right at the end of the upper temperature range.

Assembly performance of panel 1 to substructure

The following results are a measure of panel 1 to substructure assembly performance

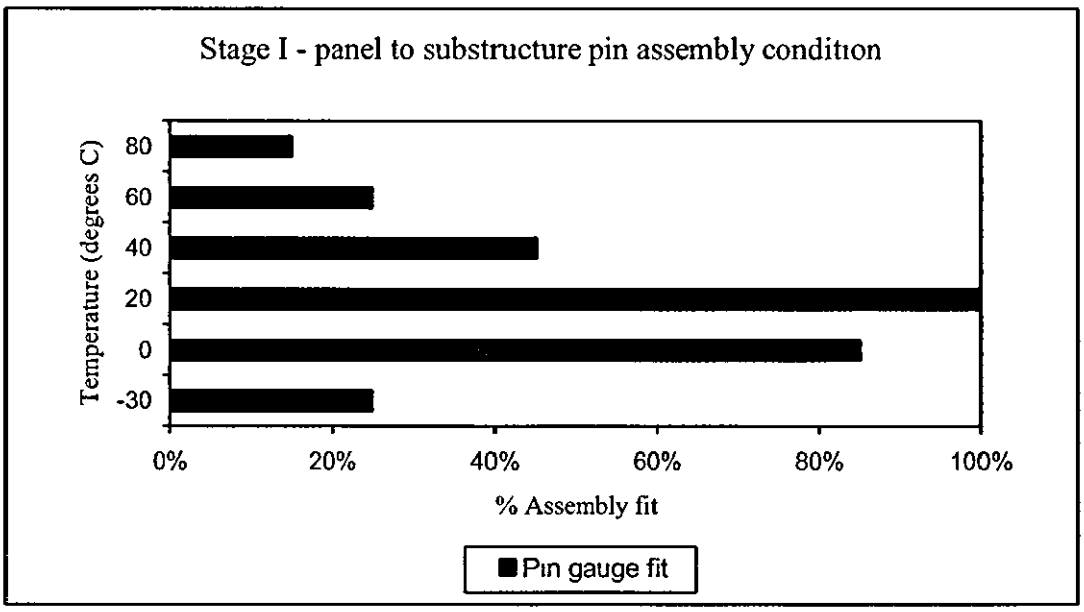


Figure 99 Stage I -- panel to substructure pin assembly condition at different temp

From the results it can be observed that an even distribution of assembly fit has occurred, with perhaps one exception The assembly performance at 0 degrees C is somewhat better than may be anticipated by viewing the other results A possible cause for this may be a non linear reaction to the way the materials expand and contract

8.16 VSA tolerance analysis results

The objective of the analysis was to predict the probable distribution and range of variation for step, gap and virtual hole condition between the stage I substructure and panel assembly.

The VSA software was used to simulate the manufacture and assembly of the substructure and panel assembly and analyse the variation that could occur. The VSA software is capable of

- The three dimensional geometry of the component parts and assembly tooling.
- The sequence in which the parts are assembled and the means used to locate position and secure the mating components
- The three dimensional variation in the geometry of the components or fixtures and the variation in the location of mating components
- The probability of dimensional variation occurring in the component parts and fixtures
- The overall combined effect upon the final assembly due to the variation in each separate component/fixture and the variation that occurs between mating components.

The simulations will provide the statistical data to predict the probable range, distribution and root causes of the variation in the local assembly

8.16.1 Analysis objectives

The objective of the study was to create a dimensional model of the stage I substructure and panel assembly. The model was used to determine the statistical distribution and range of variation in output, measured in terms of the following parameters:

- Variation in step and gap between substructure and panel assembly
- Virtual hole to hole misalignment due to manufacturing variation.
- Compare the above to actual experimental measured data.
- Review results and produce conclusions and discussion.

8.16.2 Modelling assumption

Included within the VSA model are the following basic assumptions:

- All parts will be considered rigid
- All component tolerances will be represented by normal distributions with $\pm 3\sigma$ range centred on design nominal (1 0Cpk capability)
- The components will be modelled at ambient temperature (the model will not consider thermal effects)
- During assembly simulation, part positions will be allowed to float freely within available assembly clearances.

8.16.3 Assembly simulation

The VSA model was used to perform the following assembly simulations

- Nominal simulation to confirm initial geometry
- Monte Carlo Simulation to predict the mean and range for each measurement.
- HLM Simulation to identify and rank the leading contributing tolerances to each measurement

8.16.4 Component datum and tolerance

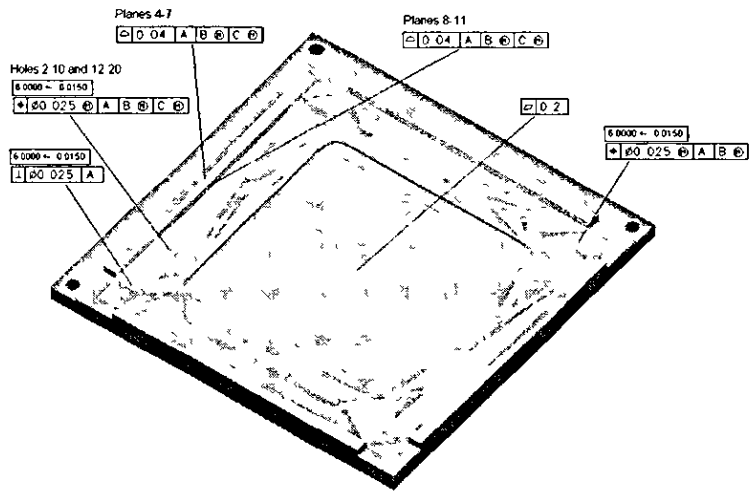


Figure 100 Substructure datum and tolerance

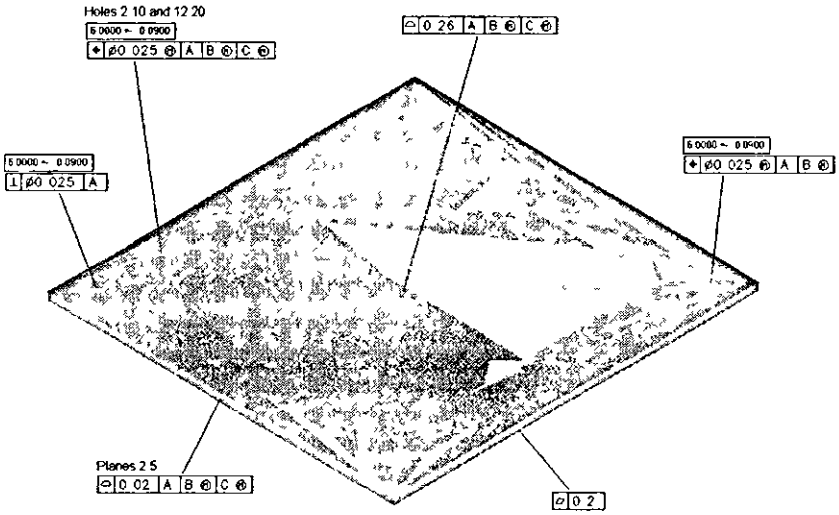


Figure 101 Panel datum and tolerance

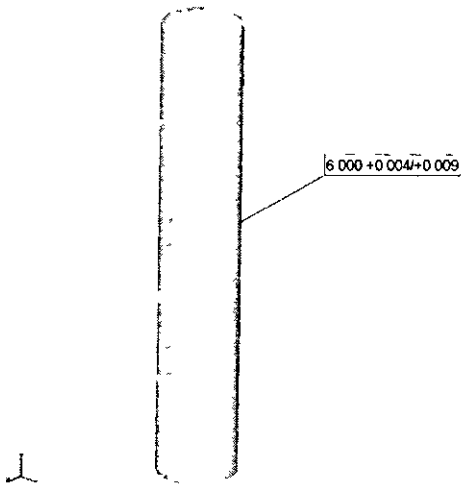


Figure 102 Pin datum and tolerance

8.16.5 Analysis measurements

The following areas were identified for investigation. These included step, gap, and virtual hole condition measurements The limits for each of the measurement types were defined as·

- Steps +/-0.100
- Gaps +/-0 150
- Virtual holes +/-0.100

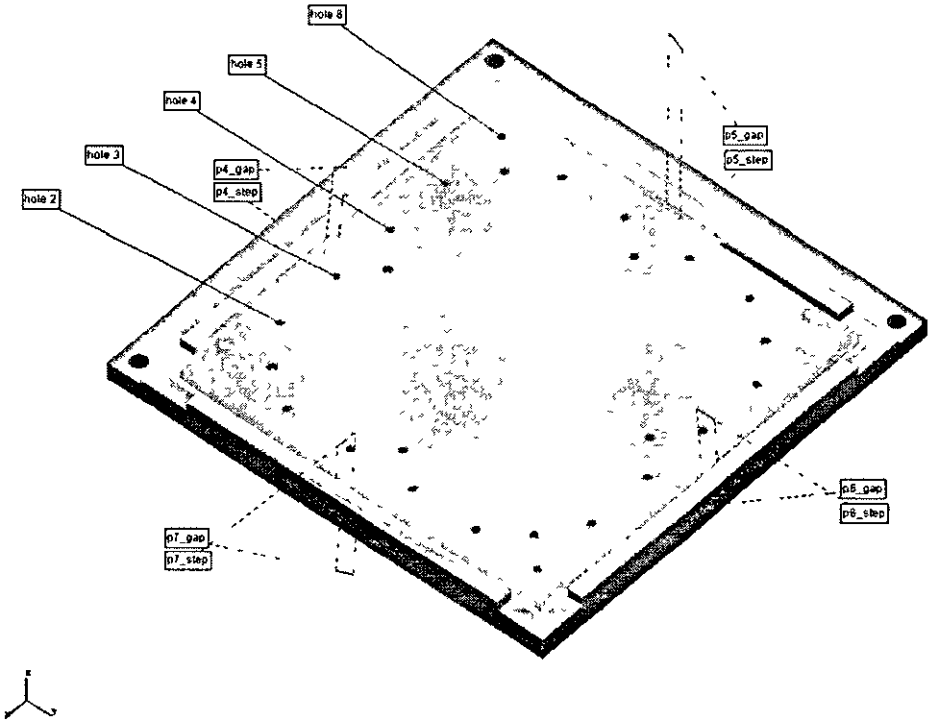


Figure 103 Step, gap, and virtual hole conditions to be measured

8.16.6 Analysis results

A number of output measurements were taken to established variation levels for critical features associated with the stage I assembly interchangeability This was established through a number of measurements for step and gap around about the edges of the assembly. A sample of virtual hole conditions were taken between the two common holes in the panel and substructure A sample of the analysis results are presented below The full set of results from this analysis is available in the appendices of this thesis.

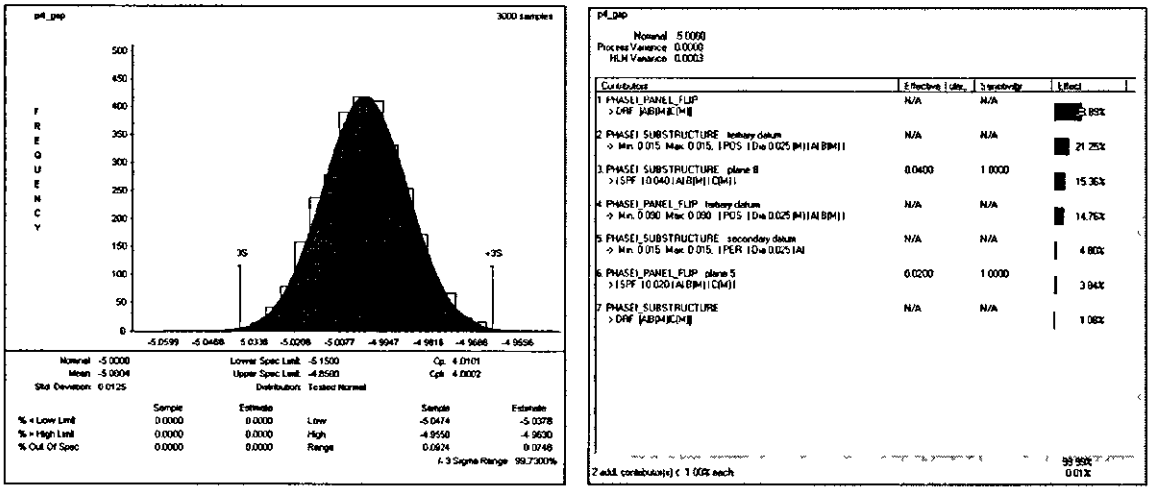


Figure 104. Gap condition at location plane 4 substructure

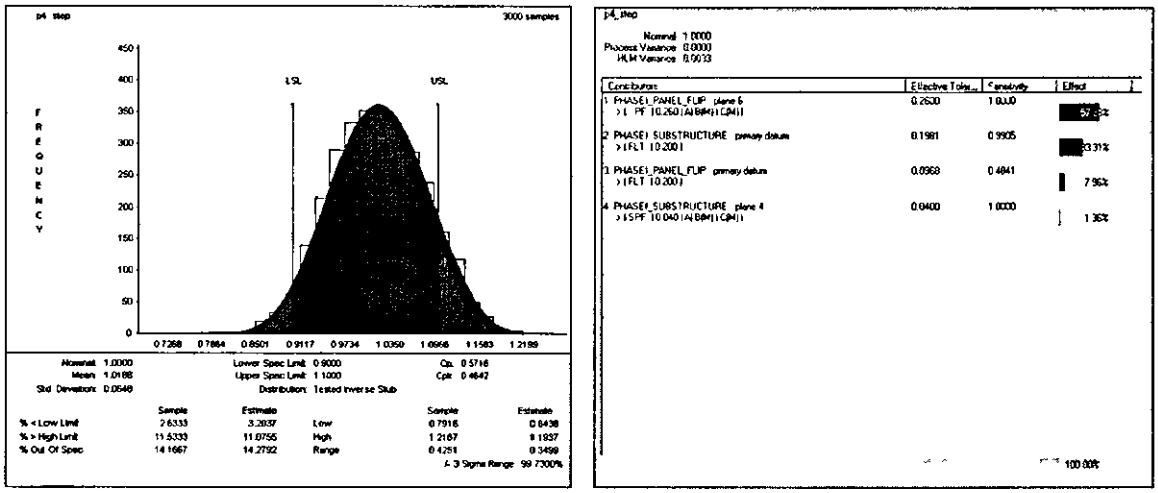


Figure 105 Step condition at location plane 4 substructure

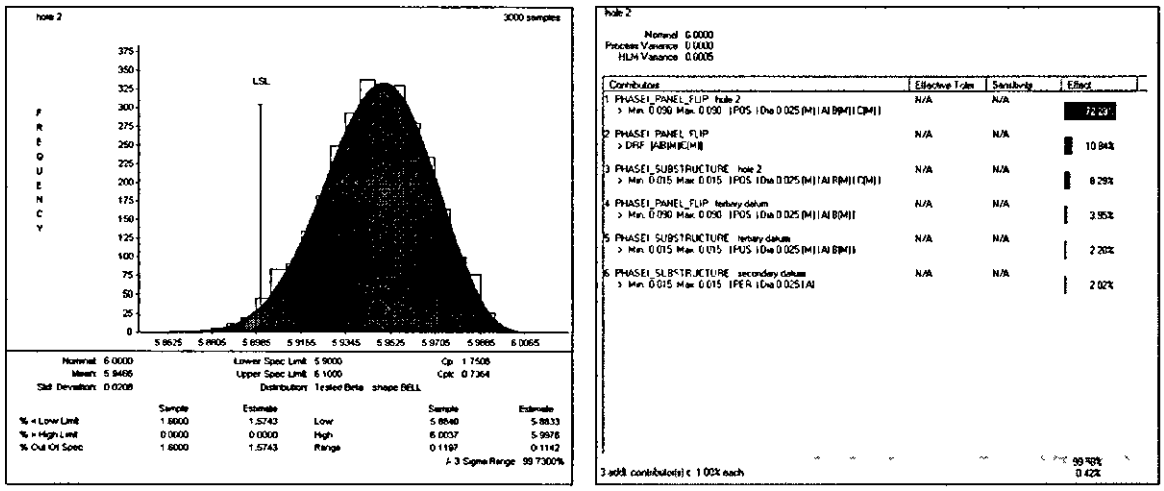


Figure 106 Hole 2 virtual hole condition

8.17 Experiment discussion

Manufacture of panel and substructure

The machining of net routed edge and drilling of holes in each panel produced some problems Panel 2, the first panel, was machined using an inappropriate feed rate of 1 5m/min for the maximum rpm of 8,000 available on the Wadkin machining centre This led to panel 2 sustaining laminate damage about the edges Although it has been concluded that the excessive feed rate was responsible for the edge damage, the CNC program was written such that the router was directed to change direction of the cutting tool whilst within the panel. This may have also

contributed to panel 2s edge damage. The hole drilling operations for panel 2 went without incident apart from the expected burst through lamination damage local to the hole edges

Panel 1, the second panel, was machined using a different technique The panel was sandwiched between two layers of PVC plastic The entire sandwich was then mounted onto the tooling plate in the same manner as for panel 2 but with an additional plate. The five entities were bolted together in order to apply pressure to the CFC panel In addition, when the router made its pass along the edge it cut the sandwich of PVC plastic as well as the panel which probably helped stop the laminate damage that occurred in panel 2 Other aspects of the cutting process also probably helped reduce laminate damage These were the reduction of machining feed rate to 0 4m/min and directing the cutter path clear of the panel after each cut.

After an initial face milling operation, the substructure was machined in one operation This occurred without incident

Panel thinness variation

The planar geometry in stage I panel thickness variation has had little or no effected on hole to hole assembly fit or panel/substructure gap condition However, the step condition has been affected Panel width variation will have a bigger effect on cylindrical or complex panel geometry It will probably cause hole to hole misalignment, out of specification step conditions and may even affect gap condition The result of this will be a no fit condition for the assembly of panel to substructure.

Manufacturing process observations

Assemblies that rely on component part specification and not tooling i e kit build, the process capability relating to the manufacture of each component will have a big effect on the resulting assembly performance. The manufacturing processes associated with carbon fibre composites (CFC) are still in their infancy Anomalies such as hole shrinkage after drilling and net edge dimensions (after a machining operation) appear to be to be left oversize are not well understood although empirical data is available From the experimental results the CFC manufacturing processes effect

- Panel hole diameter and form, hole diameters suffer form shrink back. Hole form can also be effected by burst through causing internal hole profile damage.
- Panel hole to hole position; *pitch* error recorded on the panels were very good Provided the panel is placed in the fixture correctly and machine accuracy is high, hole to hole pitch error is not considered to be a problem

- Panel planar and surface form, *the* panels in Stage I demonstrated three types of form error The first on the panel top side (plane 1) which is accumulated form the mould tool surface The second on the bottom side of the panel (plane 6) which is accumulated from the mould tool surface and resultant lay-up process parameters The third form error, found on the edges of the panel (planes 2, 3, 4 and 5) initially is the result of the cork dam lay-up geometry. But the final form error is attributed to the routing process capability.
- Panel surface waviness of form, this error is generated during the CFC lay-up and curing processes The crossing fibre bundles cause internal stress and strain in local areas of the panel leading to waves appearing in the surface
- Panel edge form, Initially from cork dam profile, but after routing net edge relates to routing/machining capability

Panel waviness detected on both the panels form will have had two fundamental effects. The first is to cause the panel to sit up on its high points (lower peak of wavelength) contributing to greater virtual thickness. The second is to change the virtual orientation of the panel in relation to substructure orientation Waviness error is effectively a subset of form error

A range of form errors were detected during the inspection Form error can be described as the deviation of a geometric surface, planar or other, form a defined datum. Contained within form error will be a waviness error which can be described as a form error that displays amplitude and wavelength From the surface measurements taken at Taylor Hobson it can be seen that waviness error can themselves contain harmonic error. Harmonic error can be described as a cyclic error possessing amplitude and wavelength which is situated about waviness error Finally, harmonic error will contain surface roughness error

Thickness variation on the Stage I planar surface has little effect on the assembly of panels to the substructure. It has not caused misalignment of hole to hole axial pitch or gap conditions error, but has affected the step condition of the assembly

From the experimentation it was identified that features with larger volumes tended to exhibit higher or similar geometric error in comparison to smaller volume features This is despite the fact that the larger volume features were produced by a more accurate manufacturing process

The manufacture of the substructure went without incident and a post machining inspection indicated no unpredictable conditions.

VALISYS inspection results

Panel 2

It can be seen form the results that all four gap edges on the panel failed the inspection. The perpendicularly tolerance of 0 02 to datum A was to tight for the manufacturing process used to router the edges Datum C also failed on position accuracy, but passed on diameter The 18 hole pattern also failed on position accuracy but the report does not specify which hole or holes were responsible All other features measured in the process passed

Investigation of panel waviness and its effect on hole alignment on 2D panel and substructure geometry

Excessive panel waviness on a 2D form will have two fundamental effects The first is to cause the panel to sit up on its high points making its overall virtual thickness greater than that detected through discrete measurement The second is to change the virtual orientation of the panel. These effects upon interchangeability specifications are to be investigated on 2D and 3D complex surface parts.

Explore CFC panel geometry error taxonomy

The variation of form tolerance can be reduced to several sub sets, these being

- Form error
- Waviness error (cyclic)
- Surface roughness (cyclic)

Investigate panel thickness variation and its effects on a 2D panel and structure geometry

Thickness variation on a 2D and 3D complex surface will cause the misalignment of hole to hole axial pitch In extreme, it will affect both step and gap condition with respect to panel to substructure fit.

Explore CFC manufacturing process

Anomalies such as hole shrinkage after drilling and net edge dimensions (after a machining operation) appear to be to be left oversize From the experimental results hole shrink appears to be consistent and therefore predictable. Future work should include the development of a process model derived from empirical test data on aspects such as:

- Hole diameter - drilling shrink back.
- Panel edge profile - feeds and speeds for routing.
- Panel lay-up - lay-up tool accuracy (tolerance chains)

- Panel cure - cure tool distortion

Investigate feature volume to conformance relationship

From the experimentation it was identified that features with larger volumes tended to exhibit higher or similar geometric error in comparison to smaller volume features This is despite the fact that the larger volume features were produced by a more accurate manufacturing process

Discussion drawn from the VSA simulation results

The analysis predicted the attributes of step, flush, and virtual hole conditions based on panel and sub structure tolerance allocation and defined assembly process The modelling process was essentially the same as for the GVA studies described in chapter 7 The results predicted that in the main the panel to substructure assembly philosophy would be capable of achieving the gap specification and virtual hole condition However, the model predicted that up to 15% of the step condition would fall out of the specified limits

8.18 Concluding remarks

A number of practical experiments designed to explore the design, manufacture, assembly, and inspection of composite panels to a metallic lightweight fuselage have been presented in this chapter.

There are a number of over all conclusions that can be drawn from this chapter, these are

- The effect of different operating temperatures on components made from materials with different thermal properties, for example, aluminium and carbon fibre composite is significant. This was particularly noticeable in the experimentation following the assembly of a CFC panel to aluminium substructure when the environment temperature approached the equivalent of aircraft extreme operation limits,
- The manufacture of materials such as CFC is complex and time consuming and demands an advanced manufacturing process. In producing the CFC panels some damage was sustained form the net routing and the hole machining operations. The net routing damage was caused by incorrect CNC machine tool spindle speed in conjunction to travel movement. This was unavoidable due to the available CNC machine tools not having the required capacity to accommodate CFC machining operations Damage sustained on the hole as 'burst through' was caused by not using special drilling tools appropriate for CFC due to unavailability No problems were encountered with the manufacture of the metallic mould tooling plate or aluminium substructure components.

- Increasing geometric shape complexity from planar to cylindrical form affects their related overall assembly characteristics. The measurement results of the planar and cylindrical panel and substructure assemblies after comparison indicate that a higher magnitude of deviation is present in the cylindrical geometry. Measurements such as hole position, panel thickness were of a were higher resulting in greater assembly no conformance
- The GVA tool was used to model the planar components and predict their assembly performance The key features identified for analysis were the step and gap conditions between the panel and the substructure interface
    - Gap condition; the variation range for the gap condition between the panel and corresponding substructure edge feature prediction by the GVA tool correlated well with the actual measured condition The measurements also detected some panel distortion probably caused by waviness. The measured gap variation can be attributed to the machined panel having a course surface finish caused by machining process restrictions Furthermore, the CFC panel consistently machined undersize (CFC characteristic) which accounts for a small mean shift in the measured data when compared to the GVA estimated data
    - Step condition, the variation levels for the step condition between the panel top surface and corresponding substructure feature as predicted by the GVA tool was higher by a magnitude of 2 compared to the actual measured data This can be accounted for by the tolerance specification given to the GVA analysis as being high by about 50%
    - Virtual hole condition, the variation levels for virtual hole condition predicted from the GVA tool indicated that available hole size for the pin would be reduced by approximately 0 1mm per hole from the nominal 6.00mm. Given the precise tolerance on the dowel pin, which measured at 6 009mm with virtually no range, the GVA analysis tool essentially concluded that there would be an interference fit on a large number of holes. This, however, was not seen during the assembly of the experimental parts The reason for this is because the CFC holes were drilled using a 6 1mm drill to allow for CFC shrink back (CFC characteristic) The holes drilled resulted on average to be 6 08mm resulting in a predictable 0 02mm shrink back. The resultant larger hole diameter allowed for more float allowing the fit up of all 20 pins between the panel and substructure Initial drilling of the CFC panel with a 6 00mm drill resulted in a hole of 5 08mm diameter causing an interference fit up between panel and substructure.

Chapter 9

9 Discussion

Objective: This chapter identifies the main issues for discussion and sets the foundation for the concluding remarks presented in the next chapter. The discussion is based around the aims of this research project which includes the DM discipline, its principles, the assembly experimentation, and the proposed DM methodology

9.1 Review of dimensional management

The domain of DM has been reviewed in chapters 2 and 3 from two perspectives, these being a literature review of all public domain material and a comprehensive industrial review generated from a study tour of leading automotive and aerospace companies and the author's commercial knowledge

The DM discipline has developed out of the automotive industry which has been striving to improve product quality while addressing key generic business goals such as vehicle and process unit cost reduction, development cost reduction, and shorter time to launch schedules. It was first to recognise the potential commercial advantages resulting from DM practise There is evidence of the DM activity in automotive since the mid 70's in the USA Many of the influential manufacturing methodologies currently used in the aerospace sector have in the first instance been developed and matured in the automotive industry As with other initiatives, the aerospace industry has the opportunity to draw upon the experience of the automotive sector with respect to DM techniques and practices. The aerospace sector could benefit from a potential technology transfer from automotive with respect to DM practice

The literature and industrial review highlight that aerospace manufacturing companies currently face the biggest commercial and technical challenges to date. More recently the aerospace sector has revised the approach to development and production in response to aggressive customer driven changes such as purchase cost reduction, cost of ownership reduction, improved operation performance for both dynamic and maintenance characteristics. The aerospace industry traditionally has been associated 'craft' based product development producing one-off products each being unique to the next. This has influenced the type of manufacturing methodology used

traditionally in the industry The introduction of new manufacturing methodologies such as CE, SE, and lean production into the aerospace sector has generated considerable focus on development lead-time reduction, production efficiency, waste reduction, and higher quality. In direct support of these initiatives, DM techniques have been introduced into the development and production methodology to better define and control key areas of engineering to accommodate larger production runs where issues such as modularity, interchangeability, and more efficient assembly procedures exist

The aerospace industry is beginning to recognise the potential benefits of applying DM techniques to validate aircraft design for manufacturing and assembly variation robustness DM techniques in the aerospace sector were initially used for aircraft structure (fuselage, wings, surface controls, etc) validation. These techniques are now extending, for example, to propulsion units (jet and piston hydride engines), drive units, and engine nacelle assembly, and undercarriage assembly. The area of DM analysis is still expanding through research and commercial partnerships. Further areas include inclusion of FEA analysis to model effects of process distortion, inclusion of real SPC data on tolerance analysis models, creation of full closed loop analysis

In support of the industrial review a study tour of selected aerospace and automotive companies within the USA was planned and undertaken. Each of the companies visited were believed to be practitioners of DM Other companies believed to be practitioners of DM within Europe were also visited In general, the major automotive companies visited in the USA had been using DM techniques and supporting software tools for the longest period of time compared to the USA aerospace sector Furthermore, the automotive sector has been practising DM for longer periods than their European counterparts For each of the automotive and aerospace companies visited a set of DM case examples were identified. The range of case examples for the automotive sector suggested that the majority of DM activity has been targeted at BIW quality validation. With respect to the aerospace sector the case examples indicated the majority of DM activity was on airframe structures

The key areas identified in the literature and industrial review have been presented. The discussion now addressed the need for DM in support of aircraft development and production

9.2 The need and nature of dimensional management

The finding of the review forms the basis for the need outlined in chapter 4 for improved DM activity with airframe development and production.

The next generation of both military and commercial aircraft will be designed using novel concepts, new materials, and revised manufacturing and assembly strategies. It is only through these significant step changes in technology can today's challenging cost and weight targets of the aircraft customers (both military and commercial) be fully met To be successful, aerospace manufacturing organisations need to fully understand the available technology and it's supporting tools and techniques by managing the whole production design to assembly cycle as a single integrated process To achieve this it is imperative that the design specification takes full account of the down stream effects of hardware variability on the manufacturing, assembly, and inspection activities and their effect on achieving aircraft customer and domestic specification Conversely, the manufacturing and assembly business centres must capture all available process knowledge and make this available back upstream to design.

Aircraft manufacturing organisations currently fail to take the full advantage of tools, techniques and methodologies for the management of product and process geometric variation Aerospace manufacturing organisations have the opportunity to increase engineering efficiency in future commercial projects through the adoption of a number of mature best practice techniques such as CE, SE, and lean production The DM discipline embedded into an IPD process would extend and compliment the capability of these initiatives.

The requirements outlined above could be met through the design and development of a specific DM methodology Such a methodology is has been proposed and is discussed in the following section.

9.3 PARES; proposed methodology

The proposed PARES methodology is presented in chapter 5 and has been proposed to address the needs identified in chapter 4, section 4 3 The main aim of PARES is promote an integrated process for the identification, analysis and management of complex product variation throughout all the phases of aircraft structure development and production

The PARES methodology structure has been developed against a generic IPD process for aircraft production providing a timeline reference to specific activities and their synchronisation to the IPD process backbone It includes a number of concurrent activities designed to integrate the overall DM process required for product hardware variability control. The PARES process involves a number of activities that need to be synchronised with an IPD backbone.

Aerospace companies in the USA and Europe have invested significantly in new and advanced software tools such as CAD, CAM, and CAE, to gain competitive advantage Leading engineering software development companies such as Dassault Systemes and UGS are currently responding to this demand by developing ever more integrated products under the banner of product lifecycle management (PLM) These PLM software solutions attempt to address the needs of DM requirements through the development of specific software modules to support activities such as tolerance designation, tolerance analysis and synthesis, quality (measurement) data analysis, key feature identification These modules however are deployed by manufacturing companies in an ad hock manner with little consideration to an end-to-end DM strategy.

The PARES methodology could become the driver for a more structured approach to the deployment of DM associated software tools and techniques. A software centric architecture has been developed to support this approach and is made up of six main chunks, each of which would be supported by a specific software module The activities flow for DM has been developed to position how the PARES methodology could be supported by current modules of commercial software tools This is presented in chapter 5

PARES is a proposed methodology and therefore has not been fully evaluated. The development of the PVA tool and the GVA case studies have, in part, evaluated some of the key activities To fully evaluate PARES the remaining activities would have to be deployed and evaluated within a suitable aerospace organisation. Deploying PARES will require a well defined implementation plan designed to challenging the established process The deployment will need to consider the following actions

- Establish a deployment team made up from appropriate members of the organisation with the required skills and internal position This should include an executive sponsor, a project manager, and the individual team members.
- Create a direct link of accountability to the organisation's management
- Create extensive project plans with actions and timelines
- Create a set of PARES related process performance metrics that the can be used to measure where the organisation was at the beginning, and it progress path during and after the implementation

The proposed PARES methodology identifies the need for more up front assembly analysis In order to address this requirement a PVA tool was developed.

9.4 Development of a PVA assembly analysis tool

The need for a PVA tool to support aircraft wing box structure concept design prior to detail 3D geometry being available was identified by the industrial review There is an opportunity to investigate assembly process prior to significant levels of CAD geometry being available After this stage, design concepts are considered mature and the design organisation would be reluctant to make significant feature and geometry change based on any analysis undertaken at this stage. The PVA tool can be used to review product architecture (parameter based) for baseline functional assembly concepts in 1D and 1 5D to validate early target attributes

The PVA tool was designed and developed based on an Excel spreadsheet application but also incorporating the statistical analysis tool Crystal Ball Pro from Decisioneering. The initial development consisted of identifying the type of generic wing box components to be included and defining their assembly sequence and process

Within the analysis model all significant 1D tolerance chains were identified based on component features and assembly process Analysis tables were then developed within the excel spreadsheet to represent these features and tolerance chains The analysis tables were defined to input information required to perform the analysis including parameter feature nominal distances, applied tolerances, and distribution type.

To perform statistical analysis, the crystal ball pro software was added to the application This allowed the statistical simulation of parameters defined in the analysis driver tables including Monte Carlo and Latin Hyper Cube. Furthermore, root cause analysis could be performed through rank correlation based on the individual parameter chains The PVA tool is capable of producing WC, RSS, and statistical predictions of measurements These statistical predictions can be output into a formatted report for printing. Analysis sessions can be saved and recalled

PVA works well as a 1D front loaded analysis tool It is capable of giving a strong indication of how capable an assembly press will be in terms of delivering target attributes, and where these are not achievable, what elements are the main contributors to variation The main limitation of the PVA tool is its inability to take into account the effect of full 3D and geometric variation.

The opportunities to develop the functionality within this type of simple parametric tool are considerable Some of these include temperate compensation, development of 1 5D and 2D study parameters, radial parameter analysis, limits and fits specification Other areas are identified in the further work section of chapter 10

When early PVA analysis has been completed it paves the way for more detailed GVA analysis based on available 3D CAD geometry.

9.5 Case study for GVA assembly analysis tool

Three case studies were identified in conjunction with Airbus to investigate the use of a commercial GVA tool called VSA. The case analysis was based on a set of wing box configurations being used in support of the A3XX aircraft development program The main aims were identified and agreed between the author and key Airbus personnel. These were to predict the capability of a specified assembly operation involving a joining process for mechanical fastener, paste bonding, and film bonding techniques Principle area for consideration was the rib to skin, and C spar to skin interface

In conjunction with the case studies, an analysis process was developed to drive the GVA software tool The process was made up of eleven steps and these have been defined in chapter 7. This type of analysis normally requires a significant level of 3D CAD geometry to be available However, some CAD geometry was not available from Airbus. This resulted in the author having to design many supporting parts and fixture elements using the Dassault Systemes CATIA V4 CAD software The tolerance analysis was performed using the CAT3D-VSA software. Some modelling problems were encountered and all bugs and functional issues were documented by the user This list was sent to the VSA developers in the USA for review

The analysis produced a large amount of predicted measurement data based This data has been sorted and collated into a number of analysis project files From the results a number of conclusions were draw The conclusions and analysis were data presented to back to Airbus for their evaluation. The conclusions drawn were very specific and indicated predictions of assembly capability based on the different part zones and their assembly using mechanical fastener, paste bonding, and film bonding process techniques The actual model data and VSA results are treated as confidential by the author and cannot be released without permission from Airbus.

The GVA studies provided comprehensive analysis data on the different case assemblies based on mechanical fastener, paste and film bonding feature interfaces These were based on design tolerance and variation metrics Further analysis can been undertaken by replacing the design tolerance values with actual measurement data and rerunning the analysis model In addition, the

use of FEA integration analysis to model component or tooling deflection may be undertaken to support existing data models in VSA.

The GVA case analysis investigated a metallic assembly process to evaluate its potential for use in CFC assembly. Issues relating to the manufacture and assembly of aluminium and CFC structures were investigated as part of an experiment These are discussed in the following section.

9.6 CFC panel to Aluminium substructure experiment

Advanced airframe design incorporates a mixture of materials including CFC and aluminium. The aim of this experiment was to investigate the potential issues arising form the design, manufacture, and assembly of CFC panels to aluminium substructures and their effect on product key attributes such as step and gap This was conducted through an experiment based on planar and cylindrical geometry configurations

At the design stage all panel and substructure geometry were generated within the Unigraphics CAD system using solid geometry function From the panel solid models the accompanying moulding tool plates were designed again in solid geometry These solid models then formed the basis to produce the off-line CNC machining programs, the off-line CMM measurement programs, and were at all times used as the product master for all geometric and dimensional reference.

The off-line CNC program was generated by the Unigraphics CAM module based on the solid geometry All cutter paths and tool selection were generated and then validated in the Vericut simulation software This software validates the process for tool / fixture / part clash detection, path pattern verification, and resultant part net shape integrity. The same process was used to generate the post process programs for the CFC moulding tools, the aluminium sub structures, and the net machining of the CFC panels.

The machining routing for net CFC panel edge and hole drilling produced a number of manufacturing problems The first problem resulted in all panels sustaining laminate damage about the edges during the CNC machining operation The second problem resulted in hole damage resulting from a condition called 'burst through' which caused lamination damage local to the hole edges. Both these conditions were expected as they are well documented as manufacturing issues for CFC materials The manufacture of the sub structure and CFC tooling occurred with no real problems

Following the manufacture of the individual components, they were inspected for accuracy. The inspections of the CFC moulding tools indicated that the form existed on both tools This was particularly evident on the cylindrical (phase II) mould tool and which displayed characteristic of good form error but having a poor size dimension.

The panel and substructure for stage I and stage II were investigated for dimensional accuracy using a CMM and advanced inspection software A number of tests were also performed to evaluate the assembly capability of panel and substructure at nominal temperate Further analysis was undertaken to review assembly capability at different temperatures based on ranges typically demanded by military and commercial aircraft.

The VSA variation analysis tool was used to model the panel to substructure assembly process. The analysis aim was to predict the attributes of step, flush, and virtual hole conditions based on panel and sub structure tolerance allocation and defined assembly process The effects of manufacturing and environmental (temperature) variation on functional assembly capability, for example, interchangeability of panel to substructure, were investigated Due to the different thermal properties of aluminium and CFC, during extreme temperatures, conditions of non assembly were detected

The main discussion for the principle areas of this research have been presented above These areas now form the basis of the conclusions presented in the next chapter.

Chapter 10

10 Conclusions and further work

Objective: This chapter presents a list of conclusions drawn from the material presented in this thesis and identifies the opportunities for further work.

10.1 Conclusions

With reference to the aims and objectives outlined in chapter 1, an overview of the conclusions are:

Need and nature: The literature and industrial review provides the background and the positioning of the subject area A tour of leading aerospace and automotive companies in the USA and Europe has characterised the need for the DM discipline as part of an integrated product development process One clear message is that DM needs to permeate through the whole development process including aspects of design, development, manufacture, and assembly of aircraft structures, covering both military and commercial sectors.

Methodology: An outline DM methodology has been presented to address the need for a wider scope of activity in support of robust engineering at all stages of product development The methodology outlines the core activity at each stage of product lifecycle, including the need for front load effort early in the process, and its impact on the extended manufacturing enterprise

Variation analysis tool: The need for a baseline variation analysis tool to be used at the early design stage has been identified The design and development of such a tool has been undertaken and its scope, benefits, and limitations have been highlighted. The baseline tool was validated, and used in support of a project at Airbus to investigate the capability and suitability of a metallic wing assembly tooling specification for use with carbon fibre wing assembly.

Experimentation: This research work has identified a number of potential designs for manufacture and assembly opportunities in both the commercial and military sectors for future programs of aircraft manufacture These opportunities rely primarily on evaluating the assembly

fit and function capability of carbon fibre composite (CFC) primary structures to lightweight aluminium (Al) sub structures taking into account product specification on interchangeability.

The conclusions outlined above are expanded in the following sections

10.1.1 The need and nature of dimensional management

The discipline of DM was reviewed to determine the best approach in which to address the DM of aircraft structures termed here as 'need and nature'. The review included undertaking a literature search, the planning and undertaking of industrial review of key companies, and identifying key commercial information known to the author. The main findings of the review are summarised as.

- The literature and industrial review revealed a number of pressures currently faced by the aerospace industry underpinning the requirement for better product variation management These pressures can be broadly grouped as
    - Lower cost of aircraft ownership, requires improved flight efficiency which is dependent on structure alignment, stringent step and flush specification to avoid turbulence
    - Higher maintainability and operational flexibility, requires customer level ICY.
    - Safety, requires new material test for structural integrity
- A number of engineering techniques and practices have been identified by the author as a means of addressing the requirements outlined above, these are
    - Develop new, or revise existing, manufacturing and assembly business process
    - Adequately and effectively characterise manufacturing and assembly processes
    - Reduce manufacturing and assembly jig/fixture 'hard' tooling requirements
    - Elimination, as far as possible, of physical MTG and master media.
    - Develop digital inspection techniques
    - Introduce geometric dimensioning and tolerancing concepts and standards
    - Early and efficient use of variation analysis CAD/CAE simulation tools.
- The DM process originated in the automotive sector and its use continues to grow to present day DM techniques are gaining wider acceptance across a number of industrial sectors and is now emerging in the aerospace product development processes
- The industrial review identified the need for early assembly tolerance analysis to be performed prior to CAD availability. This parametric analysis would be one or two dimensional and would identify key areas for down stream three dimensional geometric analyses. Current tolerance analysis work in both the automotive and aerospace sectors is

undertaken too late in the development cycle resulting in little or no opportunity to make design change.

- The industrial review revealed that aerospace manufacturing companies are developing advanced materials for the manufacturing and assembly of aircraft structures. These new materials and processes require investigation to fully understand their dimensional capability.
- The case and industrial review also highlighted the need for a DM methodology to be developed in order to support the IPD process within aerospace. The main attributes of such a methodology can be broadly described as.
    - Supports a total view for product development and production and underpins the design to manufacture as a single process
    - Aid alignment of critical product and process activities which are traditionally conducted independently.
    - Introduce real world product and process variation to be analysed as part of the digital mock-up activity
    - Drive the definition and selection of particular analysis software tools and techniques used to model variation
    - Ensure that, organisation, product and process capability knowledge may be captured and reused directly to set appropriate product quality standards.

10.1.2 Proposed dimensional management methodology; PARES

The PARES methodology was designed and developed to support this research work and in response to the needs outlined in chapter 4 It is made up from a number of concurrent process tasks which span a major segment of an aircraft product development lifecycle The main conclusions for this section are

- A proposed methodology for DM of aircraft structure development has been presented in support of this research work. The methodology is called physical architecture robustness system (PARES).
- The PARES methodology key activities have been mapped onto a generic aerospace IPD process and presented in chapter 5 The key phases of the PARES methodology are.
    - Innovation
    - Selection
    - Specification
    - Validation
    - Production.

- The PARES methodology is centred round the need for better integration of DM activities within the full scope of the aerospace structure development process
- Some of the key areas addressed by PARES were.
    - Evaluation of key characteristics against planned design, manufacture, assembly, and inspection process
    - Maximise the use of DMU analysis techniques for product variation management.
    - Capture product and process capability knowledge for use in future product development
    - Develop a methodology for IPD process synchronisation to span the whole product lifecycle.
- Where organisation, product and process capability knowledge data is not available the methodology promotes its introduction providing a closed loop quality function.
- The top level architectural chunks of PARES have been outlined in chapter 5. These chunks (listed below) can be supported by a number of different software tools and respective techniques These are
    - CAD and BoM
    - SPC quality data
    - Tolerance analysis and synthesis
    - Root cause analysis
    - Quality data viewing
    - Data collaboration
- The effective design, development, and deployment of any DM methodology cannot be undertaken without first understanding the existing business process specifically including software tools and techniques already committed by an organisation and PARES provides the framework that takes this into account.

10.1.3 PVA tool development for early wing box analysis

The need for a PVA tool to support concept design prior to detail 3D geometry being available was identified by the industrial review. Part of the need stems from the desire to conduct front loaded assembly analysis before a significant level of CAD geometry is available. By the time this level of detail is available many of the main design concepts are considered mature and design organisation would be reluctant to make significant geometry change based on any analysis undertaken.

- The PVA tool functional specification was designed jointly between key personnel at Airbus and the author. The development of the PVA tool was undertaken by the author.

- The PVA tool is a 1D analysis tool developed in MS Excel using the Decisioneering Crystal Ball module for statistical simulation and root cause analysis.
- The PVA tool was designed and developed to analyse the major assembly elements of a generic wing box structure at the early (parametric) design stage The analysis tool essentially has a number of pre-configured sub assembly study options which may be built up level by level The study output provides a measurement of variation and its contributors at identified key features for the related assembly. Some of the main wing box parameters were:
    - D nose and front spar assembly
    - A frame to aft spar assembly
    - Rib to front spar and D nose assembly
    - Rib to aft spar and A frame assembly
    - Front and aft top and bottom skin assembly
    - Splice plate assembly
- The baseline findings from any PVA study may be fed into the down stream GVA activity
- The development of the PVA tool presented in chapter 6 identifies some of the advantages as being
    - Relatively quick and simple tool to use once set up
    - Does not require detailed 3D CAD geometry to be available.
    - May be used at early design stage if generic assembly data is available.
    - No complex software required Only requires a common desk top application such as MS Excel to operate.
    - The Decisioneering Crystal Ball Professional software module may be integrated if statistical and root cause analysis is to be performed.
    - Can incorporate actual manufacturing measurement data or available industrial process capability into the model
- The three GVA wing box case studies each provided a number of conclusions, some of which were
    - Skin thickness variation (surface profile) in the majority of cases has proven to be the biggest contributor to out of specification conditions in assemblies simulated.
    - Improvements in skin surface (thickness) control will significantly improve assembly dimensional quality.
    - With regard to the assembly fixture and its feature tolerance, a general tightening of specification would have little effect with regard to improving the functional quality of the assembly.

- There may be an opportunity with machine finished CFC component features to improve their surface position control with reference to their datum system This would result in better component and therefore assembly quality control.

10.1.4 GVA case studies on wing box structure

The PVA studies were capable of evaluating the effect of parameter tolerances on overall assembly characteristics at the early stages of design These areas then become the focus of attention for later GVA analysis when more detailed geometry becomes available Three tolerance analysis case studies were undertaken using a leading 3D GVA software tool called VSA This type of approach forms part of the PARES methodology for the analysis of assemblies when 3D CAD data is available. The case studies gave a valuable insight into the effort and process required to undertake a full GVA study in 3D The main conclusions from this work are

- The three case studies were undertaken in conjunction with Airbus on early A3XX concept geometry Airbus identified the study areas, their scope, and the type of analysis to be undertaken The areas for analysis were:
  - Rib to complex skin assembly
  - Rib to skin assembly
  - C spar equipping assembly
- The main objective of each case analysis was to predict how capable an assembly system may be based on the type of fixture technique, the assembly sequence, the individual part tolerance scheme, and predict critical AKC interface measurements.
- Case study CAD data made available from Airbus and generated by the author allowed the use of 3D GD&T to define each key feature, the datum system, and individual feature tolerance This was defined using the CATIA V4 functional dimensioning and tolerancing (FD&T) module which defined a functional tolerance soft gauge based on GD&T specification as described by the ASME or ISO standard
- The case study tolerance analysis was performed with the CAT3D-VSA software product integrated into CATIA V4 This analysis tool uses Monte Carlo simulation and rank correlation to drive statistical based outputs based on the measurement condition defined. Using the CAT3D-VSA software product revealed:
  - Tolerance analysis using the CAT3D-VSA integrated module in CATIA V4 was time consuming
- Specific conclusions have been defined based on the output results for each analysis cases. These have been documented against their respective analysis case in chapter 7 of the thesis

10.1.5 CFC panel to aluminium substructure experimentation

The experimentation provided an insight to the potential issues when an aerostructure is designed, manufactured and assembled from a range of different materials and manufacturing processes A two phased experiment investigated the potential assembly problems when fitting CFC primary panels onto aluminium substructures.

- In support of the experimentation, all components, manufacturing tooling, and assembly fixtures, were designed as 3D solid models using the Unigraphics V18 and CATIA V4 CAD systems.
- Based on the 3D solid models created in the design phase, all CNC machine tool program generation was developed through the Unigraphics CAM post processor.
- The manufacturing activity outlined the potential difficulties associated with producing components from materials such as CFC For some manufacturing operations, for example, the edge routing and hole drilling of the CFC panels, the machining facilities were not ideal. This resulted in machining process problems producing damaged features on some component parts.
- Undertaking all of the design and manufacturing activates to produce the component parts and associated tooling / fixture gave the author first hand experience of some the design to manufacture difficulties and the potential lead times for their production
- The VSA variation analysis tool was used to model the panel to substructure assembly process. The analysis aim was to predict the resultant assembly quality attributes of step, flush, and virtual hole conditions based on panel and sub structure tolerance allocation and defined assembly process
- The modelling process for this analysis was the same as for the GVA studies described in chapter 7 No problems were encountered during the modelling process
- The results predicted that the panel to substructure assembly philosophy would be capable of achieving the gap specification and virtual hole condition However, the model predicted that up to 15% of the step condition would fall out of the specified limit (see figure 94, section 8 16.8 Analysis results) This predicted result also indicted a manufacturing capability index of Cpk 0.57 which would be unacceptable in the aerospace industry as a deliverable process

10.2 Further work

The areas of research which were not possible to address due to time constraints, or were beyond the scope of this thesis, have been collated as further work The areas considered for further work have been divided into the following categories:

- DM methodology and process
- DM tools and techniques
- DM experimentation

10.2.1 DM methodology and process

- Conduct further investigation into the principle of DM within the aerospace industry Extend the process further into a complete product lifecycle management process Develop the PARES methodology to address the challenges.
- Develop a DM process audit to evaluate the level of process integration within an aerospace manufacturing organisation
- Design a structured implementation strategy for the current and further developed PARES methodology.
- Development of a specific variation analysis model for military aircraft for the assessment of observability characteristics taking into account the full design, manufacturing and assembly product variation elements The low observability model could be developed using a rule based technique to include both parametric and geometric design to model resultant outer surface variation due to manufacturing and assembly process. This would result in an evaluation that gave the nominal radar cross section and the plus / minus value range based on variation parameters.
- Review the integration of design for 6 sigma concepts to support the PARES methodology
- Develop the PARES methodology to greater level of detail based on systems engineering framework.
- Introduce a cost model to the PARES methodology. Cost of product and process may be based on required product and process capability.
- Extend the DM analysis of products to identify the appropriate specification for manufacturing facility design, i e , for CNC machine tool volumetric accuracy.

10.2.2 DM tools and techniques

- Develop comprehensive feature taxonomy to address the feature design and management as part of a component / assembly / product hierarchy This may be developed in conjunction with the KC feature classification
- Consider the use of combining FEA and DM analysis techniques to model and predict structure deflection and distortion due to the assembly of components with different stiffness properties There may be issues with the assembly of rigid none conforming CFC panels to flexible conforming aluminium substructures such that the aluminium part will be deform and comply with the CFC matching interface
- Consider the inclusion and integration of both tolerance and FEA based analysis tools to efficiently investigate the effect of variation resulting from thermal expansion, mass deflection, manufacturing process distortion (i e , heat related), residual force distortion (reactive effect from door seals, pneumatic and hydraulic closure mechanisms) as part of aircraft structures design validation. The effects of operating temperatures on products such as airframes could be modelled to understand the impact of natural variation Temperature change propagation models based on FEA technology could be use to gauge the effect on feature relationships and their potential displacement The experimentation results from this research project suggest that temperature change propagation is not linear therefore further investigation is required to produce further analysis models
- The baseline PVA assembly analysis tools may be developed to take in to account thermal variation, i.e , hole position displacement, and it's effect on ICY This may be used at the early design stage for 1D, 1 5D, and 2D parameter analysis when detailed design geometry is not available The parametric models should then be integrated into the full 3D analysis tools such as VSA when 3D geometry is defined
- Develop a comprehensive process capability library based on geometric dimensioning and tolerance principles, feature size definition, and manufacturing process families
- Explore the opportunity to develop a component cost model based on feature tolerance allocation Features could be classified through a multidimensional matrix which gave consideration to manufacturing process capability, part material family, parametric and geometrical mathematical feature type and size This matrix database could provide valuable tools when considering component definition and its resultant cost.

10.2.3 DM experimentation

- Investigate the effect of surface finish elements on component variation This may include surface roughness (Ra) and surface waviness (Wa) elements and the design of a variation hierarchy
- Further areas of DM experimentation may be investigated, for example
    - Shimming of panels and substructures to control thickness variance.
    - Evaluate CFC panel spring back using FEA predictive tools; produce spring back models for different materials and manufacturing process.
    - The effect of introducing steel grommets and inserts into CFC panels with respect to product variation
    - Introduction of countersink features on CFC panels
    - Introduction of mechanical fasteners
    - Perform further tolerance analysis studies on larger aircraft sub-assemblies.
- Investigate the use of DM techniques to support computational fluid dynamic analysis on aircraft structure airflow The predicted variation data output from DM studies could be used as input for the analysis of flying surface step / gap key characteristics performance

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Appendices

1.	Tools and techniques for SPC	204
2	Computer aided tolerancing (CAT) software tools and process	208
3.	Analysing tolerance accumulation	222
4.	A dimensional control methodology for the variation analysis of aircraft structure assembly (Publication by author)	225
5.	Dimensional control as an integral part of next generation aircraft development (Publication by author).	232
6.	Stage I – VSA panel to substructure tolerance analysis results	239
7.	VSA process reports	245
8	Different methods of constructing tolerance zones in CAD systems	249
9	Wing Box Assembly Analysis Tool – User manual	252
10.	Publication Review; Tolerance design: A handbook for developing optimal specifications	257
11.	Stage I - Valisys measurement report	258

Appendix 1

Tools and techniques for SPC

There are a number of tools and techniques which support SPC These are

- Frequency histograms
- Check sheet
- Pareto chart
- Cause-and-effect diagrams
- Control charts
- Defect concentration diagram
- Correlation diagrams
- Control chart

Frequency histogram

A frequency histogram is used as a technique to graphically represent process data It can illustrate three basic characteristics of the data

- Magnitude of the mean (average)
- Outline the variability of the data
- Indicate the pattern of variability (i e the distribution type)

The figure below is an example histogram of aircraft structure CFC panel thickness data

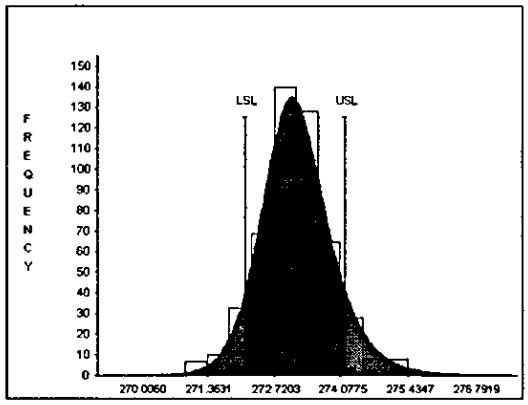

Figure 1. Example histogram displaying distribution curve and limits.

Check sheet

The check sheet is used to collect historical data for a process that may be under investigation It is designed to help identify the causes of process failures, which in turn will indicate potential product failures

The check sheet helps identify the sources of defects with respect to time This may be significant due to faults that occur through different operator or machine use An example of a check sheet for monitoring a cylinder head is given in figure 2

Check sheet for cylinder head defects	Day 1	Day 1	Day 2	Day 2
Type of defect	Shift 1	Shift 2	Shift 1	Shift 2
Block interface surface out of form	5	3	6	4
Casting defects	2	1	0	1
Machined ports out of form	0	0	0	0
Block interface surface finish out of specification	0	0	1	1
Damage to internal threads	1	0	1	0

Figure 2. Check sheet for cylinder head defects

Pareto chart

The Pareto chart is based on the research by Alfred Pareto whose law suggests that on average 80 percent of problems stem from 20 percent of the causes In principle it suggests that a small amount of problems typically account for a large percentage of the total number of problems that occur, although Bicheno (1994) suggests that this is probably more in the ration of 90 percent to 10 percent

Pareto analysis charts are commonly used in many disciplines including inventory control (A, B and C categories), forecasting, marketing, and personnel

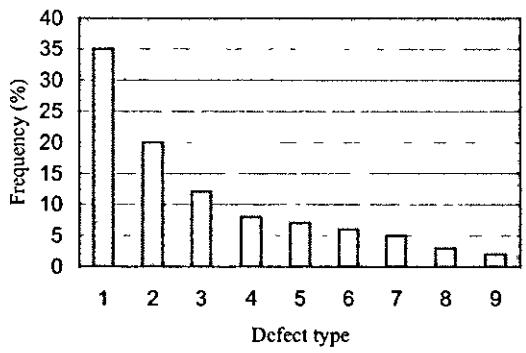

Figure 3. Pareto analysis bar chart

Its initial use was for the ranking problems from the highest to the lowest Once the biggest problem areas have been identified then teams can work on a suitable solution The Pareto chart (bar type) presents all defect types and their quantities These are presented as a percentage output, resolving each problem element into its correct percentage proportion with the accumulated totals adding up to 100 percent (see figure above)

Cause and effect diagrams

The cause and effect diagram, also known as the Ishikawa and fishbone diagram, is used as a data framework for the brainstorming of possible contributing causes of an identified problem or defect (Bicheno 1994) The techniques are credited to Dr Kanoru Ishikawa and is often utilised following the development of a Pareto

analysis chart (see above) Each category of ranked fault identified can then be transferred to the spine of the fishbone, with most effort being focused on the highest ranked problems Each of the major problems can then be subdivided into secondary factors and these can also be subdivided if necessary to identify the root causes The cause and effect analysis constituent 'bones' cascade toward a single objective which is usually quality orientated

Although they are not in themselves a statistical tool, they are generally included in SPC programmes because of their useful nature with regard to visualising sources of problems (Pitt 1994) They also encourage multifunctional team approaches to problem or defect solutions

Defect concentration diagram

The defect concentration diagram, sometimes known as the measles chart, is a highly visual tool Defects or problem areas are physically plotted on an engineering drawing at the area of where the defects occur. The accumulation of marks on the drawing gives a quick impression of where problems occur. This type of simple representation can be useful in understanding the types of defects and their possible related causes

Correlation diagram

The correlation diagram is used to identify relation characteristics between two variables It is effectively a scatter diagram with the defect level plotted on the 'x' axis and the experimental variable on the 'y' axis Once a correlation diagram has been developed it is possible to observe if there is any relationship (correlation) between the plotted data points Data analysis is usually categorised into no correlation, clear correlation and possible correlation Often initial studies cannot identify any correlation and other factors are experimented with one at a time

Correlation can be measured automatically through computer applications and is called the correlation coefficient Stratification techniques can also be used This is where groups of data are split and plotted on graphs This technique is used to identify defects against time For example, large groups of data may not appear to have any correlation but if categorised into individual machines or operators a pattern may become apparent

Control charts

The control chart is the main weapon in the armoury of the SPC method Certain engineering processes are monitored to ensure conformity with a target specification This is done through SPC control charts (Bicheno 1994) There are two main types of chart used, the variable chart and the attribute chart

Variable charts can be described as a chart that records a measured characteristic within a related scale Examples are the measured diameter of a hole, the surface finish on machined component

The main variable chart records the average and range characteristics of a process sometimes known as the 'x' bar and 'r' chart respectively There are two elements to the chart, the first monitors the average measurement of the sample, and the second calculates the range, which is the maximum minus the minimum

value Variable charts explain process data in terms of both location (average) and spread (component-component variability) and are used in pairs

Attribute charts some process characteristics cannot be recorded against a metric scale Attribute charts are used in such situations where a logical judgement is made and recoded Examples are a pass or fail criteria on an electric circuit, a pressure test on a vessel

There are a number of attribute control charts for different process applications, some of these are

The *p* chart section of units is nonconforming (sample size not necessarily constant)

The *np* chart number of units is nonconforming (content size of sample)

The *c* chart number of nonconformities or defects (samples of constant size)

The *u* chart number of nonconformities per unit (sample size not necessarily constant)

The main benefits of using control charts are

- Aids communication about a process so that multifunctional teams can quickly understand the recorded characteristics
- Main statistical based tool in support of the SPC methodology
- Helps in prediction of future process events based on recording of the past and present trends
- Assists the detection of assignable process defects and deviations

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Appendix 2

Computer Aided Tolerancing (CAT) software tools and process

A number of Computer Aided Tolerance (CAT) and quality software tools and processes have emerged in support of the dimensional management activity. Some of the major CAT software tools are available are

- UGS PLM Solutions
- Quick stack.
- Dimensional Control Systems
- CATIA V5 – Tolerance Analysis of Deformable Assemblies (TAA)
- Varatech
- Tecnomatix Technologies Ltd
- Cognition Corporation
- CE/TI 6 sigma
- Saltire Software
- Toltech

UGS PLM Solutions

UGS PLM Solutions (Unigraphics Product Lifecycle Management Solutions) is a multinational company formed as a result of a number of mergers and acquisitions They are involved in a number commercial areas related to dimensional management, these are

- Development and sales of dimensional management analysis software tools known collectively as Teamcenter Quality Solution (TQS)
- Dimensional management process and deployment training
- Dimensional management process tools, i e , geometrical dimensioning & tolerancing, statistical process control,
- Service based variation control consultancy support

VisVSA: The VisVSA software was developed initially from the variation simulation method originally developed at General Motors at Detroit know as VSM The VSA software tool has developed considerably following its migration from the original VSA company to Engineering Animation (EAI) in 1999 who themselves were acquired by Unigraphics in 2001 This product is a direct result of a VSA/EDS software development team collaboration, which has married the VSA core analysis software with Teamcenter visualisation tools to create an add-in component to run with in the visualisation software The VisVSA software is now owned by UGS following its separation from EDS in 2004 The current capability of VisVSA is

- 3D assembly variation analysis
- Monte Carlo, worst case, root sum square, plus any statistically defined variation can be represented
- Support ANSI Y14 5M and ISO geometric dimensioning and tolerancing standard with respect to geometric definition, rules applied to tolerance with material condition and tolerance to datum
- Full graphics user interface (GUI) integration into VisMockup CAD visualisation software
- Generation of analysis data including process histograms and pareto ranking of feature effects on assembly variation

- Import all leading CAD geometry and supporting meta data and product assembly structure via translation into the jt visualisation format
- Import and export of all CAD neutral standards (IGES, STEP, etc)
- Ability to perform a limited graphical animation of an assembly sequence within the CAD environment The graphical representation of variation 'sweep' can also be represented within the CAD environment

VisMockUp: EAI originally created VisMockUp as a digital prototyping software tool to allow the viewing and verification of CAD data on an ordinary office PC or UNIX workstation This can be used to aid concurrent engineering practices during product development to verify assemblies for collision and annotate the CAD data with comments about corrective action Where different areas of design may be based great distance apart VisMockUp can be used for online data collaboration and product data management. VisMockUp provides further functionality such as the ability to animate assembly processes and to take measurements from the CAD geometry which can be useful in assembly line situations to replace engineering drawings as a means of communication

Vis Quality: A software tool used to graphically display, analyze and communicate measurement data in a high-end visualization environment It is currently used in industry to troubleshoot assembly build problems and share quality information throughout the extended enterprise. Graphical reports combining measurement inspection data with lightweight 3D geometry can be created Extremely large assemblies from multiple CAD systems can be plugged directly into the lightweight visualization environment

VisPublish: Provides the ability to produce dynamic and concurrent production of Technical Documents and Publications, with HTML reporting capabilities An Assembly option is also available providing the ability to display the assembly process of products throughout the life cycle

e-Vis: Allows direct visual collaboration of complex, engineered products in 3D Allows the data and tools for interacting with that data in a secure, Internet-connected workspace

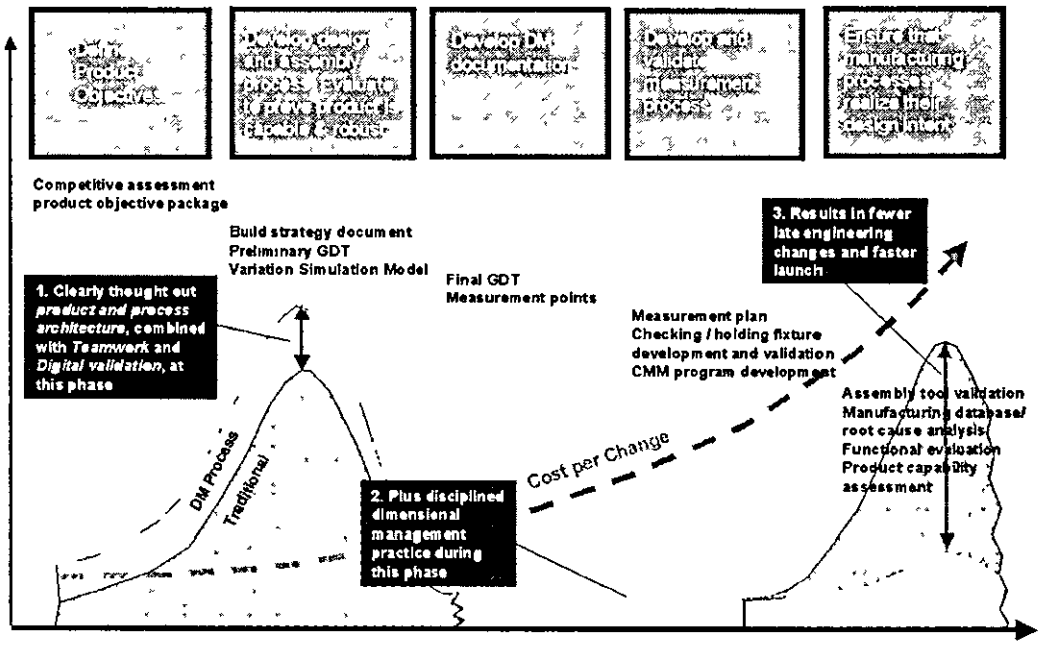

Figure 1 UGS PLM dimensional management process (UGS PLM Solutions)

The UGS/VSA dimensional management process is defined in a six step process (see figure 1), these being

i. Define product dimensional objectives
ii Develop the design, manufacturing and assembly process Evaluate to prove product is capable and robust
iii Develop dimensional management product documentation
iv Develop and validate the measurement process
v Ensure that the manufacturing process realises their design intent
vi Production to design feedback loop

Quick stack

This is a legacy product capable of undertaking simple 1D-3D stack analysis and is integrated directly into the Unigraphics CAD/CAM/CAE Software

Dimensional Control Systems

Dimensional Control Systems (DCS) is an engineering consulting firm that have been involved in the field of dimensional management, or dimensional control as they consider, for some 15 years Mostly working in the automotive industry they had little involvement in the aerospace industry but are working to penetrate this market. They have undertaken some work with Raytheon but this has not been followed up Based in Troy, they are well placed to service the big three automotive companies namely Ford, Chrysler and General Motors, and have undertaken dimensional control projects for all three

DCS has emerged from the Trikon Corporation, Trikon Design, Inc and therefore DCS and Trikon products traditionally displayed some similarity, however the DCS product has now replaced Trikon which is now discontinued

The DCS' tools for variation analysis are similar to those used in VisVSA in that they rely on geometric part information coupled with tolerance/GD&T data to create a 3D tolerance model This 3D model is then subject to two statistical tests, a Monte Carlo variation analysis and a HLM sensitivity study

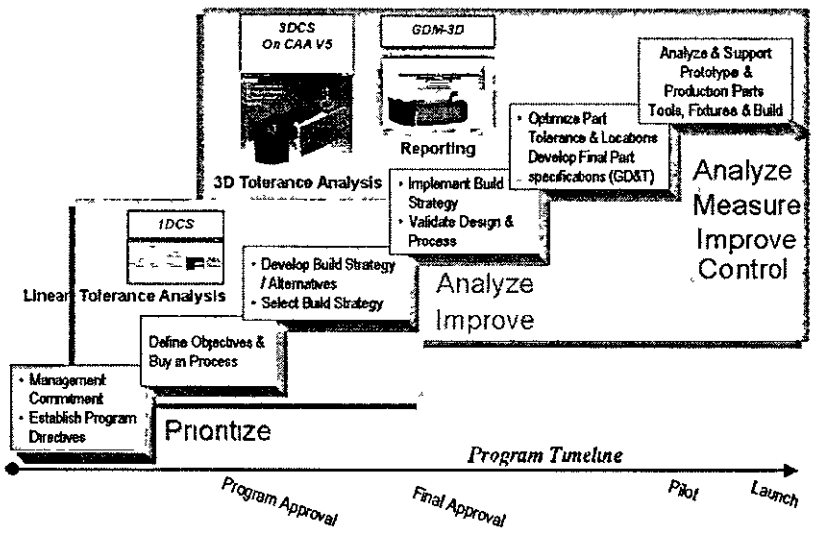

Figure 2 DCS dimensional control process (DCS)

This software study forms an integral part of DCS' ten-step dimensional control procedure (see figure 2), which is defined as·

1 Identify and document dimensional quality goals
2 Team consensus and signatures
3 Develop strategic plans to achieve all dimensional quality goals
4. Determine global tolerance and major datum for sub-assemblies
5. Generate tolerances and datum for all parts and assemblies, statistical simulation, work towards buy in from all team members – this is the key engineering phase
6. Optimise the design/process through 3-D analysis
7 Verify prototype tool and fixture designs – validate gauge and fixture capability.
8. Evaluate prototype results
9 Verify production tool and fixture designs – validate gauge and fixture capability
10 Support during pilot, launch and production.

Information gathered from steps 8 and 10 acts as feedback to be put back in at step 6 to allow optimisation of the product for dimensional robustness

The software tools used operate on a standard PC workstation platform easing accessibility to non-CAD operators The 3-D geometry is imported from CAD data via an IGES file converter and there is also the option to manually build simple geometry Because of this CAD-like operation there is no manual programming language accessible to the user, which does mean that the ability to develop custom code is lost The 3-D geometry can be visualised within the dynamic tolerance simulation package (3D-DTS)

DCS currently support 4 products types·

1-Dcs software solution: this is one dimensional linear tolerance simulation software It runs on a p c platform and is a point based coordinate analysis system It can support a range of tolerance capability including Worse-Case, RSS/RMS, or Monte Carlo with a range of statistical distribution types DCS has the ability to graphically indicate the 'sweep' of component/subassembly variation DCS claim that this supports engineers when interpreting analysis results It has no capability of creating graphics but IGES files can be imported and exported DCS claim that their 1D product can be very quick and effective for some types of tolerance analysis DCS suggest use of full 3D is not always necessary

3-Dcs software solution: as 1-DCS above, but has full three dimensional capability These are to be run on both pc and workstation platforms One advantage of the 3-Dcs software is its ability to graphically animate assembly sequencing which includes the correct orientation and approach of all components into as assembly This is a big advantage when presenting an assembly analysis to an engineering group

3-Dcs for mechanical desktop software solution: the product is similar to 3-CDS software solutions but is fully integrated within the AutoCAD mechanical desktop product

GDM-3D: Used to graphically display measured data from a number of sources including raw coordinate measuring machine (CMM) data, mobile arm measuring and Datamyte type devices Measured data is formatted into comparator or accumulator outputs and hard copies can be produced in a standard report Raw x, y and z data can be also displayed

3-DCS for CAA – CATIA V5 integrated solution: Similar capability to 3-DCS but directly integrated into the CATIA V5 CAD environment With a direct link to the CATIA FD&T, tolerances are automatically incorporated into the model helping to reduce model creation time

Model creation is aided by visual tolerance deviation of CATIA solids and visual animation of the assembly sequence. In exploring the V5 architecture DCS claim the following key benefits

Faster integration by enforcing an Object Oriented Design with C++ and JAVA
Enabling distributed computing across platforms by utilizing CORBA/COM
Interfacing the DCS application with other knowledgeware tools in the CATIA V5 "hub"

CATIA V5 – Tolerance Analysis of Deformable Assemblies (TAA)

The new P3 module has been developed for the Tolerance Analysis of Deformable Assemblies (TAA) Its function is to 'assess the impact of the assembly process on flexible components ' In real-world terms this will allow users to create a digital simulation that follows the assembly of a particular set of components (such as a car body panel) and gauge the effects that the various production processes have on the tolerance of that assembled product Whereas this type of work may be possible within other high-end systems at a basic level, what will make this most interesting will be the ability to use the CATIA knowledgeware functions to experiment with different manufacturing processes (such as variation in welding positions and timing) and accurately gauge the effects they have on the tolerance of the final product All of this allows users to optimise, not only the form of the part, but also the production of the part Key product features include

1 Deformation and assembly process approaches — This product is based on a mechanical approach that takes both deformation and the assembly process into account to predict the tolerances for welded (riveted, bolted, or glued) assemblies of sheet metal parts
2 Creation of data and assembly process specifications
   - Commands for specifying the attributes to be included in the analysis
   - Commands to specify the assembly process
3 Process verification before simulation — this function avoids simulation deficiencies by allowing the user to make sure the specified process does not contain faults For instance, it can detect if there are two spot weld operations for one point
4 Simulation of the assembly to perform a set of tolerancing analyses — the product provides sensitivity analysis, determinist analysis, and statistical analysis that are based on the same common computation Integration of Finite Element Analysis models the elastic "deformability" in the assembly process and results in a finer and more realistic simulation The user can get a sensitivity analysis to identify the key characteristics of the assembly
5 Easy re-computation of the simulation — this product avoids the use of time-consuming Monte Carlo simulation Additionally, there is no need to re-compute the simulation if only the input variations are modified The type of simulation used allows the user to do a quick update simulation when the assembly process or few attributes need to be modified, added, or removed
6 Multi-display of the simulation
   - Graphical display of statistical and determinist analysis results are provided through displacement presentation (using FEA representation) and point deviation (using arrow and ellipsoidal representation)
   - Graphical display of sensitivity analysis results is provided through the representation of input deviation contributions (in percentage) of output deviation
   - Statistical and determinist analysis results are also available through numerical display

The module indicates the potential for seriously in-depth analysis of not only the behaviour of a product during its use, but during the manufacturing and production process

Varatech

Varatech is a technical engineering consulting firm based in Michigan Their main business in centred around support for product development and assembly systems optimization They offer dimensional management services utilising their own software solution and supported by the use of design for six sigma (DFSS) techniques

Varatech dimensional control engineers offer experience in the following areas.

- Design for assembly
- GD&T/Functional datum structure
- 3D variation modelling
- Functional gauge and fixture design

Key steps for the Varatech dimensional management process

1. Qualify and quantify an assembly's build objectives
2. Evaluate the geometric sensitivities of design concepts
3. Define and document locating schemes, datum structures, and GD&T
4. Gather and assess processing capability
5. Evaluate assembly process

Varatech develops the Sigmund range of analysis software for assembly and piece-part tolerance analysis The software product line includes

Sigmund 1D: Sigmund 1D evaluates one-dimensional tolerance stacks to obtain verifiable results using industry accepted analysis techniques such as Worst Case and RSS analysis

Sigmund 3D: Sigmund 3D evaluates, optimizes, and validates the capability of proposed designs and assembly processes by creating virtual assemblies that emulate piece-part tolerances and assembly process variation

Sigmund 3D allows engineers to build a large number of virtual assemblies for evaluation with respect to pre-defined build objectives It emulates manufacturing process variation following the ASME Y14 5M-1994 GD&T standard as well as assembly process variations such as clamping sequence, part orientation, and gravity effects

Supported CAD/CAE

Sigmund 3D - Stand Alone

Sigmund 3D - SolidWorks Integrated

Sigmund 3D - Pro/Engineer Integrated

Sigmund 3D - Solid Edge Integrated

Sigmund 1D - Stand Alone

Sigmund 1D - SolidWorks Integrated

Sigmund 1D - Pro/Engineer Integrated

Sigmund 1D - Solid Edge Integrated

Tecnomatix Technologies Ltd

Tecnomatix was established in 1983 The Company went public in 1993 (NASDAQ symbol TCNO) and today has a widespread, international network of subsidiary offices and distributors in North America,

Europe, the Pacific Rim and Latin America. Tecnomatix are involved with companies in the automotive, aerospace, electronics and heavy equipment industries in the area of product analysis and product life cycle management

Tecnomatix offers the following software analysis tools·

eM-TolMate enables the prediction and effect of tolerances and mating operations on an assembly process It identifies key characteristics of an assembly—such as the flushness of an airplane wing, the gap between a door and the fender of a car, or the clearance between the removable hard disk and the bay in a portable PC—as well as the critical features of an assembly eM-TolMate can calculate the variations in these characteristics and the contribution of tolerances to these variations The simulation and analysis tools are designed to help deliver optimal tolerances for manufacturing and assembly

eM-Probe

eM-Probe enables the creation, optimization and verification of off-line inspection programs for CMM and CNC machines It provides collision detection capabilities for complex parts and fixture set-ups with outputs containing DMIS programs for specific CMM manufacturers

eM-Probe CAD

eM-Probe CAD enables the creation of off-line inspection programs for CMM and CNC machines within a CAD environment, and provides the ability to define measurement probes, and inspection processes Inspection processes created by eM-Probe can be run only by eM-Inspect and eM-Inspector

eM-Inspector

eM-Inspector enables reading in DMIS files, and their execution on NC Machine Tools and CMMs through a direct bi-directional communications link It brings 3D CAD data to the shop floor with a Windows NT based inspection system, and can drive NC machine tools with DMIS 2 1 and 3 0 commands eM-Inspector provides consistent mathematical diagnostic analyses regardless of the measurement device

eM-Inspect

eM-Inspect enables the inspection and analysis of parts on the shop floor It supports over 30 CMMs and NC machine tools, performs online modification of inspection processes, and reviews analysis results of measured features in real time eM-Inspect-UG is an embedded product in the UG CAD system. eM-Inspect-SA is a standalone product (not embedded in any CAD system) and is available on UNIX platforms only.

eM-Qualify

eM-Qualify enables the analysis and evaluation of measured data against nominal models, and provides consistent mathematical and graphical data to perform best-fit analyses and the verification of possible

causes of failure

eM-Reverse

eM-Reverse enables the creation of accurate 3D-CAD models from physical parts or master tooling and provides best-fit analyses on measured inspection data It features adjustable accuracy levels and is fully embedded within CATIA and Unigraphics

Tecnomatix Technologies produce a range of software products and services which link the virtual manufacturing environment to the real Their main product line is

ROBCAD; for the design, simulation, optimisation and off-line programming of automated and manual manufacturing systems

EXALINE; for the design, simulation, optimisation and off-line programming of the printed circuit board assembly process

PART; for the numerical control (NC) process planning and programming

VALISYS; for the definition, inspection and management of product tolerances throughout the manufacturing process

DYNAMO; for the design and verification of assembly, packaging and maintenance processes

The VALISYS product is made up of a suit of modules

1 Design, used to define 3D tolerance information in accordance with ANSI Y14 5M - 1982 GD&T standard The tolerances are created directly from CAD data Design contains four functions:

Features, allows the selection of CAD features (faces, planes etc) to be controlled

Gauge, enables a 3D tolerance model (soft gauge) to be placed on selected features The 'soft gauge' is a computer representation of an allowable 3D geometric tolerance zone associated with a feature being controlled (i e feature of flatness) When a statistical variation simulation is operated the soft gauge represents the limits of that tolerance zone Gauge also performs a functional check to verify the relationship between the feature selected and the tolerance applied are compatible

Check, used to validate dimensions and tolerances are in accordance to the GD&T standard Y14 5M

Vutility, allows the user to access, edit and save changes to the VALISYS database

2 Programming, enables the off-line programming of CMMs and NC machine tools with inspection capabilities Programming contains five functions

Path1, Path 2, Path 3, employs the features data form design to create a generic inspection path for use by NC inspection equipment

Generate, creates the VALISYS control language (VCL) which contains instructions for NC measuring equipment This may be to perform VALISYS functions or to enable NC instructions to drive inspection equipment

Probe, allows VALISYS information to be attached to a CAD models of probes for the execution of calibration, orientation and inspection processes

3 *Inspection,* allows the inspection program to be validated and modified if necessary Also produces the analysis data form the inspection program Inspection is made up of four functions,

Files, enables the user to access, import, delete and list part files
Inspection, uses VALISYS programming instructions to drive the inspection equipment, takes, retrieves and stores measurement data
Qualify, creates a math model form inspection data and compares that against the related soft gauge math model and creates a report comparing design and measured data
Control, used for defining and executing machine functions

4 *Analyse,* uses a graphical representation to compare the measured against CAD data to identify areas of soft gauges in terms of pass, fail and rework Contains only the analyse function

5 *Assemble,* incorporates the use of statistical simulation techniques to predict variation stack up resulting form an assembly of a group of parts It also checks the assembly methods and identifies conditions of over constraint and under constraint Reports are produced identifying critical part and assembly tolerances which contribute to variation There are six functions in assemble

Compmgr, enables component models to be managed to facilitate assembly modelling
Gauge, see *Gauge* in *Design* section
Features, see Features in Design section
Vutility, see Vutility in Design section
VSA-FCN, used to identify the incomplete, incorrect and inconsistent application of GD&T with regard to the VSA simulation software

6 *Reverse,* allows the construction (digitization) and manipulation of physical features within a CAD system which may then be used in the construction of complete component geometry This module only consists of the Reverse function

7 *Process control,* designed to track manufacturing process information to determine if or when process is out of statistical control Makes use of graphical control charts and reports to allow the detection of process deviation and rapid correction

Tecnomatix do not have a well documented dimensional control process However, they promote a dimensional quality process closely associated with the various VALISYS software modules Currently this is the only software available which offers an integrated closed-loop path form tolerance allocation to dimensional inspection

Their main business objectives are software sales, consultancy and training Their primary business area is in software sales with the consultancy and training elements run in direct support They are a multinational company and their headquarters is based in Herzliya, Israel

Advantages of the software

- Offers an integrated closed-loop dimensional quality process
- Can model and analyse complex 3D geometry
- Tolerance application in accordance with GD&T ANSI Y14 5M standard
- Possible to check tolerance application for incorrect and illegal call outs
- Can be used with leading CAD systems - CATIA, Unigraphics, and IDEAS
- Promotes the use of GD&T in an organisation
- Collision free off-line programming of NC and CNC inspection equipment

Disadvantages of software

- Cost of software and hardware
- Software is complex and therefore requires extensive training.
- Software is embedded within a CAD system therefore there is a requirement to become familiar with that CAD system

The author has used all the modules of the VALISYS integrated software The software was used for the digital inspection of a number of aerospace and automotive component parts using a CMM in native mode Assembly analysis has also been undertaken on the author's experimental component part assemblies

Cognition Corporation

The Cognition Corporation is a multinational company who develops and markets the Advantage Series of software products These are a suite of engineering decision support tools designed to be used with an evolving product development process focusing on re engineering the design process

A major objective of the company is to achieve a 5 to 1 reduction in time and cost of bringing a product to market while increasing product quality and eliminating product and tooling changes caused by design error. They aim to achieve this by the development of the virtual conceptual prototype method which is to replace the current dependency on physical prototypes to facilitate the design development process They strive to deliver a software solution to the customer and make it operational very quickly

Major Objectives of Cognition are

- Deliver and train customer on software solutions very quickly.
- Enable customer to customize and modify software solutions very easily and quickly.
- Product only released when fully developed and proofed
- Promote the modelling of the entire product/process development
- Promote the modelling of the entire engineering program
- Conceptual model should drive CAD detail design models

Cognition produce the following products

1 Mechanical Advantage I and II a feature-based variation solid design system built for performance modelling, design optimisation, critical parameter management, tolerance allocation and analysis, and kinematics and dynamics

Modules are made up of

- Tolerance modelling and analysis.
- Critical parameter analysis.
- Solid note
- Sketch note
- Math note
- Program note
- Data capture and presentation (DCAP) note

2 *Cost Advantage*· a design analysis tool that assists in cost assessment for both parts and assemblies The software can be configured to allow the user to perform production analysis, manufacturing alternative studies, DFM and DFA The modules are made up of

- Injection melding model
- Manual assembly model
- Electronic system assembly model
- Costlink/PE

3 *Design Advantage* an ANSI/ISO standard drafting system that can accept 2D/3D wire frame models, 3D surface models, and any ACIS solid model for the purpose of documentation

Training focuses around use of software products and related procedures Cognition appears to have well defined training courses for all its software products They identify the duration, prerequisites, and objectives of all courses All training based on real engineering problems and solutions Cognition focus their business on software sales rather than dedicated consultancy, therefore they require their software to be relatively friendly for the engineer to use Therefore the user skill requirement to drive the products will be low to medium

A product development process is currently being evolved Their process starts with a quality function deployment (QFD)approach which feeds requirements into a system called SLATE produced by TD Technologies SLATE is requirements control software for design and manufacturing data on such items as time, resources, capacities, capabilities etc Each item is then considered as an object, i e people, tooling, processes, and is modelled in an object related data base. Cognition argue that relational data bases cannot sufficiently handle large changes and tradeoffs' effectively and become difficult to manage

This process allows engineering to focus on the aspects of product parameter management during the concept design phases in a 2D and 2 5D sketching environment Virtual models are created of the product and parametric tolerancing and simulation can be undertaken The virtual models can be linked to data tables and engineers can model "what if" type equations to explore parametric variation Cognition is developing their system in order to tolerance all parameters and not just geometric

Their process focuses on identifying and modelling all contributors to parametric variation and it is possible to plot them graphically in order to analyse their range They promote product development by primarily modelling all parameters and then converting this data into detailed 3D CAD geometry at a later stage Cognition argue that organisations commit to much time and money in detailed 3D design before all parametric concerns have been resolved If left unresolved these parametric concerns if left will only force design engineers to make time consuming and expensive detailed redesigns at a later stage
Cognition suggests that engineers need to undertake virtual prototyping for all parametric variation not just geometric tolerance analysis They recognize three levels of tolerance analysis, these are

- Manual calculations hand written solutions, use of spread sheets Problem is reluctance of engineers to undertake this and when it is done many mistakes can occur due to length and complexity of calculations
- Cognition type - Tolerance Modelling and Analysis can deal with 95% of tolerance problems in engineering very quickly and easily Problem is the software cannot handle complex 3D analysis - therefore it is limited
- VSA type can deal with almost all tolerance related modelling and simulation Problem is product complexity requiring high level of skill to operate and interpret analysis results

The tolerance analysis module of the Mechanical Advantage Sketch Note application is an integrated tool that works within normal design activity Observations made of the tolerance modelling and analysis software module

- Cannot handle 3D complex surface tolerance problems
- Integration to CATIA and UG via IGES format
- No support of STEP standard to date
- Cognition views their role as fast tolerance analysis, 1D and 2D which they claim can solve 95% of tolerance engineering problems. They see themselves as the bridge between paper based calculations and full (VSA) 3D tolerance analysis.
- Tolerance data geometry to ANSI and ISO standard with regard to GD&T but visually does not appear the same
- Analysis models created in 2D and extruded to produce 2 3/3D
- Dimensions on models can be "locked" if desired
- Critical dimensions are not locked - remain flexible for variation simulation
- Introduction of feature based ACIS solid model integrated with ANSI standard associative 2D drawings for parts and assemblies
- Capable sensitivity analysis, % contribution analysis, 6 sigma and Monte Carlo analysis
- Directly compatible with ACIS based systems

Cognition does not have a well documented dimensional management process The three main areas of Cognition are:

- Software development and sales
- Engineering consultancy
- Education and training on software and engineering processes

There are three main areas that Cognition market, these are in

- Software sales· This is their primary area of business Cognition would prefer to keep a high level of software sales and training and keep engineering consultancy to a minimum
- Training· This is a major supporting part of the business to software sales
- Engineering consultancy Cognition can provide a broad range of consulting services to the manufacturing engineering industry They can provide services relating to product support, including implementation, planning, training, consultation and software. However, consultancy is a secondary market aim following software sales.

CE/TI 6 sigma

Sigmetrix LLC is a software development company focused on providing easy-to-use assembly tolerance analysis and optimization software for mechanical engineers Sigmetrix is a partnership between the original creators of the CE/TOL 6 Sigma tolerance analysis software and Rand Worldwide CE/TOL 6 Sigma has been shipping to Pro/ENGINEER customers since 1992 and is distributed exclusively by Rand Worldwide and Parametric Technology Corporation on a worldwide basis

Sigmetrix is continuing to develop CE/TOL 6 Sigma as the premier tolerance optimization software in the world today Through the company's unique research relationship with the top universities developing complimentary technologies, like Brigham Young University's ADCATS program, as well as the strategic software development and distribution relationship with Rand Worldwide and Parametric Technology Corporation,

Most of Sigmetrix key customers are the same industry leaders who are deploying 6 Sigma methodologies on a broad basis and realizing significant returns on investment and additional market penetration Sigmetrix unique understanding of 6 Sigma methodologies, Pro/ENGINEER integration, tolerance modelling and optimization methods has given the company a demonstrated leadership position in helping spearhead 6 Sigma programs in our customer base The partnership between Sigmetrix, Rand Worldwide and Parametric Technology Corporation is allowing these three premier companies to combine their collective talents in providing integrated solutions that meet the demands of a rigorous 6 Sigma program

Saltire Software

Analytix is a sophisticated mechanism design-and-analysis software package It is essentially a parametric modeller where embedded kinematic equations are available for fast analysis. It also has the flexibility to let the user write their own more formula for various type of analysis

It has the capability of undertaking statistical or maximum/minimum tolerance stack-up on designs An interactive calculator is also embedded that enables the user to develop their own equations to analyse certain design parameters

It operates form a PC in from within a Microsoft Windows environment. Its data exchange is limited to the data exchange format (DXF) or Windows Dynamic Data Exchange (DDE), cut and paste

Some of its functions are

- Parametric sketching -2D, patented variation geometry engine, with auto-dimensioning
- Mechanical model input, distances and angle values, velocities and acceleration Tolerance on input distances and angles Applied forces and moments Masses and moments of inertia
- Mechanical model output, Geometric position, velocity and acceleration Reaction forces Shear force and bending moments Stress and deflection Tolerance stack, sensitivity, trace, zones, absolute or statistical
- Simulation and analysis tools, Animation, point trace, envelope Equation calculator and interactive equation solver Graphs and tables of output parameters

The product is targeted at the up front concept stages of design development Relatively little is known about this product

Toltech

The Toltech computer aided tolerancing system has been developed by The Norwegian Institute of Technology, Division of Production Engineering (Bjorke) The system is named TOLTECH, from TOLerance TECHnology, and is designed to interactively perform tolerance related calculations.

The TOLTECH system has its own developed language in which the tolerance analysis must be written in a series of statements These statements contain four categories of information·

Numbers, expressed as integers or reals

Symbols, formed as a series of letters (A-Z), digits (0-9), and characters " "

Punctuation's, consist of one alphanumeric character and have a special meaning in the TOLTECH language

Ignorables, consist of one non-alphanumerical character

Appendix 3

Analysing tolerance accumulation

There are four main groups associated with analysing tolerance accumulation, these are

- Worst case
- Root-mean square (RMS) or root sum square (RSS)
- Statistical analysis
- Kinematic analysis

Worst case; does not take into account distribution of size of feature and that they do not exceed their respective specifications The tolerance variables will take a value at one of its limits in such a way to yield an extreme condition at a point of analysis, i e the maximum expected variation at that point This analysis is only recommended for a limited number of dimensions and where very high assembly confidence is required

Root-mean square (RMS); predicts variation at a given point which is not expected to be exceeded more than 1 in 370 assemblies (99 73%) This analysis was developed as a more accurate representation of variance when considering a large number of tolerances One assumption made is that the analysis represents features that are manufactured about the mean point of the tolerance, i e an equal bilateral tolerance is assumed

Statistical analysis; employs a statistical distribution which represents more accurately the expected process variation of each dimension It is possible to use actual manufacturing process data or an approximation of a distribution curve and limits to give a better representation of actual or calculated variation data Several different methods have been developed for statistical analysis

- Linearization method
- Method of system moments
- Approximation by numerical integration or quadrate technique
- Monte Carlo Simulation
- Reliability index
- Taguchi method and modified Taguchi method
- Croft's method
- Extended Taylor series approximation.
- Hasofer - Lind index method

Currently in manufacturing there is a migration towards 3D solid modelling for detail design application With the availability of the STEP information interchange standards, the CAE systems will need to further develop the ASME/ISO tolerance standards which will include statistical tolerance analysis. Current commercial systems use two types of statistical simulation modelling, namely linear stack up and Monte Carlo. This is also the case with wire frame and point based analysis systems

The most commonly used methods by commercial tolerance analysis software is linear stack up and Monte Carlo simulation Linear stack up, or root sum square (RSS) method, is used when an assembly response function can be expressed as a linear function of the component parameters The math function for linear stack up is·

$$T\ total = (t1^2 + t2^2 + t3^2 + \quad + tn^2)^{0.5}$$

T total = Total tolerance
tn^n = Individual tolerances

Where T total = total predicted assembly tolerance (equal bilateral variation) using the RSS model

Where tolerance distributions are known, a Monte Carlo simulation (MCS) may be performed to provide an accurate assessment of cumulative variation effects The basis of the technique is to simulate sampling of known process distribution For example, if the variation of two elements A and B are considered, the solution required is

$$P(A + B = A_i + B_i) = PA_i \times PB_i$$

The probability that the sum of elements A + B is equal to the sum of $A_i + B_i$ equals the probability of A_i times the probability of B_i If the distribution characteristics for A and B are available a computer may be used to select a random number for *i* and sample the two distributions Sampling a frequency plot would typically give two values for any given random number, therefore cumulative distributions are used instead, see figure below

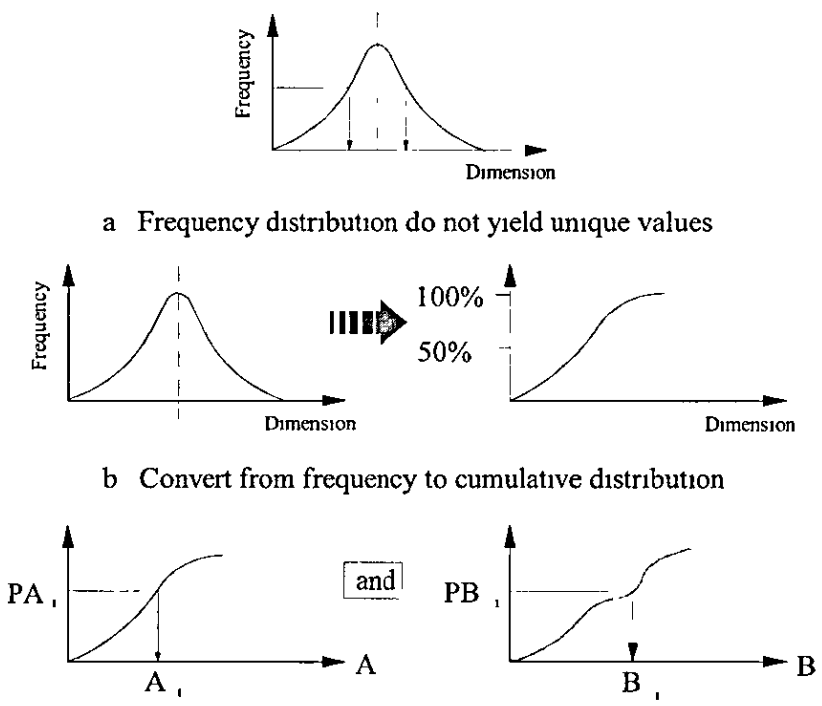

Figure 1. Monte Carlo simulation process

The following tasks are performed by the computer system

1 Derive PA_i from random number, sample the distribution for A_i

ii Derive PB_1 from another random number, sample the distribution for B_1
iii. Add A_1 to B_1 = 1st output
iv. Multiply PA_1 with PB_1 = 1st probability
v. Repeat *n* number of times
vi Add the probability of all values contained within stated limits
vii Produce a histogram of the results

If a number of elements each displaying a normal statistical characteristic are used in a variance simulation the RSS and MCS methods will produce essentially the same results However when elements are other than normally distributed MCS will yield results unattainable by the RSS method.

Appendix 4

A dimensional control methodology for the variation analysis of aircraft structure assembly

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ABSTRACT

This paper describes the methodology used in a dimensional control analysis case study undertaken in conjunction with British Aerospace Airbus Ltd (BAAL) The methodology was applied for the assembly variation modelling of a carbon fibre composite (CFC) wing box structure developed for future civil large aircraft projects With the planned introduction of large scale CFC components into future aircraft structures, BAAL are using dimensional control analysis to investigate and evaluate new manufacturing and assembly techniques and processes Focusing on tolerancing and assembly operations, both components and fixture have been investigated to identify areas where dimensional quality could be improved further The methodology is closely supported through the use of an advanced simulation software tool and requires a systematic approach from design to manufacture The assembly variation studies are currently assisting BAAL with both manufacturing and assembly process evaluation leading to the design optimisation of both component and tooling entities.

1. INTRODUCTION

Sources of variation (dimensional noise) need to be identified and managed if aircraft manufacturing organisations wish to become more competitive in the global market place Variation can be found in manufactured components and subassemblies, assembly tooling and fixture, the design/manufacturing/assembly/inspection processes, and human intervention, (1).

Traditionally, design engineers are primarily concerned with issues of style, function, and structural integrity The communication of tolerancing, datum and location schemes of the product then becomes a secondary concern, (2) An important part of the design process requires the determination of nominal dimensions and

the application of tolerances. These need to be administered such that each individual part will meet the performance intent of the design and requirements of interchangeability Dimensions therefore not only specify the size and shape of an object, but they maintain the design integrity of the part during manufacturing and assembly, (3 and 4) Many of these issues are covered by blanket company and international standards and are then left to various interpretations by the down stream activities of manufacturing, tooling and assembly building in unnecessary cost into some areas This has led to the existence of the 'hidden factory' (5), where even at the late stages of production operators and fitters are "adjusting" out variation problems The result of this is wasted time and money, as well as compromising product quality

The introduction of dimensional variation from upstream manufacturing processes in addition to poorly defined location and datum schemes may produce major problems for an assembly organisation The discipline of dimensional control is an engineering methodology that manages variation from the early product definition stages through to full production Computer 3D simulation tools are used to predict how much and where variation will occur in an assembly due to component variation, assembly methods, and assembly sequences, (6) A major objective of a dimensional control methodology is to expose the hidden factory to the whole organisation creating a network of cross functional activities that actively promotes engineering concurrency

The aim of this paper is to report a particular methodology adopted for a geometric dimensional analysis study on a development wing box structure, to highlight why the assembly analysis was necessary, and what was achieved The assembly analysis technique was undertaken to investigate and evaluate dimensional control issues surrounding the use of new production techniques, technologies and processes in the application of large CFC components into future large civil aircraft structures at British Aerospace Airbus Ltd, (BAAL)

2. THE ASSEMBLY VARIATION MODELLING APPROACH

The appropriation and preparation of data necessary to facilitate the assembly variation modelling requires a systematic approach for robust results In this case study the nature and the source of the data are outlined and key points are highlighted The acquisition of appropriate data was time consuming and iterative but became a major contributor in helping focus in on factors potentially effecting dimensional quality prior to the assembly variation simulation and analysis Due to the amount of preparation time required to undertake an assembly analysis, a structured approach in the investigation, preparation and presentation of data will save time, reduce errors and produce a clear data audit trail Both manufacturing and assembly process knowledge (process limits and the expected variation between these levels) needed to be captured for components and tooling at each related assembly stage

The assembly modelling, simulation and analysis were undertaken using the Variation Systems Analysis VSA-3D (7) software product embedded in the CATIA Computer Aided Engineering (CAE) system and

operated on an IBM RS/6000 AIX platform The VSA-3D product has several sections which rely on CATIA's Functional Dimensional and Tolerancing (FD&T) module to generate feature, datum and tolerance data

The development CFC wing box programme at BAAL is at an advanced stage of development Physical as well as functional detail architecture has been defined for component and fixture geometry As a consequence, the following data was available for the assembly simulations

Detailed 3D CAD models were made available for use in CATIA for all geometry with assembly sequencing defined for the development structure
The development CFC wing box structure detailed product dimensional objectives were known (targets and metrics)

In the early stages the process is sequential but later becomes more concurrent and iterative The assembly modelling process was divided into the following twelve steps.

(i) Define the engineering challenges
The challenges were highlighted and documented by the composite wing programme engineering team resulting mainly from work undertaken previously on prototype builds and from experimentation Defining the engineering challenges allowed the formulation of aims and objectives for the analysis This was an important stage which determined the 'focus' and 'context' for the analysis

(ii) Define aims/objectives of the assembly analysis study
From the documented challenges a set of analysis aims and objectives were developed These defined the analysis boundary (both physical and functional) not allowing any one model to become over complex The challenges were grouped and several analysis studies were planned, each having its own set of aims and objectives

(iii) Determine the analysis zone
Physical zones were created for the analysis and only the components having an effect on the dimensional quality within that zone were included The boundaries of the zones were determined by the aims and objectives of the analysis, but encompassed all physical components and elements of manufacturing and assembly tooling potentially having an effect on the 'focus' of the investigation

(iv) Identify all the key features for components and tooling
These were the physical features (areas of surface geometry) owned by components, manufacturing, inspection and assembly tooling that influence the dimensional quality aspects of the zone under analysis Component features can be split into the following categories

- Features that are associated with the manufacture of the component part
- Features associated with the location system

- Features associated with component and fixture interfaces
- Features associated with product dimensional quality control
- Features to be used as a component and fixture datum

Some features shared more than one category An example of this is when a plane, a hole and a slot in a component shares the status of being both a locating and datum feature set

(v) Quantify manufacturing and assembly process variation

This was undertaken for all component parts and assembly tooling For this to be achieved, knowledge on all manufacturing processes used to produce the individual component and assembly tooling key features was required This data was made available from manufacturing and assembly development process inspection data

Assembly simulation incorporating unrealistic statistical formulae of tolerance variation can give misleading results It is important to recognize that steps need to be taken to adequately ascertain manufacturing process data through current SPC programmes or other inspection data systems Manufacturing and assembly processes at BAAL were being measured for capability limits (Cp), how well the process is under control (Cpk), and how adequate samples are being distributed within those limits (distribution type)

The use of the Geometric Dimensioning & Tolerancing (GD&T) standard Y14 5M-1994, ASME (8), allowed each component to be described in clear and concise geometric and mathematical terms avoiding ambiguous tolerance and datum communication The FD&T function in CATIA automatically determines the feature type and only allows the placement of datum and tolerances in accordance to a GD&T standard Datum and component tolerances are defined in conjunction with feature definitions ensuring that no datum and tolerance call outs can be created violating a given GD&T standard

(vi) Determine the sequence of component assembly

For each analysis study a sequence was defined representing in which order components were assembled together The components were taken from a parts list defined at an earlier stage and were represented diagrammatically as an assembly 'tree,' with the components and subassemblies diverging into the total assembly for that stage The assembly tree defined whether components were located directly through jigs and fixtures (independent location, via holes, pins, offsets), located via other component parts (kit build, via component interfaces, offsets) or located via a combination of the two The assembly tree allowed tractability at every stage and provided a tolerance map highlighting a 'variation route' progressing through to the final assembly via component and fixture features

(vii) Define assembly method (assembly moves) for each component part

To ensure a dimensionally stable build each component was constrained in all six degrees of freedom (DOF), three in translation and three in rotation Each component was analysed for conditions of over constraint (more than six DOF) or under constraint (less than six DOF) If either condition existed the assembly

'philosophy' for that component was investigated and revised where ever possible to ensure the correct constraint status in 3D space

VSA-3D was used to facilitate the component to fixture assembly moves using the following software templates

Datum target based moves this allows the placement of an unlimited number of datum target points on component and fixtures to facilitate the assembly of curved and complex features
Assembly feature based moves allows the assembly of feature combinations such as hole/hole (via pin), hole/pine, pine/slot, plane/plane, or any combination of these

For any type of assembly move the normal convention references the component being moved as the 'Object' and the component/fixture into which it is to be moved as the 'Target'

(viii) Define the analysis measurements to be undertaken
The VSA-3D software was used to measure the following entities of the development wing box·

Gap clearance the gap condition between rib bottom edge and skin surface to facilitate mechanical fastener, film and paste adhesive bonding assembly processes
Virtual hole condition the virtual condition between skin and rib holes to facilitate mechanical fasteners

(ix) Undertake tolerance analysis simulation
When all the proceeding steps had been completed the assembly of the wing box section was simulated 2,000 times for each scenario Three types of tolerance analysis were undertaken for each measurement

Monte Carlo a random number generator which is related to a distribution type
High-Low-Medium this simulation holds each individual tolerance in turn at its high, low and medium level while alternating all remaining tolerances through all combinations of high, low and medium levels
Extreme case simulates the build setting all variation at the widest level, i e the worst combination to produce maximum variation in an assembly

(x) Analyse the simulation results
When the simulation was completed a report was compiled by the VSA-3D software for each measurement analysis Each type of analysis undertaken was presented in its relevant report format The Monte Carlo (MC) simulation presented the results in a distribution and provided information on the magnitude of variation associated with each measurement The High-Low-Median (HLM) results were presented as a Pareto analysis indicating the percentage contribution to each tolerance in the analysis in relation to the variation in the output measured MC and HLM analysis were undertaken for each measurement.

(xi) Revise parameters and repeat process for further investigation

Several analysis studies were undertaken of defined assembly zones Subsequent studies of each zone were undertaken with the different tolerance parameters revised to explore the resultant effect upon the assembly structure This process of rerunning the analysis models with different tolerance parameters allowed the assessment of major contributors to geometric variation It also helps in defining the most adequate tolerances required to achieve a high level of confidence of assembly through the relaxation of tolerances that have little contribution and tightening of tolerances that have a major contribution

(xii) Document the analysis results

The final stage was to document the analysis results of the different zones in a formal report. The report should include clear data trails of where the required information was gained for each step of the approach, therefore in the event of inconclusive results these data sources may be revisited A typical analysis report should contain information such as objectives, assumptions, modelling methodology, drawing/CAD data, results and conclusions

3. CONCLUSION

This paper outlines a systematic approach used for the modelling of manufacturing, tooling and assembly issues used in support of the composite wing programme at BAAL These projects continue to ensure the successful development and productionisation of future large civil aircraft and provide a base for the development of advanced manufacturing and assembly technologies The dimensional control approach of assembly analysis is currently assisting in identifying, quantifying and managing sources of variation potentially introduced to CFC wing box structures

Assembly variation modelling required both product and process knowledge most of which had been characterized Such data is forming the basis for a better understanding of the products control and development resulting in improved robustness The credibility of any simulation result to be used for component, subassembly and tooling design or redesign purpose relies upon model validation. This in turn will be dependent upon clear audit trails in the acquisition of data

The case study experience also points to the need for a multifunctional team approach for effective product and process design and revision The aim of introducing the assembly variation modelling process at BAAL is to characterize process and product capability and to make this information available to all engineering functions in so far as this will enable variation management to be exercised at all stages of aircraft development and production This dimensional control methodology is ensuring that tolerance verses variation related data can be fed back to the design, manufacturing, assembly and inspection areas of the organisation This will provide essential information at all stages of product development necessary to ensure total aircraft robustness

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Appendix 5

Dimensional control as an integral part of next generation aircraft development

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ABSTRACT

The next generation of both military and civil aircraft are now being designed and developed Research undertaken by the authors has highlighted particular product and process characteristics that are becoming more critical in the design and manufacturing of modern and future aircraft structures A particular requirement is for reduced assembly variation This requirement emerges, for example from design strategies seeking to maximize the structural use of carbon fibre composite materials, from the increasing requirements for low observability in military aircraft, and from the need for flight cruise efficiency in civil aircraft Large companies such as Boeing, McDonnell Douglas, BAe Systems and Airbus have all performed studies in dimensional control One theme that emerges is that dimensional control must be exercised with design and manufacturing working in close partnership This is particularly true when considering the introduction of advanced material technologies such as carbon fibre composites and in the application of automation to major aircraft sub-assemblies Such challenges are found to occur across both military and civil sectors This communication highlights some such challenges and identifies a seven-point response for the basic technological infrastructure to support the deployment of an effective dimensional control methodology as an integrated part of the next generation aircraft product development process Further work is in progress on detailing and demonstrating such a methodology

1. INTRODUCTION

Study tours of US aerospace companies by the authors has highlighted a number of issues relating to new aircraft structure development programs **(1), (2)** These issues relate to the design, manufacture, inspection and assembly processes related to next generation military and civil aircraft The product and process characteristics associated with these aircraft are more radical and demanding when compared to current designs, partly triggered by the introduction of new structure materials such as carbon fibre composites

This trend towards the use of advanced materials has also been the focus of the civil sector for the last few years for the next generation of commercial aircraft Such developments present challenges, and opportunities, to engineers across the whole spectrum of design to manufacture In today's competitive aircraft industry, new design, manufacturing and assembly methods are being developed to lower costs and provide a more consistent product (3) One of the biggest challenges facing engineers is to ensure the control of product dimensional variation Sources of variation (dimensional noise) will need to be identified, quantified and managed if aerospace organisations wish to pursue a competitive edge in the global market place Variation exists in all manufacturing activities and is evidenced in manufactured components and subassemblies as well as assembly tooling and fixture and all design, manufacturing, assembly, and inspection processes.

Traditionally, design engineers are primarily concerned with issues of style, function, and structural integrity The communication of product tolerance, datum and location schemes then becomes a secondary concern (4) However, an important part of the design process is the requirement for the determination of nominal dimensions and the application of tolerances These need to be administered such that each individual part will meet the performance intent of the design Dimensions and tolerances therefore not only specify the allowable size and shape of an object, but they maintain the design integrity of the part during manufacturing and assembly (5) Many of these issues are inadequately covered by design through the use of blanket tolerances from company and international standards and are then left to interpretation by the down stream activities of manufacturing, inspection and assembly This can lead to the existence of the 'hidden' factory where components and subassemblies undergo 'adjustments' to facilitate assembly (6) The result is excessive product and process noise being introduced to a development program and is a major inhibitor to the introduction of more advanced automated assembly technologies Dimensional variation which is not adequately dealt with during design and component manufacture, in addition to poorly defined feature location and datum schemes, will inevitably produce concerns which may only become evident late in the assembly stage (7) The discipline of dimensional control is an engineering methodology designed to address these issues through the management of variation from early product definition stages right through to full series production It is the fundamental requirement that must be addressed if true Design for Manufacture and Assembly (DFMA) is to be achieved

2. TRADITIONAL VERSUS NEXT GENERATION MILITARY AIRCRAFT

In the military sector the design and development of programs such the joint strike fighter (JSF) has heralded a departure from conventional aircraft structure design A major objective of the JSF project is to develop and demonstrate advanced technologies, which enable the affordable development of next generation strike weapon systems (8) In addition, the JSF project aims to identify the impact of affordable next generation airframe designs in terms of their suitability for multi-service commonality An ongoing program called the 'advanced lightweight aircraft fuselage structure' (ALAFS) has already begun to explore some of these issues using new design methodologies which include extensive use of carbon fibre composite (CFC) materials, see Figure 1

There is a general trend to increase the structural efficiency of aircraft sub-assemblies This is an obvious goal if reduced weight and cost targets for new structures are to be realised. Even after many years of advanced research airframe sub-structures and exterior skins are still mainly assembled using large numbers of mechanical fasteners such as rivets and bolts Sub-structure and skin components are generally drilled using 'hard' (fixed) jig/fixture tooling templates and the holes facilitate both assembly location and fastener insertion access features (9) Next generation aircraft are moving more and more away from these traditional technologies towards lighter material technologies and integral and bonded structures Such approaches should not be done at the expense of dimensional control but with careful consideration of dimensional control, if the objectives of reduced cost and weight are to be achieved This move has allowed the development of 'monocoque' type airframe structure where a significant proportion of the dynamic in flight loads are carried by CFC outer panels. In some instances these advances in technologies can be contradictory, for example carbon fibre composites have the potential of significantly reducing component weight but the material itself historically has suffered greater variation than metal machined components Care must be applied during design to ensure the benefits are exploited to the full whilst minimising the impact of the shortcomings of some technologies CFC panels must also be capable of inter variant interchangeability, i e , any CFC panel of an aircraft variant must fit any other aircraft of that same type These CFC panels will also need to be removed and replaced efficiently in order to allow access for service and repair This has led to a design trade off between relaxed tolerance specifications to facilitate CFC panel to substructure interchangeability, versus tighter tolerance to satisfy the transfer of stress loading between mechanical fasteners, the CFC panels, and corresponding substructures

The incorporation of CFC materials in both the outer flying surface panels and internal substructures is likely to be substantial Unlike conventional materials such as aluminium (Al) and titanium (Ti), CFC materials will not readily 'conform' via distortion of component by pressure during manufacturing and assembly process finesse. Where Al and Ti substructure subassemblies are to be used their part count is likely to be reduced, typically up to 80% compared to traditional aircraft This will result in each structural component becoming more geometrically complex, substantially stronger, and possessing more free state rigidity

3. TRADITIONAL VERSUS NEXT GENERATION LARGE CIVIL AIRCRAFT

The civil aircraft manufacturing giants such as Boeing Commercial Airplanes and the Airbus Industry consortium are also considering the next generation of large aircraft design and development concepts As previously mentioned this aerospace sector is alongside the military sector with respect to reducing assembly part counts, in the reduction of in process tooling and fixture, and the more extensive integration of CFC materials into primary structural assemblies to reduce total aircraft mass

The successful use of CFC materials for some aircraft components has been evident for some years It has been utilised for vertical stabiliser components as well as the primary structure material for horizontal stabilisers (Airbus Industries being the lead of the industry in both these cases) Airbus are exploring the possibility of producing a wing box constructed predominantly from CFC material, Figure 2, a significant departure to traditional wing construction which consists of mostly Al and Ti materials Traditionally, wing box assembly throughout the civil aircraft manufacturing sector involves the use of techniques such as 'fettling', the removal of excess material from a component or subassembly feature Another technique known as 'shimming' involves the depositing of material upon a feature surface to facilitate an effective subassembly interface Shimming techniques are primarily used by the military sector of the industry with the civil sector relying in the main on fettling These techniques have evolved because certain manufacturing processes associated with wing components and their subassembly interface features cannot be controlled well enough to achieve the target specification without subsequent processes The need for such processes is reducing as greater understanding is gained as well as maturing of metal manufacturing technologies in terms of achievable tolerances

The introduction of CFC materials will greatly reduce the feasibility of fettling techniques due to the constraining nature of the material Given this, much greater control of component to subassembly interface features will be required for a range of new and advanced assembly processes to be deployed, such as film and paste bonding for example

4. THE CHALLENGES FOR FUTURE AIRCRAFT PROGRAMS

The next generation of both military and civil aircraft will be designed using novel concepts, new materials, and revised manufacturing and assembly strategies It is only through these significant step changes in technology can today's challenging cost and weight targets of the aircraft customers (both military and civil) be fully met The challenge to new aircraft programs can in part be characterised by the following

- Integration of digital design and test environments - virtual product development (VPD)
- New airframe structure design concepts including high levels of airframe commonality and the introduction of 'monocoque' type CFC structures.
- Introduction of new material types such as CFCs and radical manufacturing processes
- Development of improved aircraft maintenance systems to reduce owner-operating costs.
- Migration from physical to digital master tooling gauge (MTG) systems - this heralds a move from a checking to a measuring philosophy Furthermore, quality inspection activities should be developed following a 'lean' philosophy where aircraft key characteristics remain the focus
- Introduction of complex component and assembly inspection analysis techniques
- Large investment reductions in manufacturing and assembly tooling and fixture
- Component-to-component assembly strategy – the reliance on a component to locate the next component within an assembly process resulting in minimal fixture (so called jig less assembly).
- Much greater emphasis on product and process costing

5. ADOPTING A DIMENSIONAL CONTROL METHODOLOGY FOR NEXT GENERATION AIRCRAFT DESIGN AND DEVELOPMENT

Some of the new product and process concepts to be introduced in the next generation of military and civil aircraft have been highlighted It is proposed that some sections of the aerospace industry will need to re-evaluate a number of these engineering business processes in order to accommodate these new concepts The need can in part be addressed through the deployment of a developing dimensional control methodology to link the engineering effort from product requirements, design, manufacture, through to full series production In fact some of the points identified below have already been implemented in large scale applications and the benefits of these approaches are already starting to be realised in practice However full implementation of the whole methodology still requires significant effort to become reality and only then will the full cost and quality benefits of the approach will be fully realised A seven point response is proposed as a prerequisite for the methodology, these being·

i *Adequately and effectively characterise manufacturing and assembly processes,* the introduction or evaluation of current statistical process capability (SPC) data for all manufacturing and assembly processes SPC has been known and implemented for some time although generally post design The implementation of an SPC methodology early in the design process will enables greater link between design, manufacture, and assembly, ensuring that the design process is complementary to the down stream process to be employed

ii *Develop new, and revise existing, manufacturing and assembly processes,* the manufacture of components from CFC provides a number of engineering challenges, including the tight control of variation and the large scale integration across the manufacture and assembly of the CFC structures Their use is relatively new for primary structural components and major sub-assemblies The continued development of these technologies is leading to functional and cost improvement for a variety of new applications

iii *Reduce manufacturing and assembly jig/fixture 'hard' tooling requirements,* a number of manufacturers are now using large precision (5 axis) high speed machining facilities Terms such as hole to hole and part to part assembly are often used to describe this design concept These facilities are being used to drill/countersink and net profile CFC panel components in preparation for mechanical fasteners The machining of accurate features for component–to-component assembly strategies will significantly reduce the need for location and fixture tools

iv *Elimination of physical MTG and digital master media,* the introduction of precision and flexible measuring equipment is already showing significant cost benefits in aiding the inspection process of jigs with respect to digital MTG, and hence the need for physical master tooling and static storage sites can be eliminated This has reduced the requirement for physical MTGs' These systems are based on a number of technologies one of which is laser interferometery (SMART 310 system from Leica, for example) with dynamic tracking capability These systems can be used in conjunction with the digital master models created within the in-house CAD/CAM/CAE environments

v *Develop digital inspection techniques;* this will provide a process for component, assembly and fixture tooling dimensional quality verification The master digital data stored within the CAD/CAM/CAE environment can be utilised as the nominal product media

vi *Introduce geometric dimensioning and tolerancing (GD&T) concepts,* the use of a GD&T standard provides a means of communicating design intent through the manufacturing and assembly operations with the minimum of ambiguity GD&T is not about tighter control of tolerances but more about controlling tolerances appropriately, based on the function that feature plays in the final product, i e where a component feature plays a key role in either the assembly or final function of the product then particular attention can be paid to the control of this feature. Features that have negligible effect on performance or assembly can potentially have their tolerances relaxed enabling reduction of manufacturing costs related to that feature This is a significant advancement over the application of blanket tolerances to both design and manufacturing activities

vii *Efficient use of variation analysis CAD/CAE integrated simulation tools,* e g with GD&T specifications available in digital CAE systems it is possible to undertake 3D variation analysis

studies on critical assembly issues Such techniques truly enable the manufacturing costs to be evaluated within the product design and help to facilitate true DFMA

Aerospace organisations are already utilising integrated product development (IPD) strategies driven by integrated product teams (IPT), (10) Part of the dimensional control process requires product and process information from cross-functional and multidiscipline engineering sections making concurrent engineering a fundamental requirement

Due to the reduction of substructure component parts in the military and civil aircraft sectors, a new assembly philosophy is emerging This philosophy aims to eliminate a significant proportion of assembly fixture tooling through the application of new 'self tooling/location' principles Each component and subassembly will be produced with inherent self locating features and tooling features, in addition to its nominal functional architecture These features will be used to facilitate component to component location for assembly purposes Dimensional control techniques can again play a major part in the design of individual components and minimal tooling, their features and their functional tolerances The process should be used to evaluate the risk of a new design concept from component and assembly dimensional non-conformance and the associated manufacturing and assembly costs that may be incurred if this control is not maintained

6. CONCLUDING REMARKS

A study of a number of aerospace companies has revealed that the dimensional control discipline needs to be exercised early in the design phase such that the manufacture and assembly characteristics of series production aircraft are effectively taken into account This philosophy is consistent with the concurrent engineering ideal and its supporting techniques, DFMA, for example Airbus and BAe SYSTEMS have made significant advancements over recent years and are pushing further technology developments in these areas. This has been precipitated by the need to develop aircraft of improved quality, with lower development program costs, and in the light of material and technology developments

The successful deployment of a dimensional control methodology requires a multifunctional and integrative team approach for effective product and process development This will require product and process knowledge from a diverse number of engineering business centres and will need to include information such as process capability indices and process costs A seven-point response has been proposed as the basis of the technological infrastructure that relies increasingly on the extended use of digital models and digital inspection Further work is in progress on detailing and demonstrating an appropriate dimensional control methodology

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Appendix 6

Stage I – VSA panel to substructure tolerance analysis results

The complete tolerance analysis output measurements for stage I panel to substructure assembly (see figure 1) are presented below The outputs consist of process charts and HLM reports generated form the VSA software on step, gap, and virtual hole conditions. An explanation of the analysis process is available in chapter 8 An explanation the analysis results can be found in the next section entitled 'VSA process reports'

Analysis measurements: the following areas were identified for investigation These included step, gap, and virtual hole condition measurements

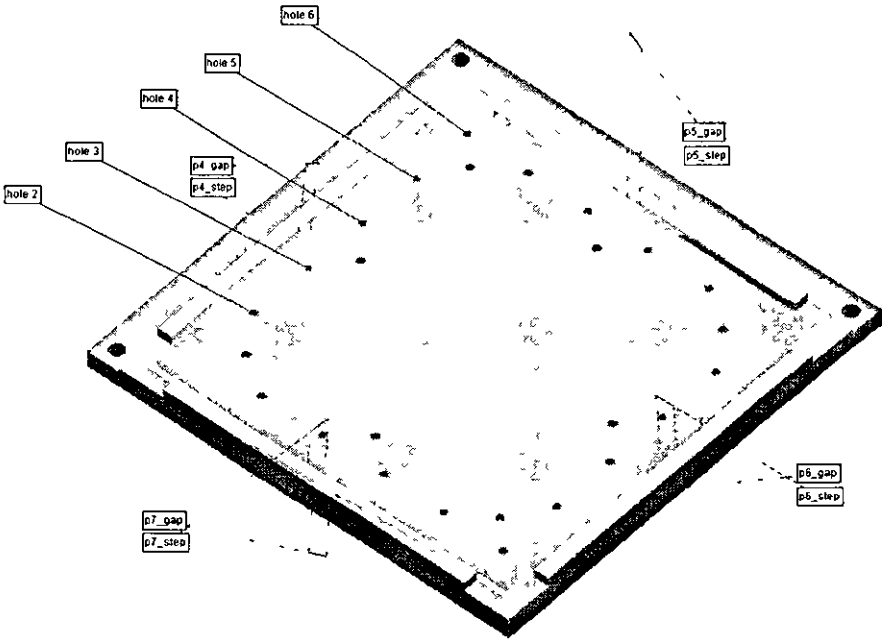


Figure 1. Stage I panel to substructure analysis measurement points

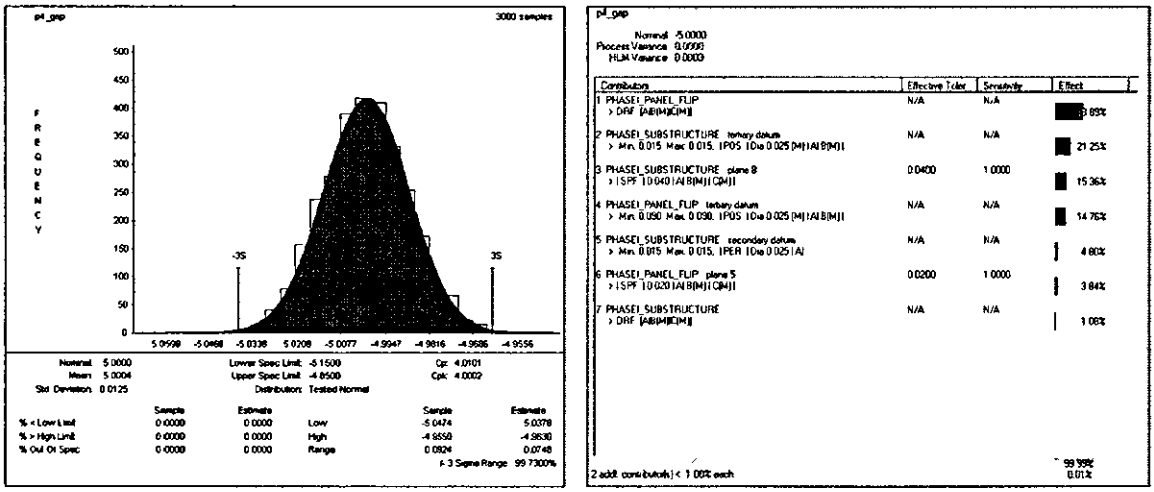


Figure 2 Plane 4 gap measurement

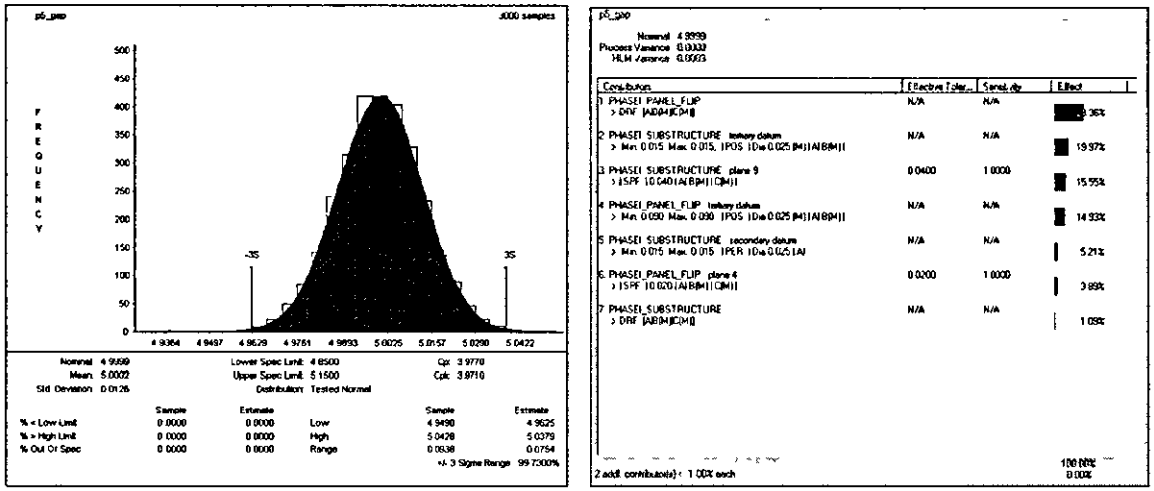


Figure 3 Plane 5 gap measurement

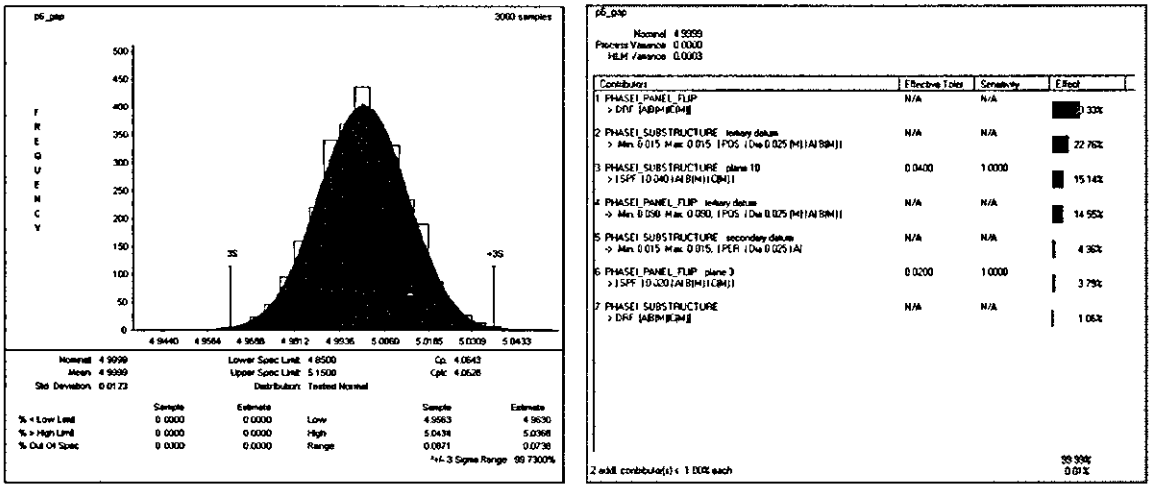


Figure 4 Plane 6 gap measurement

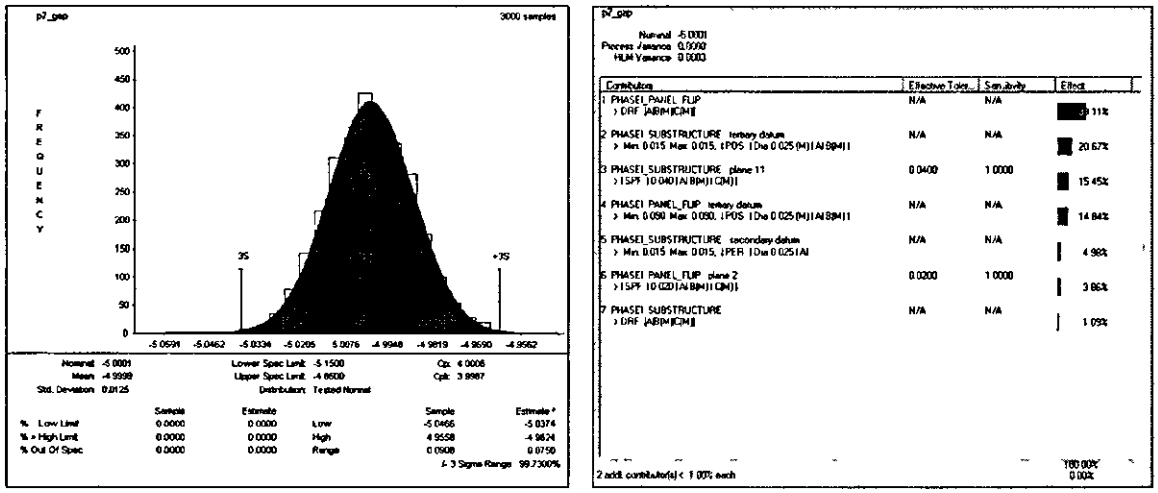


Figure 5. Plane 7 gap measurement

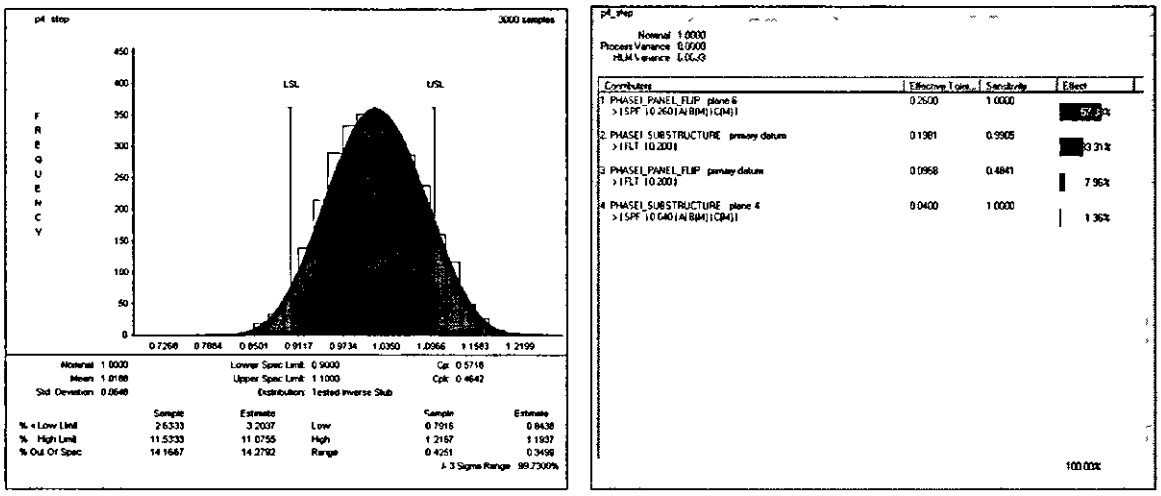


Figure 6 Plane 4 step measurement

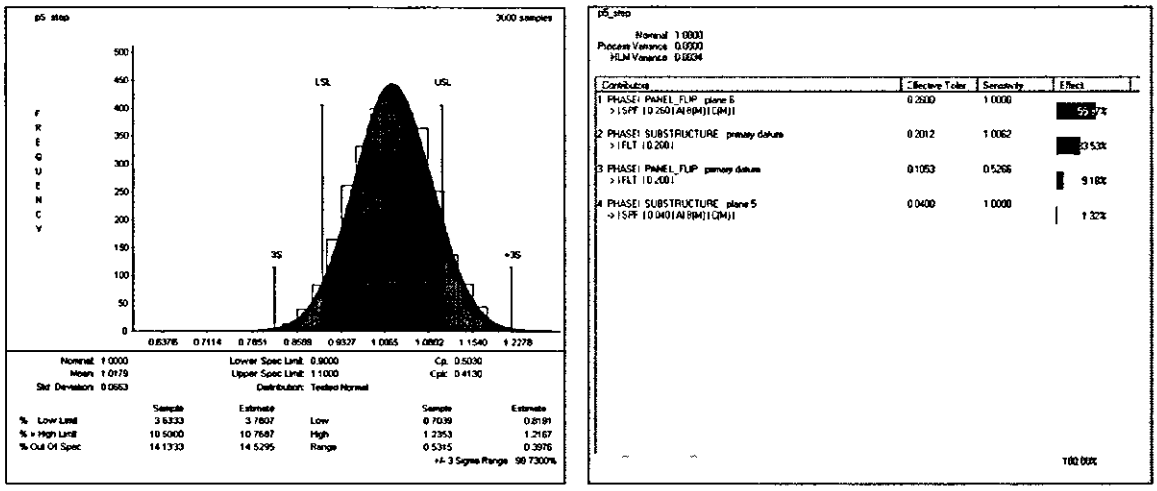


Figure 7 Plane 5 step measurement

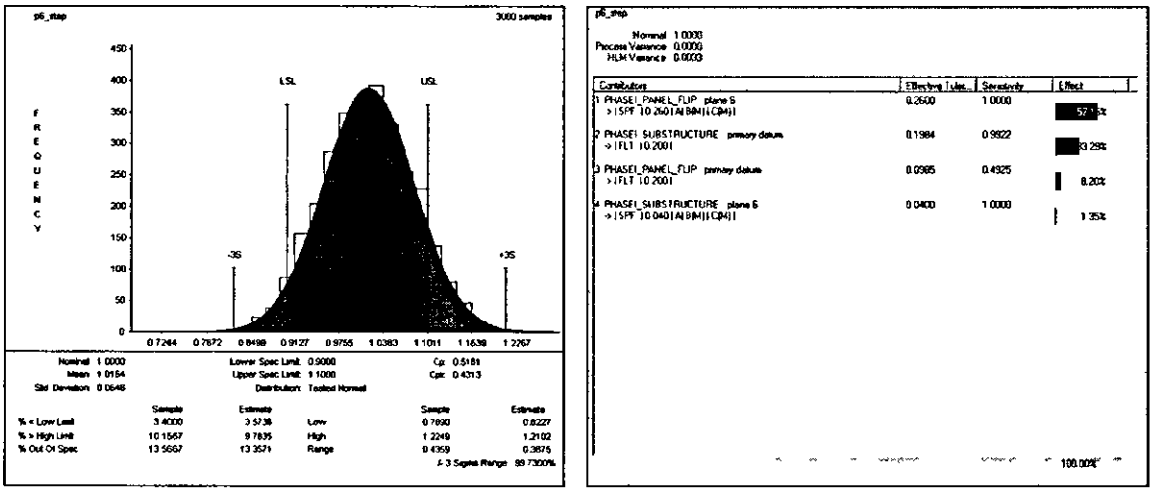


Figure 8 Plane 6 step measurement

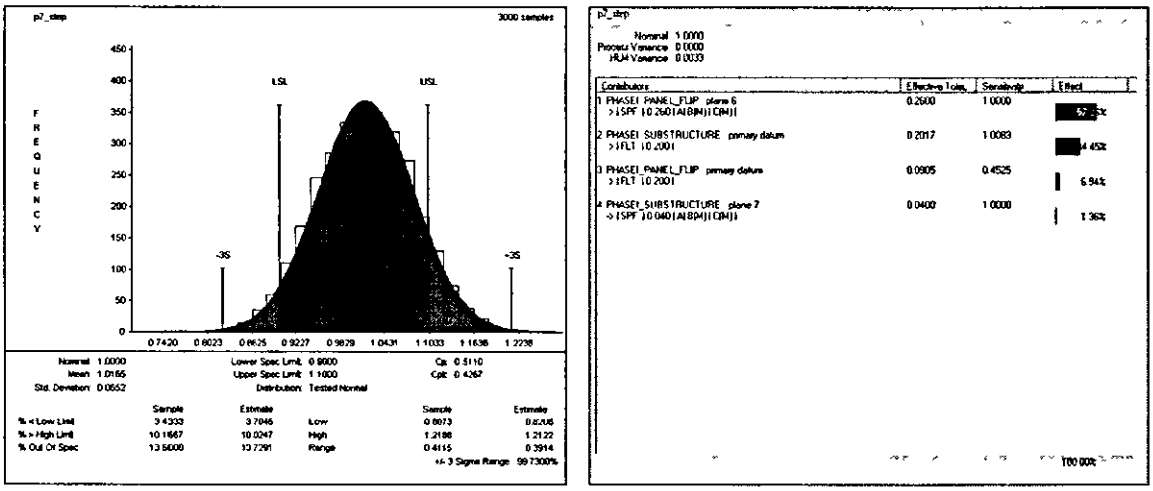


Figure 9. Plane 7 step measurement.

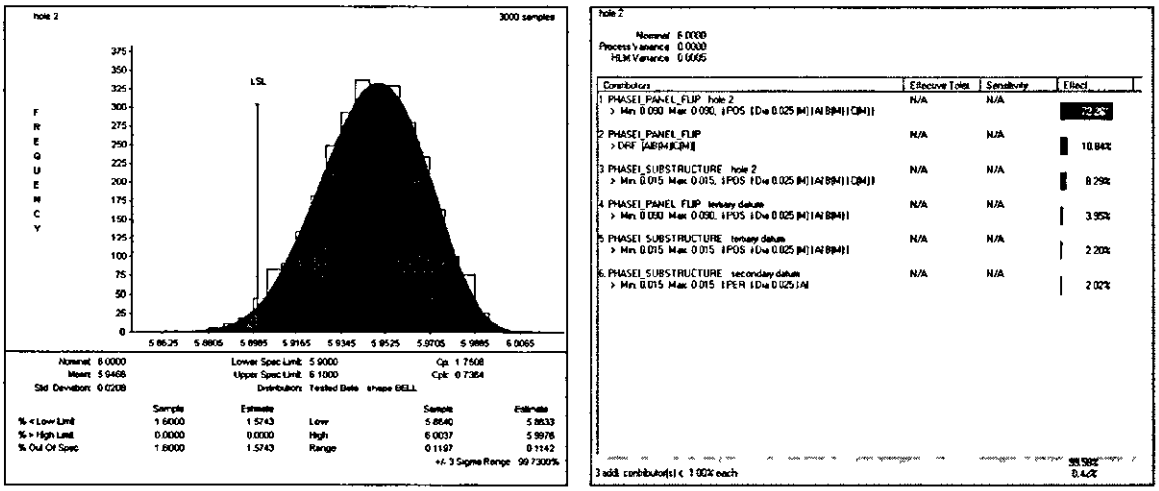


Figure 10. Hole 2 virtual diameter measurement.

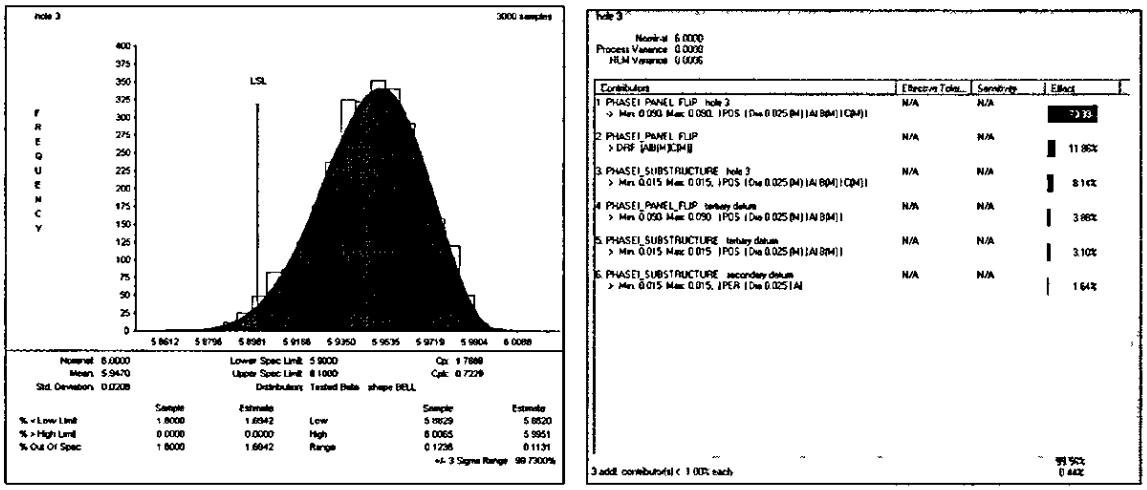


Figure 11 Hole 3 virtual diameter measurement

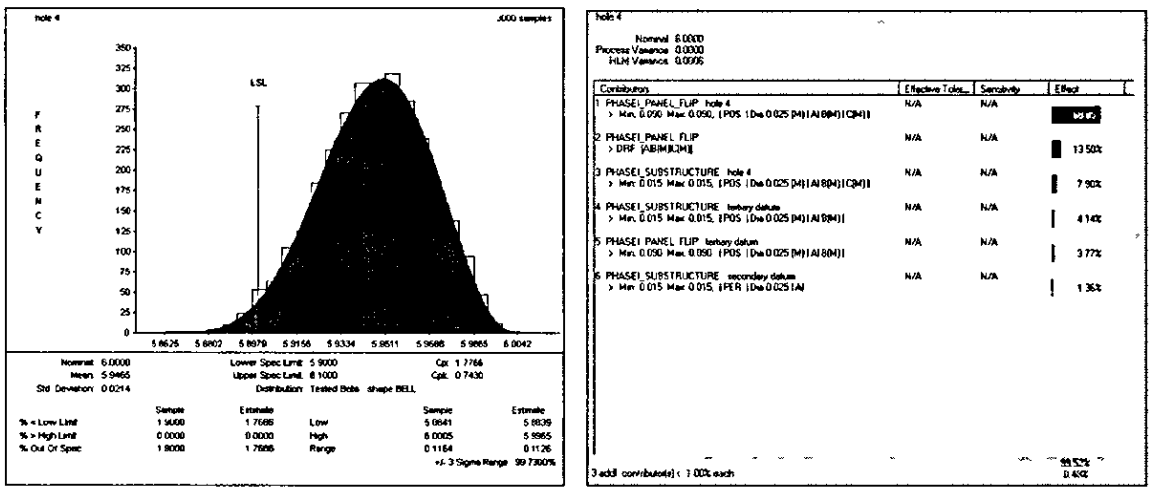


Figure 12 Hole 4 virtual diameter measurement

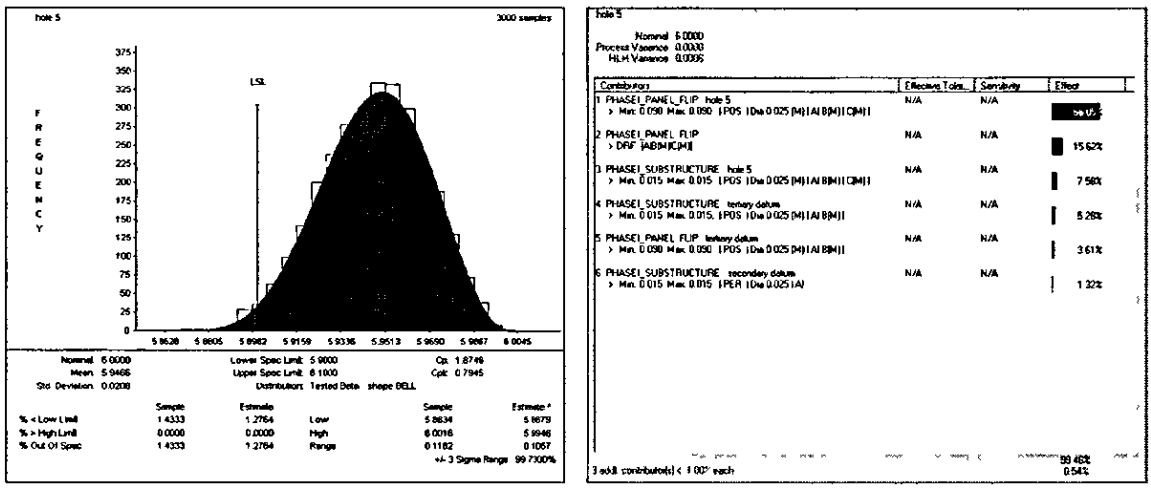


Figure 13 Hole 5 virtual diameter measurement

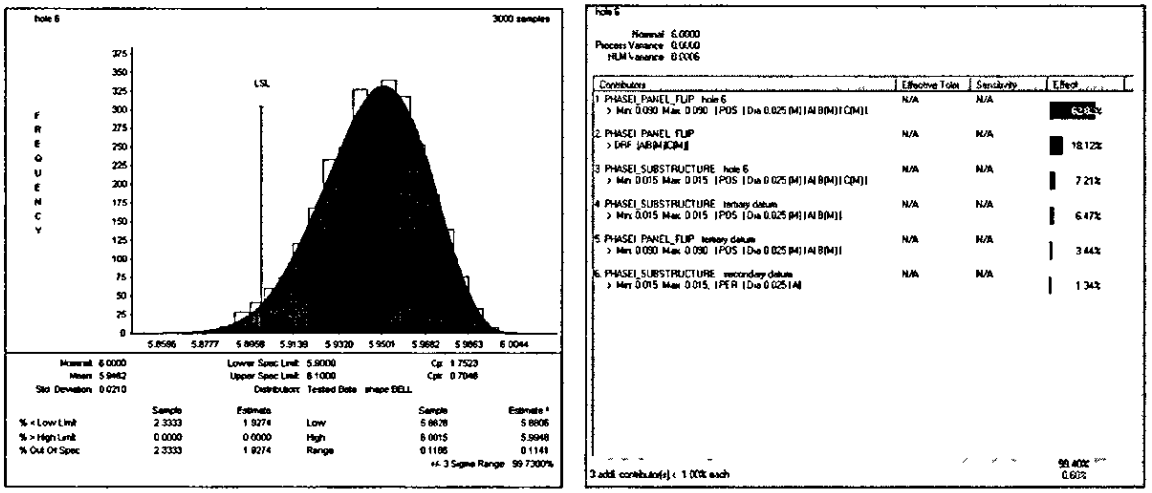


Figure 14. Hole 6 virtual diameter measurement

Appendix 7

VSA process reports

The information contained in the process report is

Sample Size

The number of simulations performed. It is important to do enough simulations to allow good estimates of the mean and standard deviation values. You should keep running simulations until these values stabilize

Nominal

The value of the measurement when all tolerances are set at their nominal values

Mean

The mean for the measurement values produced during simulations

Standard Deviation

A statistic that tells you the amount of variation in the measurement values Also called sigma

Upper and Lower Spec Limits (USL, LSL)

Any upper and/or lower design limits from your model

C p

A process capability index relating the allowable design variation to the sample variation in the simulation samples

An N/A will appear if

- Both upper and lower design limits have not been specified
- The number of accepted simulations is less than 5

C p k

A process capability index relating allowable design variation to sample variation, including a measure of curve centralness

An N/ A will appear if

- No design limits are specified It is calculated if only one design limit is specified
- The number of samples is less than 5

Refer to the Cp and Cpk calculation discussion at the end of this appendix

Distribution

This is the distribution that is fit to the data and being used to generate the estimated values shown on the lower part of the report The following alternatives are available.

Actual

When the analysis type is actual, the data is tested for normality. If it fails the test, the appropriate Pearson curve is fit. Otherwise, a normal curve is used for estimations

Normal

You have forced the analysis to use a Normal curve for estimating by setting the analysis type to Normal

Pearson

You have forced the analysis to use an appropriate Pearson curve for estimating by setting the analysis type to Pearson

Percent < Low Limit

The sample column gives the percent of simulation samples that fell below the lower design limit The estimated column contains the percentage based on the estimated distribution curve fit

This value only appears if a lower design limit was given

Percent > High Limit

Sample and estimated percentages found to be greater than any specified upper design limit This value only appears if an upper design limit was given

Total % Out of Spec

These columns contain the sum of the previous two values It is only shown if upper and/or lower design limits were given

95. 0% Confidence Interval on the Sample % Out of Spec

This is the 95 0 percent confidence interval for the sample percent out of spec value Different simulation samples from the same model will produce different percent out of spec values If you keep generating samples, using a different random number seed each time, 95 0 percent of the time the value you get for the percent out of spec will fall in this range.

Low

The sample low is the lowest value produced during this set of simulations The estimated low is the low value on the estimated distribution curve corresponding to the range setting (noted at the bottom of the report) For example, if you have the range set to 95, the estimated low value will be the value at the 0 025 cumulative probabilities on the estimated distribution curve

High

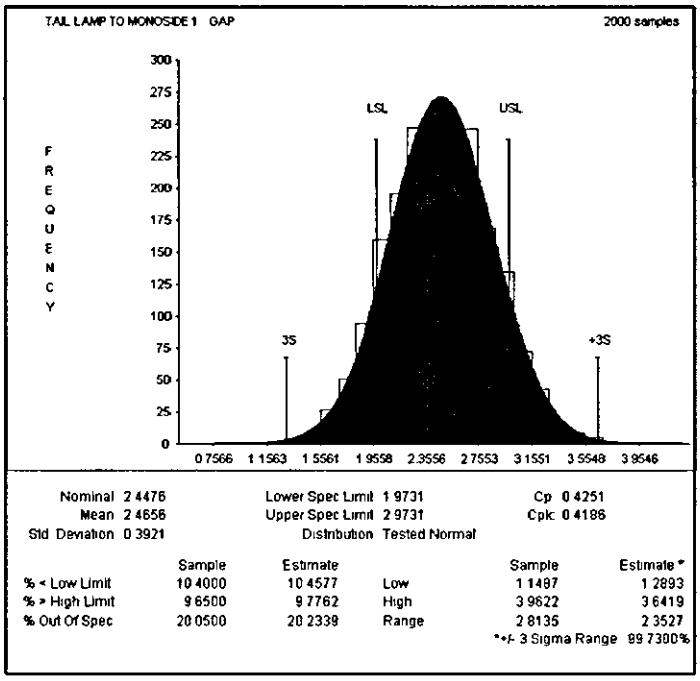
The sample high is the highest value produced during this set of simulations The estimated high is the high value on the estimated distribution curve corresponding to the range setting (noted at the bottom of the report) For example, if you have the range set to 95, the estimated high value will be the value at the 0 975 cumulative probability on the estimated distribution curve

Range

The range for each column is the high minus the low

Est Range

The estimated range is the value the range is set at based on fitting a curve to the simulated data The range is used to calculate the numbers in the estimated column



Displays the standard deviation value (e. g -3S, +3S) when the estimated range corresponds to an exact standard deviation value (e g 99 7300% = 6 standard deviations) Otherwise, URV and LRV (Upper and Lower Range Value) display The standard deviation value and the URV/ LRV designations only appear when the Analysis field in the **Report Params** tab is set to Actual or Normal Red areas indicate that the measurement has exceeded the upper or lower specification limit

Figure 1 Process chart

HLM Contributors Report

The HLM Contributors report will tell you what tolerances are contributing most significantly to the variation in a measurement This report gives you a listing in decreasing order of all the variables contributing more than a specified cut-off percentage to the HLM variation There is also a notation of the number of variables that contributed less than the cut-off percentage but more than zero

If no significant Interactive Effects are present, you will be able to reduce any undesirable variation in the measurement by reducing the variation in the tolerances showing the largest contributions Also, tolerances with low contributions may be candidates for relaxing their variation restrictions

You can check for the presence of significant interactive effects by comparing the HLM main effect variation shown on the HLM Contributors report to the square of the standard deviation shown on the process report or the variation value available on the custom reports If they are within 10% of each other there are no significant interactions affecting the results
The information on the HLM Contributors report is

HLM Nominal

The nominal value of the measurement calculated using the 50th percentile values of the tolerances.

HLM Variance
The HLM variance is equal to the sum of the measurement variation attributed to each tolerance variation You can check for the presence of significant interactive effects by comparing the HLM variance to the square of the standard deviation shown on the process report If they are within 10% of each other there are no significant interactions affecting the results

Tolerances
The names of all the tolerances in the model that have an effect greater than the HLM cut-off percentage on the variation in the measurement being analyzed They are only displayed if you have chosen to display variable names in the display parameters utility

Description
The descriptive comments that are in your model for each tolerance They will be 40 characters long if you have chosen to display variable names and 50 characters long otherwise

% Effect
Percent effect is the percent of the HLM variation due to the variation of an individual tolerance

All of the tolerances that contribute more than the cut-off percentage shown at the bottom of the report are displayed The length of the report will be dependent upon the cut-off percentage and the number of contributors

Appendix 8

Different methods of constructing tolerance zones in CAD systems

Parametric dimensioning and tolerancing: Parametric dimensioning and tolerancing (PD&T) is used as a control on scalar related dimensions such as length or angle Each linear dimension is associated with a fixed nominal value and a variable component The variable component specifies a band having an upper and lower limit in which the nominal scalar value must lie to be within an allowable tolerance. Angular, which includes vectors, are normally related to a radial tolerance referenced from an axis system Vector tolerances are used to quantify the direction, size and position of a component relative to an axis system A shortfall of parametric tolerancing is its inability to control geometric form and its lack of reference to datum systems This shortfall is met by geometric tolerances. An example of PD&T can be seen in the figure below

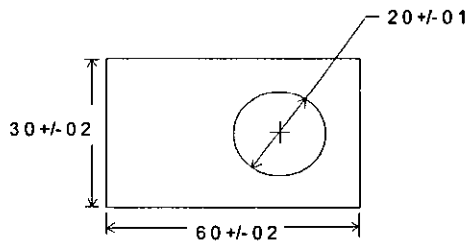


Figure 1. Simple example of parametric dimensioning and tolerancing.

Geometrical dimensioning and tolerancing: GD&T is a precise mathematical language that describes the size, form, orientation, and location of part features. It's also a design-dimensioning philosophy that encourages designers to define a part based on how it functions in the final product

Through the use of functional dimensioning, tolerances are assigned to a part by the designer based on the part's functional requirements, often resulting in a larger tolerance for manufacturing This eliminates problems that result when a designer assigns arbitrary, or too tight, tolerances to a part in a drawing because he or she doesn't know how to determine a reasonable, functional tolerance

GD&T is used on an individual or a pattern of features for the control of

Form; controls the straightness, flatness, circularity and cylintricity of individual features with no reference to a datum scheme

Profile; controls profile of a line or a surface of a feature with or without reference to a datum scheme or other features

Orientation; controls angularity, perpedicularity and parallelism of a feature with reference to a datum scheme and related features.

Location; controls position, concentricity and symmetry of a feature with reference to a datum scheme or related features

Run out; the allowable error between two or more features with regard to concentricity, perpendicularly, and alignment Also control roundness, straightness, flatness, angularity and parallelism of individual features

A description of these tolerances with their characteristics and symbols is given in the figure below.

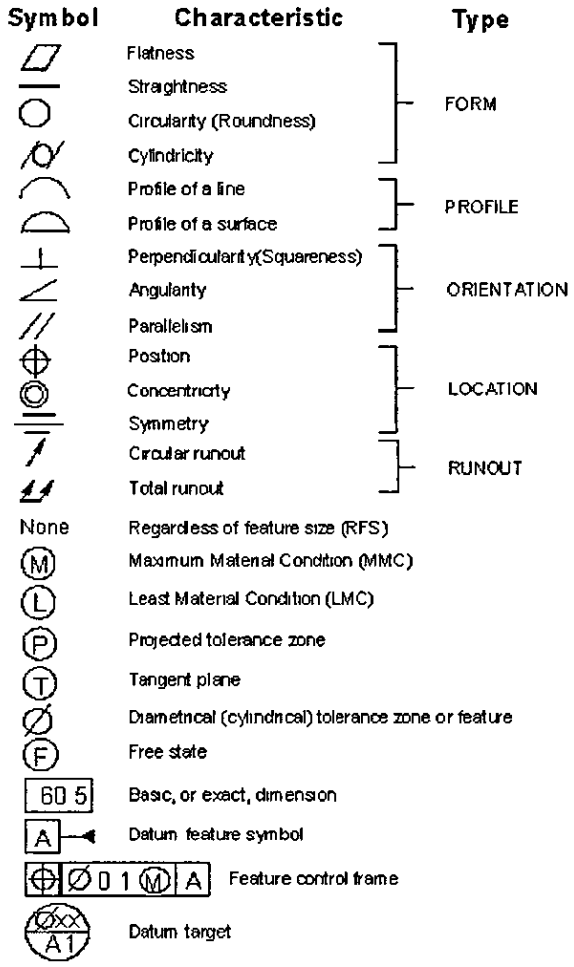


Figure 2. Geometric characteristics and symbols.

Symbols and modifiers are communicated through a feature control frame The control frame is split into different sections each containing data on geometric symbol, tolerance value, any material modifier and datum references An example of a feature control frame is given in figure 3

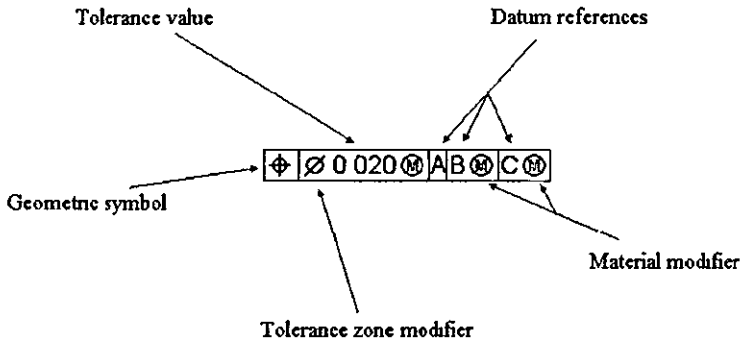


Figure 3 Example GD&T feature control frame

Kinematic dimensioning and tolerancing: The main concept of kinematic tolerance analysis can be attributed to the research work of Professor Kenneth W Chase of Brigham Young University, Utah. Kinematic dimensioning and tolerancing (KD&T) predicts variation emerging form small rigid body displacements that occur in static assemblies via a statistical solution Variation in mechanisms can also be modelled by describing the motion of a single mechanism with respect to time

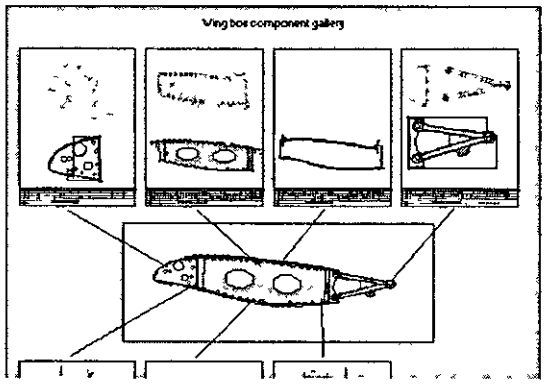
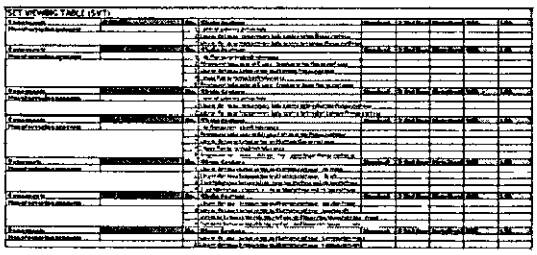
Variation modelling can be made in 2D and 3D assemblies using vector loop based analysis Chase, Magleby and Gao (1997) suggest that in this type of analysis all three sources of variation can be accommodated, i e , parametric, geometric and kinematic Kinematic variation analysis tends to be used on mechanical based assemblies where the interactions of moving parts and the effect of variation on these parts is important Kinematic analysis has been undertaken on items such as automotive drive train assemblies and computer hardware mechanical devices

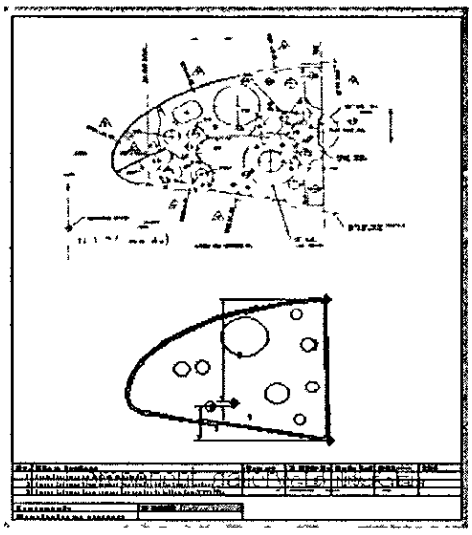
Appendix 9

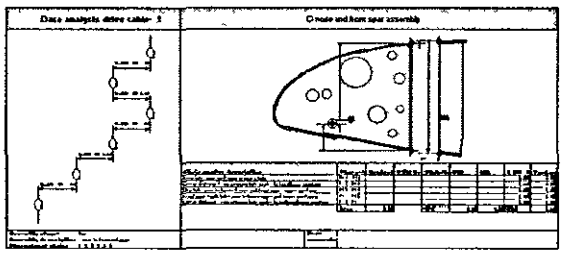
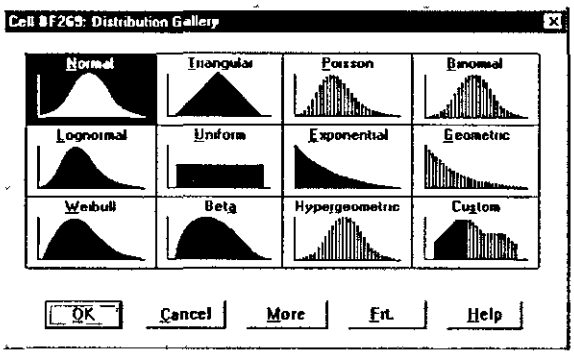
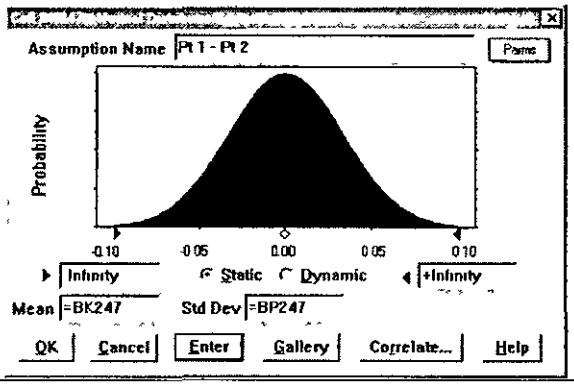
Parametric Variation Assembly Analysis Tool

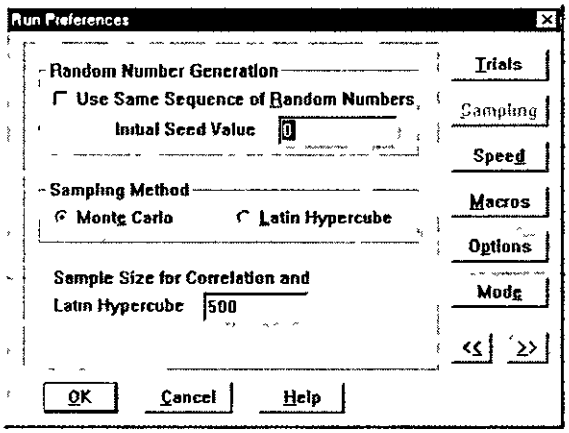
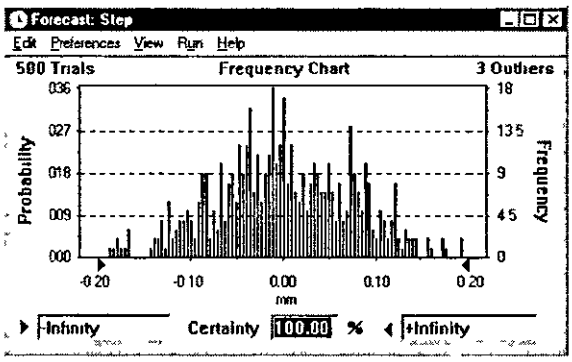
User manual

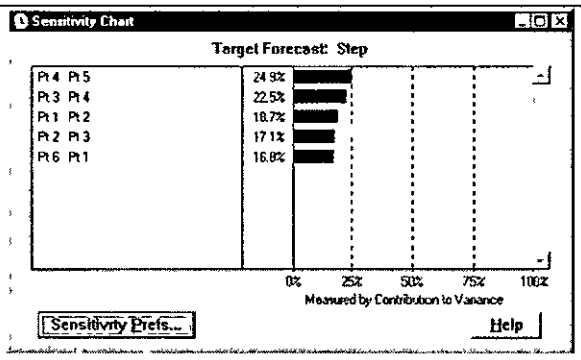
The PVA application tool user process is presented in the following table.

Step	Process description	Instruction/comment
1	Start new assembly tolerance analysis session	Start MS Excel via the Crystal Ball program icon The Excel environment will automatically be started
2	The application will open at the main banner page	
3	At this point, if the user is new to the application they may view the instruction set Alternatively, if they have used the application before they can continue to the next step	The instruction set may be accessed directly below the banner page
4	The new user can read the instruction set to understand how to use the application This may be printed off for reference if necessary	The instruction set is prepared in the default print setting for Excel The user may use the FILE, PRINT, OK options to print contents
5	Go to the application analysis area, and in the first instance to the wing box component gallery (WBCG), shown below in part 	In the first instance the used should go to the WBCG This can be done by pressing F5 and selecting 'componenet_gallery' from the list
6	User can now i Create new wing box configuration database ii Call up a previously saved wing box configuration database Previously defined databases can be recovered from the set database These can then be transferred to the set viewing table (SVT), shown below, and finally to the WBCG via the available macros 	If the user has not used the application before, they must complete the appropriate component tables in the WBCG If the user has used the application previously and has saved configuration data then this may be recalled
7	The user can go to the D nose data table.	The user can find the appropriate table by

		pressing the F5 key and selecting 'Component_gallery_D_Nose'.
8	The user can then define the D nose: i Manufacturing process type ii Nominal dimension of each chain (Nominal) iii 3 standard deviation tolerance (3 Std Dev) iv Variation distribution type v Upper specification limit (USL) vi Lower specification limit (LSL). 	Define key feature definition
9	The user can go to the front spar details	Part parameter definition
10	Define front spar details {As for step 8}	
11	The user can go to the A frame details	Part parameter definition
12	Define A frame details {As for step 8}	
13	The user can go to the rear spar details	Part parameter definition
14	Define rear spar details. {As for step 8}	
15	The user can go to the rib details	Part parameter definition
16	Define rib details {As for step 8}	
17	The user can go to the top and bottom skin details	Part parameter definition
18	Define top and bottom skin details {As for step 8}	
19	When all the appropriate data tables in the WBCG have been filled, this section is then complete	
20	The user can then save the data configuration to the SVT via the macro command	The user can save the data in the WBCG to the SVT by using the 'Copy data from component gallery to SVT' macro in the WBCG window
21	The user can then save the wing box data by transferring the data from the SVT to one of the available sets	The user can save the data from the SVT to an available set (set 1 for example) by using the 'Put data into set 1'
22	When all the required data has been input to the WBCG (and saved if required) the user will then need to down load this information to the appropriate data driver tables (DDT) This	The user can transfer the appropriate data (data for DDT1, D nose to front

	operation will need to be performed for each of the required analysis stage	spar, for example) by using the 'Update DDT1 from component gallery' macro
23	When the data is transferred to the DDT tables, worse case (WC) and root sum square (RSS) levels of variation are calculated automatically  If further analysis is required, i e full statistical analysis, they are required to undertake additional preparation within the appropriate DDT Each of the nominal dimensional values in the DDT table will need to be assigned a statistical distribution The current assigned distribution can be investigated by selecting the 'Define assumption' function form the Crystal Ball menu bar There are ranges of distribution type's available (see below) including the 'Fit' option which allows the user to create a best fit from a sample of data  When a distribution type is selected the user will need to assign the parameters if they have not already been extracted from the DDT The default setting is always a normal distribution (see example below) with the mean and standard deviation extracted directly from the DDT If the distribution is one other than normal, then it should be chosen from the distribution gallery and the parameters edited Each type of distribution is set by a number of different parameters, and the Crystal Ball manual should be consulted for an explanation on how these are correctly defined  	Transfer data to DDT tables

24	The output from the WC and RSS calculations can be observed in the relevant DDT	
25	When all distribution types and their parameters have been defined, the user will then need to select the simulation preferences These are defined by selecting the 'Run preferences' option from the Crystal Ball menu bar The user can then select and input a number of different simulation criterion and the sampling method (i e Monte Carlo or Latin Hypercube) see figure below 	Simulation parameters.
26	Part of the 'Run preferences' set up will require the user to input the number of simulations required The most appropriate number will need to be a balance between not to high – leading to excessive simulation time, and not to low – resulting in poor distribution and statistical definition	Simulation parameters
27	The user can now run the simulation for the defined criterion The resulting output is a frequency distribution, an example of which can be seen below 	Frequency charts
28	Once a simulation has been undertaken, the user can analyze the resulting output The user also has the option to run a sensitivity analysis	Sensitivity charts
29	The user can now run a sensitivity analysis This evaluates all the sources of variance and determines what contribution each element has made to the total measured variance An example of such a sensitivity chart is given below	Sensitivity charts

		
30	Now the simulation analysis cycle is almost complete The user now has the option to save the simulation output to a report generated in the excel application environment The user can do this by selecting the 'Create report' function from the Crystal Ball menu bar The user will be offered a range of options regarding what and what not, to include in the report Once the report has been generated, the user may than view the report.	Report generation
31	When the user has viewed the report, they may then save it in an Excel file format for future reference	Save function
32	Once the simulation report is saved it may be printed out in part or in full at ant time If the user does not save the report, and they do not print out the report in option 33, they will loose all current simulation data	Print functions
33	The user may print out a report by using the FILE, PRINT, and ALL options	
34	User now has the option to revise all or some of the above parameters and undertake further simulation analysis Or, they can exit out of the application, saving all changes if desired	Save analysis parameters
35	Exit the application.	Exit application

Appendix 10

Publication Review

Tolerance design: ***A handbook for developing optimal specifications.***

By C. M. Creveling (Addison Wesley), (Pp. 423), 1997.

This is an excellent book for industrialists and academics alike looking for a comprehensive introduction to tolerancing techniques for the control of component and assembly variation The book follows a sound framework containing eighteen concise chapters bringing together the study of tolerance design for both products and processes. The author does not assume the reader has a specialised background in this area but engages the subject in enough details to be informative to the more experienced engineer

The book has been written in three sections Section one includes Chapters 1 to 3 and introduces the concept of tolerance design and application It includes an overview of product design and reliability, and goes on to introduce statistics and data analysis for tolerance design in the quality engineering context Section two includes Chapters 4 to 10 and is designed to cover traditional tolerance design and analysis It introduces the basics of tolerance and sensitivity analysis traditionally practised in the West, and then proceeds to review some related advanced topics This section concludes with Chapter 10, which highlights the strengths and weaknesses of the six traditional tolerancing methodologies, suggesting none of which are capable of dealing with multidisciplinary variation functions (diverse systems and sub-system elements) Section three incorporates Chapters 11 to 17, which comprehensively outlines Genichi Taguchi's approach to tolerance design and analysis This represents the Eastern approach, which includes an introduction to the quality-loss function approach to analytical and experimental tolerance analysis Section four, the final section, contains Chapter 18 The section comprehensively outlines five assembly tolerance analysis cases, which have been designed to reinforce the techniques and methods previously outlines in sections one to three One of the case studies utilises a computer based tolerance analysis technique to investigate variability levels in a drive module of a high volume copy machine

This book is broad in scope and will be a useful text both as a teaching aid for engineering students and as a reference handbook for industrial applications The subject area of tolerance design is covered comprehensively and is supported with comprehensively worked examples This text is therefore a good introduction to the subject of tolerance design and analysis

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Department of Manufacturing Engineering
Loughborough University

Appendix 11

Stage I – Valisys measurement report

Valisys Results File Formatter Ver 5.3.1 1-19-1998 11:50:27

**** RESULTS FILE ****

FILE: PHASEI_PANEL1.res
FORMATTER: fmtrcmpl.vcl
DATE AND TIME OF REPORT: 1-19-1998 11:50:27

UNITS: MILLIMETERS

ANALYSIS MODE SUMMARY

TOL	LOS	AXIS	PLANAR	XTRAP
7	AVG	LS	BF	YES
10	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
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12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
12	AVG	LS	BF	YES
9	AVG	LS	BF	YES
6	AVG	LS	BF	YES
11	AVG	LS	BF	YES
4	AVG	LS	BF	YES
13	AVG	LS	BF	YES
14	AVG	LS	BF	YES
15	AVG	LS	BF	YES
16	AVG	LS	BF	YES

TOL NUM FEA NUM	DESCRIPTION X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
7	DIA702-7					PASSED
	7 DIA6.000+/-0.09					
702	DATUM B			6.09	0.09	0.09
				6 00	-0 09	0.01

Valisys Results File Formatter Ver 5.3.1 1-19-1998 11:50:27

TOL NUM FEA NUM	DESCRIPTION X Y Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
10	DIA703-10			PASSED
	10 DIA6 000+/-0.09			
703	DATUM C	6 08	0.09	0.08
		6.00	-0.09	0.00
12	DIA731-12			PASSED
	12 DIA6.000+/-0.09			
704	HOLE 1	6.08	0.09	0.08
		6.00	-0 09	0.01
12	DIA731-12			PASSED
	12 DIA6 000+/-0.09			
705	HOLE 2	6 08	0.09	0.08
		6.00	-0.09	0 01
12	DIA731-12			PASSED
	12 DIA6.000+/-0.09			
706	HOLE 3	6.08	0.09	0.08
		6.00	-0.09	0.01
12	DIA731-12			PASSED
	12 DIA6.000+/-0 09			
707	HOLE 4	6.08	0.09	0.08
		6.00	-0.09	0.01
12	DIA731-12			PASSED
	12 DIA6.000+/-0.09			
708	HOLE 5	6.08	0 09	0.08
		6 00	-0 09	0.01
12	DIA731-12			PASSED
	12 DIA6.000+/-0.09			
709	HOLE 6	6.08	0.09	0.08
		6.00	-0.09	0.01
12	DIA731-12			PASSED
	12 DIA6.000+/-0.09			
710	HOLE 7	6.08	0.09	0.08
		6.00	-0.09	0.01
12	DIA731-12			PASSED
	12 DIA6 000+/-0.09			
711	HOLE 8	6.08	0.09	0.08
		6.00	-0.09	0.01

Valisys Results File Formatter Ver 5.3.1 1-19-1998 11:50:27

TOL NUM FEA NUM	DESCRIPTION X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
12	DIA731-12					PASSED
	12 DIA6.000+/-0.09					
712	HOLE 9			6.08	0.09	0.08
				6.00	-0.09	0.01
12	DIA731-12					PASSED
	12 DIA6.000+/-0.09					
713	HOLE 10			6.08	0.09	0.08
				6.00	-0.09	0.01
12	DIA731-12					PASSED
	12 DIA6.000+/-0.09					
714	HOLE 11			6 08	0.09	0.08
				6.00	-0.09	0.01
12	DIA731-12					PASSED
	12 DIA6.000+/-0.09					
715	HOLE 12			6 08	0.09	0.08
				6.00	-0.09	0.01
12	DIA731-12					PASSED
	12 DIA6.000+/-0.09					
716	HOLE 13			6.08	0.09	0.08
				6.00	-0.09	0.01
12	DIA731-12					PASSED
	12 DIA6.000+/-0 09					
717	HOLE 14			6.08	0.09	0.08
				6.00	-0 09	0.01
12	DIA731-12					PASSED
	12 DIA6 000+/-0.09					
718	HOLE 15			6.08	0.09	0.08
				6.00	-0 09	0.01
12	DIA731-12					PASSED
	12 DIA6.000+/-0.09					
719	HOLE 16			6.08	0.09	0.08
				6.00	-0 09	0.02
12	DIA731-12					PASSED
	12 DIA6.000+/-0.09					
720	HOLE 17			6.09	0.09	0.09
				6.00	-0.09	0.01

Valisys Results File Formatter Ver 5.3.1 1-19-1998 11 50:27

```
TOL
NUM     DESCRIPTION
FEA                                                  ACTUAL/    TOL/       DEVIATION/
NUM          X          Y          Z                 NOMINAL    TOL+BONUS    SPREAD
-----------------------------------------------------------------------------------
 12 DIA731-12                                                                PASSED
        12 DIA6.000+/-0.09
721 HOLE 18                                            6.09      0 09       0.09
                                                       6.00     -0.09       0.01
-----------------------------------------------------------------------------------
  9 POS703-9                                                                 FAILED
    9 POS|DIA0.025(M)|A|B(M) POSITION OF 1 ROUND HOLE
                                                                  0.02
                                                                  0.20     121.73
703  DATUM C
     D:  -250 00    250.00      0.00
     A:  -249.96    249.97      0.00                              0.20     121.73
-----------------------------------------------------------------------------------
  6 POS702-6                                                                 PASSED
    6 POS|DIA0.025(M)|A POSITION OF 1 ROUND HOLE
                                                                  0.02
                                                                  0.20       0 00
702  DATUM B
     D:   124.98   -125.00      0.00
     A:   124 97   -124.99     -0.00                              0.20       0.00
-----------------------------------------------------------------------------------
 11 POS731-11                                                                FAILED
    11 POS|DIA0.025(M)|A|B(M)|C(M) POSITION OF 18 ROUND HOLE
                                                                  0 02
                                                                  0.20     121.73
704  HOLE 1
     D:    35 36     35.36      0.00
     A:    35.34     35.35     -0.00                              0.20     121.63
705  HOLE 2
     D     70.71     70.71     -6.00
     A:    70.69     70.70     -6.00                              0.19     121.56
706  HOLE 3
     D:   106.07    106.07      0.00
     A:   106.05    106.05     -0.00                              0.19     121.66
707  HOLE 4
     D:   141.42    141.42     -6.00
     A:   141.40    141.42     -6.00                              0.20     121.61
708  HOLE 5
     D:   176.78    176 78      0.00
     A:   176.76    176 76     -0.00                              0 20     121.65
709  HOLE 6
     D:   212 13    141.42      0 00
     A:   212 11    141 40      0 00                              0 20     121.68
710  HOLE 7
     D:   247.49    106.07      0.00
     A:   247.46    106.05      0 00                              0.20     121.64
711  HOLE 8
     D·   282.84     70.71      0.00
```

Valisys Results File Formatter Ver 5.3.1 1-19-1998 11:50:27

TOL NUM FEA NUM	DESCRIPTION	X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
	A:	282.81	70.70	0.00		0.20	121 69
712	HOLE 9						
	D:	318.20	35.36	0.00			
	A:	318.16	35.35	0.00		0.20	121.69
713	HOLE 10						
	D:	318.20	-35.36	0.00			
	A:	318.16	-35.35	0.00		0.20	121.69
714	HOLE 11						
	D:	282.84	-70.71	0.00			
	A:	282.80	-70.71	0 00		0.20	121.73
715	HOLE 12						
	D:	247.49	-106.07	-6.00			
	A:	247.45	-106.07	-6.00		0.20	121.65
716	HOLE 13						
	D·	212.13	-141.42	0.00			
	A.	212.09	-141.41	0.00		0.20	121 71
717	HOLE 14						
	D	176.78	-176.78	0 00			
	A:	176 75	-176 75	0 00		0.20	121.60
718	HOLE 15						
	D:	141 42	-141 42	-6.00			
	A:	141.38	-141.41	-6.00		0.20	121.60
719	HOLE 16						
	D:	106.07	-106.07	0.00			
	A·	106.04	-106.06	0.00		0.20	121 65
720	HOLE 17						
	D.	70 71	-70 71	-6.00			
	A:	70.69	-70.71	-6.00		0.20	121.60
721	HOLE 18						
	D:	35 36	-35.36	-6.00			
	A:	35.33	-35.36	-6.00		0.20	121.62

---

4 FLT701-4 PASSED
4 FLT|0.2
701 DATUM A 0.20 0 04

---

13 PER722-13 FAILED
13 PER|0.02|A PERPENDICULARITY-PLN OF 1 PLANE
722 EDGE 1 0.02 0.03

---

14 PER723-14 FAILED
14 PER|0 02|A PERPENDICULARITY-PLN OF 1 PLANE
723 EDGE 2 0.02 0.09

Valisys Results File Formatter Ver 5.3.1 1-19-1998 11:50:27

TOL NUM FEA NUM	DESCRIPTION X Y Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
15	PER724-15			FAILED
	15 PER|0.02|A PERPENDICULARITY-PLN OF 1 PLANE			
724	EDGE 3		0.02	0.13
16	PER725-16			FAILED
	16 PER|0.02|A PERPENDICULARITY-PLN OF 1 PLANE			
725	EDGE 4		0.02	0.22

Valisys Results File Formatter Ver 5.3.1 1-19-1998 11:50:27

V:INSPECT VERSION	5.3.1_SA	
PART NAME	/home/catusr/PHASEI_PANEL1_INS.prt	PHASEI_PANEL
PROCESS NO.	903	
PROCESS NAME	PHASEI_PANEL1_INS	
DATE	Thr Jan 15 9:28:06 1998	

Valisys Results File Formatter Ver 5.3.1 1-19-1998 11:50:27

SUMMARY OF GAUGE ANALYSIS

TOL	DESCRIPTION	STATUS	REQT	FEATURES
7	SIZE DIAM	PASSED		702
10	SIZE DIAM	PASSED		703
12	SIZE DIAM	PASSED		704
12	SIZE DIAM	PASSED		705
12	SIZE DIAM	PASSED		706
12	SIZE DIAM	PASSED		707
12	SIZE DIAM	PASSED		708
12	SIZE DIAM	PASSED		709
12	SIZE DIAM	PASSED		710
12	SIZE DIAM	PASSED		711
12	SIZE DIAM	PASSED		712
12	SIZE DIAM	PASSED		713
12	SIZE DIAM	PASSED		714
12	SIZE DIAM	PASSED		715
12	SIZE DIAM	PASSED		716
12	SIZE DIAM	PASSED		717
12	SIZE DIAM	PASSED		718
12	SIZE DIAM	PASSED		719
12	SIZE DIAM	PASSED		720
12	SIZE DIAM	PASSED		721
9	POSITION	FAILED	<-SEP	703
6	POSITION	PASSED	SEP	702
11	POSITION	FAILED	<-SEP	704, 705, 706, 707, 708, 709, 710, 711, 712, 713 714, 715, 716, 717, 718 719, 720, 721
4	FLATNESS	PASSED		701
13	PERPENDICULARITY	FAILED	<-	722
14	PERPENDICULARITY	FAILED	<-	723
15	PERPENDICULARITY	FAILED	<-	724
16	PERPENDICULARITY	FAILED	<-	725

Valisys Results File Formatter Ver 5.3.1 1-19-1998 21:50:41

**** RESULTS FILE ****

FILE: PHASEI_PANEL2_INS.res
FORMATTER: fmtrcmpl.vcl
DATE AND TIME OF REPORT: 1-19-1998 21:50:41

UNITS: MILLIMETERS

ANALYSIS MODE SUMMARY

TOL	LOS	AXIS	PLANAR	XTRAP
100007	AVG	LS	BF	YES
100010	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100012	AVG	LS	BF	YES
100009	AVG	LS	BF	YES
100006	AVG	LS	BF	YES
100011	AVG	LS	BF	YES
100004	AVG	LS	BF	YES
100013	AVG	LS	BF	YES
100014	AVG	LS	BF	YES
100015	AVG	LS	BF	YES
100016	AVG	LS	BF	YES

TOL NUM FEA NUM	DESCRIPTION X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
100007 DIA702-7						PASSED
100007 DIA6.000+/-0.09						
100702 DATUM B				6.09	0 09	0.09
				6.00	-0.09	0.01

Valisys Results File Formatter Ver 5.3.1 1-19-1998 21:50:41

TOL NUM FEA NUM	DESCRIPTION X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
100010	DIA703-10					PASSED
	100010 DIA6.000+/-0 09					
100703	DATUM C			6.08	0.09	0 08
				6.00	-0.09	0 00
100012	DIA731-12					PASSED
	100012 DIA6.000+/-0.09					
100704	HOLE 1			6.08	0.09	0.08
				6.00	-0.09	0.01
100012	DIA731-12					PASSED
	100012 DIA6.000+/-0 09					
100705	HOLE 2			6.08	0.09	0.08
				6.00	-0.09	0.01
100012	DIA731-12					PASSED
	100012 DIA6 000+/-0.09					
100706	HOLE 3			6.08	0.09	0.08
				6.00	-0.09	0.01
100012	DIA731-12					PASSED
	100012 DIA6.000+/-0.09					
100707	HOLE 4			6 08	0.09	0.08
				6.00	-0.09	0.01
100012	DIA731-12					PASSED
	100012 DIA6.000+/-0.09					
100708	HOLE 5			6.08	0.09	0.08
				6.00	-0 09	0.01
100012	DIA731-12					PASSED
	100012 DIA6.000+/-0.09					
100709	HOLE 6			6.08	0.09	0.08
				6.00	-0.09	0.01
100012	DIA731-12					PASSED
	100012 DIA6.000+/-0.09					
100710	HOLE 7			6.08	0.09	0.08
				6 00	-0.09	0.01
100012	DIA731-12					PASSED
	100012 DIA6.000+/-0.09					
100711	HOLE 8			6 08	0.09	0.08
				6 00	-0.09	0.01

Valisys Results File Formatter Ver 5.3.1 1-19-1998 21 50:41

TOL NUM FEA NUM	DESCRIPTION X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
100012 DIA731-12						PASSED
100012 DIA6.000+/-0 09						
100712 HOLE 9				6.08	0.09	0.08
				6.00	-0.09	0.01
100012 DIA731-12						PASSED
100012 DIA6.000+/-0.09						
100713 HOLE 10				6.08	0.09	0.08
				6.00	-0.09	0.01
100012 DIA731-12						PASSED
100012 DIA6.000+/-0.09						
100714 HOLE 11				6.08	0.09	0.08
				6.00	-0.09	0.01
100012 DIA731-12						PASSED
100012 DIA6.000+/-0.09						
100715 HOLE 12				6.08	0.09	0.08
				6.00	-0.09	0.01
100012 DIA731-12						PASSED
100012 DIA6 000+/-0.09						
100716 HOLE 13				6.08	0 09	0.08
				6.00	-0.09	0.01
100012 DIA731-12						PASSED
100012 DIA6.000+/-0.09						
100717 HOLE 14				6.08	0.09	0.08
				6 00	-0.09	0.01
100012 DIA731-12						PASSED
100012 DIA6.000+/-0.09						
100718 HOLE 15				6.08	0.09	0.08
				6.00	-0.09	0.01
100012 DIA731-12						PASSED
100012 DIA6.000+/-0.09						
100719 HOLE 16				6.08	0.09	0.08
				6.00	-0.09	0 02
100012 DIA731-12						PASSED
100012 DIA6.000+/-0.09						
100720 HOLE 17				6 09	0.09	0 09
				6 00	-0 09	0.01

Valisys Results File Formatter Ver 5.3.1 1-19-1998 21·50:41

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TOL
NUM     DESCRIPTION
FEA                                                ACTUAL/    TOL/       DEVIATION/
NUM          X          Y          Z               NOMINAL    TOL+BONUS    SPREAD
-----------------------------------------------------------------------------
100012 DIA731-12                                                          PASSED
     100012 DIA6.000+/-0.09
100721 HOLE 18                                        6.09      0.09       0.09
                                                      6.00     -0.09       0.01
-----------------------------------------------------------------------------
100009 POS703-9                                                           FAILED
    100009 POS|DIA0 025(M)|A|B(M) POSITION OF 1 ROUND HOLE
                                                                0.02
                                                                0.20     121.73
100703  DATUM C
     D:  -250.00    250.00      0.00
     A:  -249.96    249.97      0.00                           0.20     121.73
-----------------------------------------------------------------------------
100006 POS702-6                                                           PASSED
    100006 POS|DIA0.025(M)|A POSITION OF 1 ROUND HOLE
                                                                0.02
                                                                0.20       0.00
100702  DATUM B
     D.   124.98   -125.00      0 00
     A:   124.97   -124.99     -0.00                           0.20       0.00
-----------------------------------------------------------------------------
100011 POS731-11                                                          FAILED
    100011 POS|DIA0.025(M)|A|B(M)|C(M) POSITION OF 18 ROUND HOLE
                                                                0.02
                                                                0.20     121.73
100704  HOLE 1
     D:    35.36     35.36      0.00
     A:    35.34     35.35     -0 00                           0.20     121.63
100705  HOLE 2
     D:    70.71     70.71     -6.00
     A:    70.69     70.70     -6 00                           0.19     121.56
100706  HOLE 3
     D.   106.07    106 07      0.00
     A:   106.05    106 05     -0.00                           0.19     121.66
100707  HOLE 4
     D:   141.42    141 42     -6.00
     A:   141.40    141 42     -6.00                           0.20     121.61
100708  HOLE 5
     D:   176.78    176.78      0.00
     A:   176.76    176.76     -0.00                           0.20     121.65
100709  HOLE 6
     D:   212.13    141.42      0 00
     A:   212.11    141.40      0 00                           0.20     121 68
100710  HOLE 7
     D:   247.49    106.07      0.00
     A:   247.46    106.05      0 00                           0.20     121 64
100711  HOLE 8
     D:   282.84     70.71      0.00
```

Valisys Results File Formatter Ver 5.3.1 1-19-1998 21:50:41

TOL NUM FEA NUM	DESCRIPTION	X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
	A:	282.81	70.70	0.00		0.20	121.69
100712	HOLE 9						
	D:	318 20	35.36	0.00			
	A:	318 16	35.35	0 00		0.20	121 69
100713	HOLE 10						
	D:	318.20	-35.36	0.00			
	A:	318.16	-35.35	0.00		0.20	121.69
100714	HOLE 11						
	D:	282.84	-70.71	0.00			
	A:	282.80	-70.71	0.00		0.20	121.73
100715	HOLE 12						
	D:	247.49	-106.07	-6.00			
	A·	247.45	-106.07	-6.00		0.20	121.65
100716	HOLE 13						
	D.	212.13	-141.42	0.00			
	A:	212.09	-141.41	0.00		0.20	121.71
100717	HOLE 14						
	D:	176.78	-176.78	0.00			
	A:	176.75	-176.75	0.00		0.20	121.60
100718	HOLE 15						
	D:	141.42	-141.42	-6.00			
	A:	141.38	-141.41	-6.00		0.20	121.60
100719	HOLE 16						
	D:	106.07	-106.07	0.00			
	A.	106.04	-106.06	0.00		0.20	121.65
100720	HOLE 17						
	D.	70.71	-70.71	-6.00			
	A:	70.69	-70.71	-6.00		0.20	121.60
100721	HOLE 18						
	D:	35.36	-35.36	-6.00			
	A:	35.33	-35.36	-6.00		0.20	121.62

100004 FLT701-4 PASSED
100004 FLT|0 2
100701 DATUM A 0.20 0.04

100013 PER722-13 FAILED
100013 PER|0 02|A PERPENDICULARITY-PLN OF 1 PLANE
100722 EDGE 1 0 02 0.03

100014 PER723-14 FAILED
100014 PER|0.02|A PERPENDICULARITY-PLN OF 1 PLANE
100723 EDGE 2 0.02 0.09

Valisys Results File Formatter Ver 5.3.1 1-19-1998 21:50:41

TOL NUM FEA NUM	DESCRIPTION X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
100015 PER724-15						FAILED
100015 PER|0.02|A PERPENDICULARITY-PLN OF 1 PLANE						
100724 EDGE 3					0.02	0.13
100016 PER725-16						FAILED
100016 PER|0.02|A PERPENDICULARITY-PLN OF 1 PLANE						
100725 EDGE 4					0.02	0.22

Valisys Results File Formatter Ver 5.3.1 1-19-1998 21:50:41

V:INSPECT VERSION	5.3.1_SA	
PART NAME	/home/catusr/PHASEI_PANEL1_INS.prt	PHASEI_PANEL
PROCESS NO.	903	
PROCESS NAME	PHASEI_PANEL1_INS	
DATE	Thr Jan 15 9:28:06 1998	

Valisys Results File Formatter Ver 5.3 1 1-19-1998 21:50:41

SUMMARY OF GAUGE ANALYSIS

TOL	DESCRIPTION	STATUS	REQT	FEATURES
100007	SIZE DIAM	PASSED		100702
100010	SIZE DIAM	PASSED		100703
100012	SIZE DIAM	PASSED		100704
100012	SIZE DIAM	PASSED		100705
100012	SIZE DIAM	PASSED		100706
100012	SIZE DIAM	PASSED		100707
100012	SIZE DIAM	PASSED		100708
100012	SIZE DIAM	PASSED		100709
100012	SIZE DIAM	PASSED		100710
100012	SIZE DIAM	PASSED		100711
100012	SIZE DIAM	PASSED		100712
100012	SIZE DIAM	PASSED		100713
100012	SIZE DIAM	PASSED		100714
100012	SIZE DIAM	PASSED		100715
100012	SIZE DIAM	PASSED		100716
100012	SIZE DIAM	PASSED		100717
100012	SIZE DIAM	PASSED		100718
100012	SIZE DIAM	PASSED		100719
100012	SIZE DIAM	PASSED		100720
100012	SIZE DIAM	PASSED		100721
100009	POSITION	FAILED	<-SEP	100703
100006	POSITION	PASSED	SEP	100702
100011	POSITION	FAILED	<-SEP	100704, 100705, 100706, 100707, 10070
8,				
				100709, 100710, 100711, 100712, 100713
				100714, 100715, 100716, 100717, 100718
				100719, 100720, 100721
100004	FLATNESS	PASSED		100701
100013	PERPENDICULARITY	FAILED	<-	100722
100014	PERPENDICULARITY	FAILED	<-	100723
100015	PERPENDICULARITY	FAILED	<-	100724
100016	PERPENDICULARITY	FAILED	<-	100725

Valisys Results File Formatter Ver 5.3.1 1-19-1998 12:01:48

**** RESULTS FILE ****

FILE: PHASEI_SUBSTRUCTURE_INS.res
FORMATTER: fmtrcmpl.vcl
DATE AND TIME OF REPORT: 1-19-1998 12:01:48

UNITS MILLIMETERS

ANALYSIS MODE SUMMARY

TOL	LOS	AXIS	PLANAR	XTRAP
5	AVG	LS	BF	YES
8	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
10	AVG	LS	BF	YES
7	AVG	LS	BF	YES
4	AVG	LS	BF	YES
9	AVG	LS	BF	YES
2	AVG	LS	BF	YES
11	AVG	LS	BF	YES
12	AVG	LS	BF	YES
13	AVG	LS	BF	YES
14	AVG	LS	BF	YES

TOL NUM FEA NUM	DESCRIPTION X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
5	DIA702-5					FAILED
	5 DIA6.000+/-0.015					
702	DATUM B			6.02	0.01	0.02
				6.00	-0 01	0.00

Valisys Results File Formatter Ver 5.3.1 1-19-1998 12:01:48

TOL NUM FEA NUM	DESCRIPTION X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
8	DIA703-8					FAILED
	8 DIA6.000+/-0.015					
703	DATUM C			6.02	0.01	0.02
				6.00	-0.01	0.01
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
704	HOLE 1			6.01	0.01	0.01
				6.00	-0.01	0.00
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
705	HOLE 2			6.01	0.01	0.01
				6.00	-0.01	0.01
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
706	HOLE 3			6.01	0.01	0.01
				6.00	-0.01	0.00
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
707	HOLE 4			6.01	0.01	0.01
				6.00	-0.01	0.00
10	DIA722-10					FAILED
	10 DIA6.000+/-0.015					
708	HOLE 5			6.02	0.01	0.02
				6.00	-0.01	0.00
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
709	HOLE 6			6.01	0.01	0.01
				6.00	-0.01	0.00
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
710	HOLE 7			6.01	0.01	0.01
				6.00	-0.01	0.00
10	DIA722-10					FAILED
	10 DIA6.000+/-0.015					
711	HOLE 8			6.02	0.01	0.02
				6.00	-0.01	0.00

Valisys Results File Formatter Ver 5.3.1 1-19-1998 12:01·48

TOL NUM FEA NUM	DESCRIPTION X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
712	HOLE 9			6.01	0.01	0 01
				6.00	-0.01	0.00
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
713	HOLE 10			6.01	0.01	0.01
				6.00	-0.01	0.00
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
714	HOLE 11			6.01	0.01	0.01
				6.00	-0.01	0.01
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
715	HOLE 12			6.01	0.01	0.01
				6.00	-0.01	0.00
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
716	HOLE 13			6.01	0.01	0.01
				6.00	-0.01	0.00
10	DIA722-10					PASSED
	10 DIA6 000+/-0.015					
717	HOLE 14			6.01	0.01	0.01
				6.00	-0.01	0.00
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
718	HOLE 15			6.01	0.01	0.01
				6.00	-0.01	0.01
10	DIA722-10					PASSED
	10 DIA6.000+/-0.015					
719	HOLE 16			6.01	0.01	0.01
				6.00	-0.01	0.00
10	DIA722-10					PASSED
	10 DIA6 000+/-0.015					
720	HOLE 17			6.01	0.01	0.01
				6.00	-0.01	0.01

Valisys Results File Formatter Ver 5.3.1 1-19-1998 12:01:48

```
TOL
NUM     DESCRIPTION
FEA                                                ACTUAL/    TOL/       DEVIATION/
NUM          X          Y          Z               NOMINAL    TOL+BONUS    SPREAD
-----------------------------------------------------------------------------------
 10 DIA722-10                                                                PASSED
        10 DIA6.000+/-0 015
721 HOLE 18                                          6.01       0.01       0.01
                                                     6.00      -0.01       0.00
-----------------------------------------------------------------------------------
  7 POS703-7                                                                 PASSED
    7 POS|DIA0.025(M)|A|B(M) POSITION OF 1 ROUND HOLE
                                                                0.02
                                                                0.05       0.00
703  DATUM C
     D:  -250.00    250.00     -8.00
     A:  -250.00    249.99     -8 00                           0.05      -0.00
-----------------------------------------------------------------------------------
  4 POS702-4                                                                 PASSED
    4 POS|DIA0.025(M)|A POSITION OF 1 ROUND HOLE
                                                                0.02
                                                                0.05       0.00
702  DATUM B
     D:   125.00   -124.99      0.00
     A:   125.00   -124.99      0.00                           0.05       0.00
-----------------------------------------------------------------------------------
  9 POS722-9                                                                 PASSED
    9 POS|DIA0.025(M)|A|B(M)|C(M) POSITION OF 18 ROUND HOLE
                                                                0.02
                                                                0.05       0.03
704  HOLE 1
     D:    35.36     35.36      0.00
     A:    35.35     35.35      0.00                           0.05       0.01
705  HOLE 2
     D:    70.71     70.71      0.00
     A:    70.71     70.69      0.00                           0.05       0.01
706  HOLE 3
     D:   106.07    106.07     -8.00
     A:   106.07    106.05     -8 00                           0.05       0 01
707  HOLE 4
     D:   141.42    141.42      0.00
     A:   141.42    141.41      0.00                           0.05       0.00
708  HOLE 5
     D:   176.78    176.78     -8.00
     A:   176.76    176.78     -8.00                           0.05       0.02
709  HOLE 6
     D:   212 13    141.42     -8.00
     A:   212.12    141.42     -8.00                           0.05       0.01
710  HOLE 7
     D:   247 49    106.07     -8.00
     A:   247.47    106.07     -8.00                           0.05       0.02
711  HOLE 8
     D:   282.84     70.71     -8.00
```

Valisys Results File Formatter Ver 5.3.1 1-19-1998 12·01.48

TOL NUM FEA NUM	DESCRIPTION	X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
	A.	282.83	70.71	-8.00		0.05	0.02
712	HOLE 9						
	D.	318.20	35.36	-8.00			
	A:	318.19	35.35	-8.00		0.05	0.01
713	HOLE 10						
	D:	318.20	-35.36	-8.00			
	A·	318.21	-35 35	-8.00		0.05	0.01
714	HOLE 11						
	D	282.84	-70.71	0 00			
	A:	282.85	-70.71	0 00		0.05	0.01
715	HOLE 12						
	D:	247.49	-106 07	-8.00			
	A:	247.50	-106 08	-8.00		0.05	0.02
716	HOLE 13						
	D	212.13	-141.42	-8.00			
	A.	212.14	-141.43	-8.00		0.05	0.02
717	HOLE 14						
	D:	176.78	-176.78	-8 00			
	A:	176.78	-176.78	-8.00		0.05	0.01
718	HOLE 15						
	D:	141.42	-141.42	-8.00			
	A:	141.43	-141.43	-8.00		0.04	0.01
719	HOLE 16						
	D·	106.07	-106 07	-8.00			
	A·	106.08	-106 08	-8.00		0 05	0.02
720	HOLE 17						
	D.	70.71	-70.71	-8.00			
	A.	70.72	-70.72	-8.00		0.05	0.01
721	HOLE 18						
	D:	35.36	-35 36	-8.00			
	A:	35.37	-35 37	-8 00		0.05	0 02
2	FLT701-2						PASSED
	2 FLT|0.2						
701	DATUM A					0.20	0.07
11	FLT723-11						PASSED
	11 FLT|0.04						
723	EDGE 1					0.04	0.01
12	FLT724-12						PASSED
	12 FLT|0.04						
724	EDGE 2					0.04	0 02

Valisys Results File Formatter Ver 5.3.1 1-19-1998 12:01:48

TOL NUM FEA NUM	DESCRIPTION X	Y	Z	ACTUAL/ NOMINAL	TOL/ TOL+BONUS	DEVIATION/ SPREAD
13	FLT725-13					PASSED
	13 FLT|0.04					
725	EDGE 3				0 04	0.04
14	FLT726-14					PASSED
	14 FLT|0.04					
726	EDGE 4				0.04	0.03

Valisys Results File Formatter Ver 5.3.1 1-19-1998 12:01:48

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  V:INSPECT VERSION    5.3.1_SA
  PART NAME            /home/catusr/PHASEI_SUBSTRUCTURE_INS.prt  PHASEI_SUBSTRUCT
URE
  PROCESS NO.          902
  PROCESS NAME         PHASEI_SUBSTRUCTURE_INS
  DATE                 Thr Jan 15 8:58:15 1998
```

Valisys Results File Formatter Ver 5.3.1 1-19-1998 12:01:48

SUMMARY OF GAUGE ANALYSIS

TOL	DESCRIPTION	STATUS	REQT	FEATURES
5	SIZE DIAM	FAILED <-		702
8	SIZE DIAM	FAILED <-		703
10	SIZE DIAM	PASSED		704
10	SIZE DIAM	PASSED		705
10	SIZE DIAM	PASSED		706
10	SIZE DIAM	PASSED		707
10	SIZE DIAM	FAILED <-		708
10	SIZE DIAM	PASSED		709
10	SIZE DIAM	PASSED		710
10	SIZE DIAM	FAILED <-		711
10	SIZE DIAM	PASSED		712
10	SIZE DIAM	PASSED		713
10	SIZE DIAM	PASSED		714
10	SIZE DIAM	PASSED		715
10	SIZE DIAM	PASSED		716
10	SIZE DIAM	PASSED		717
10	SIZE DIAM	PASSED		718
10	SIZE DIAM	PASSED		719
10	SIZE DIAM	PASSED		720
10	SIZE DIAM	PASSED		721
7	POSITION	PASSED	SEP	703
4	POSITION	PASSED	SEP	702
9	POSITION	PASSED	SEP	704, 705, 706, 707, 708, 709, 710, 711, 712, 713 714, 715, 716, 717, 718 719, 720, 721
2	FLATNESS	PASSED		701
11	FLATNESS	PASSED		723
12	FLATNESS	PASSED		724
13	FLATNESS	PASSED		725
14	FLATNESS	PASSED		726