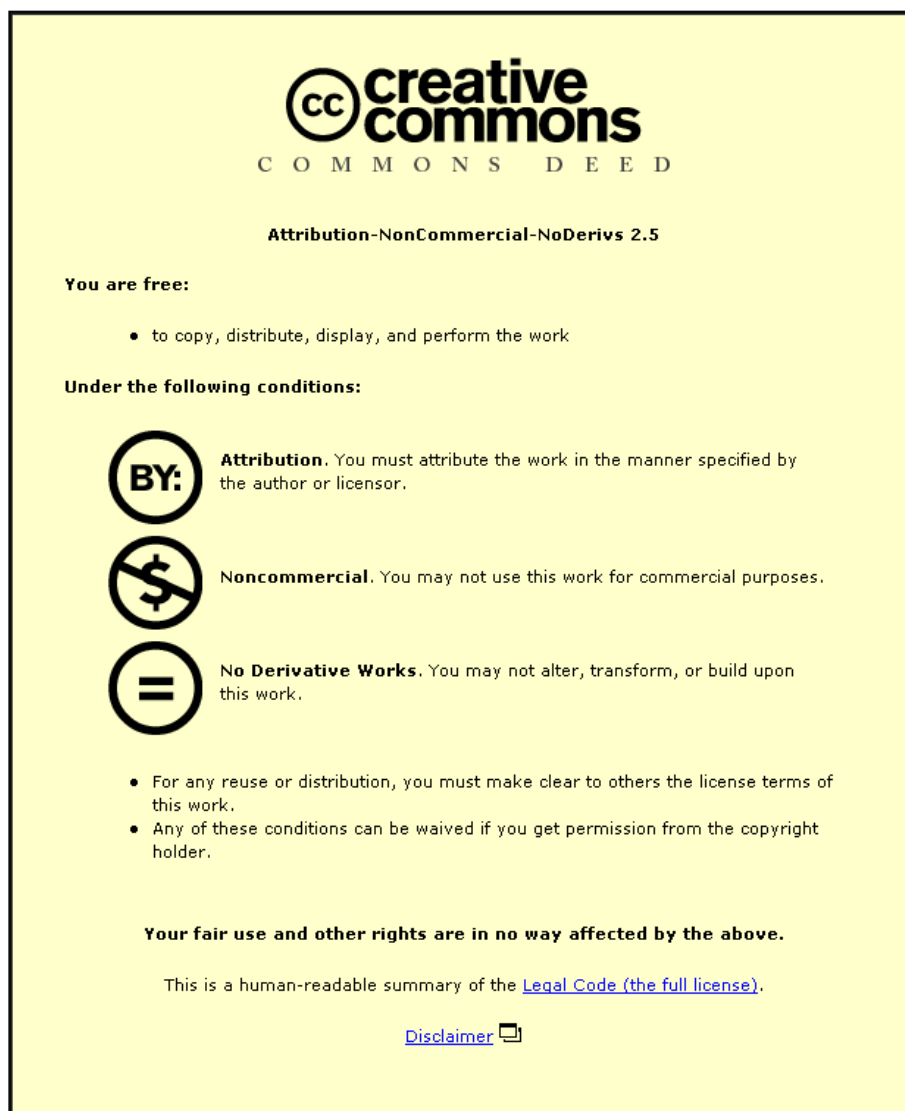


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FORWARD LOOKING INNOVATIONS IN
ELECTRONIC SPECKLE PATTERN INTERFEROMETRY (ESPI)

by

PAUL C MONTGOMERY

A Doctoral Thesis
submitted in partial fulfilment of
the requirements for the award of
Doctor of Philosophy
of the
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Supervisor: B D Bergquist
Department of Mechanical Engineering

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*To my parents and family
and in memory of
Professor John N Butters*

* * * * *

*"For God who said, "Let light shine out of darkness",
made his light shine in our hearts
to give us the light of the knowledge of the
glory of God in the face of Christ."*

(2 Corinthians 4:6)

ABSTRACT

Electronic Speckle Pattern Interferometry (ESPI) dates from 1971. Attempts at commercial exploitation were unsuccessful; at the beginning of this decade it remained essentially a laboratory technique. Problems arose from the practical operation of the instrument and the nature of the output. Correlation fringes are intrinsically noisy and their quality depends on many interrelated factors. It is shown that by simplifying the optical design and improving the quality of the optical components, the fringe contrast is greatly improved and the instrument is made easier to use. Extensions and improvements to the system are discussed: analogue image processing techniques as a low cost means of improving the appearance of the output; time invariant noise subtraction in time averaged fringes gives similar quality results as that of the subtraction mode; ensemble averaging of time variant noise is a new technique for producing holographic quality results. Electronic speckle contouring (ESC) gives a selection of methods for producing programmable contour spacings and orientations for shape measurement. ESPI is compared with other optical measurement techniques and is shown to have fundamental advantages.

ACKNOWLEDGEMENTS

The direction of this work has been influenced by the late Professor J N Butters, particularly by his visionary outlook of the application of optical techniques in engineering measurement. He and others have helped me to formulate the view that working in applied optics is another facet to the general biblical command to "subdue the earth and all that is in it" with the uses of light being one of the more fascinating areas of exploration.

To bring this work to the present stage I am thankful to my supervisor, Mr B D Bergquist for his continued guidance and help. He has taught me some valuable lessons in the art of research. Thanks are also due to Professor G Wray as my Director of Research, for encouragement and initial help in registering for the degree of Ph.D.

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INTRODUCTION

The introduction of the laser in the early 1960's has made classical methods of interferometry more amenable to daily use. Lasers are convenient sources of high intensity coherent light beams that can be easily split, directed and expanded for illumination and interference. In the same period there has been a rapid growth in the development of optical sensors. Two dimensional imaging with the video camera is now commonly used in laser interferometry for providing a remote picture of the results for analysis by eye or more complex analysis by digital image processing. The interest of this work is the development of coherent imaging techniques for detecting and measuring engineering parameters.

In engineering there are many parameters that need to be observed and measured in the course of manufacturing components and assemblies. At an early stage in the manufacturing process diagnostic analysis is used in the development laboratory for the testing of prototypes. Quality control of samples may be necessary to introduce modifications to the design and the manufacturing procedure. Inspection involves the metrology of surface shape and form, verifying that operations have been successfully performed to the required standard. A component may be checked individually in the inspection room or on the assembly line with the automatic implementation of the inspection procedure. Non-destructive testing (NDT) techniques may be used in both diagnostic analysis and inspection. A number of techniques are available for detecting weaknesses due to cracks, adhesive failure or other non-uniformities. Ultrasonic testing reveals faults by reflecting sound waves from fault boundaries. Eddy current techniques show up discontinuities in an applied electro-magnetic field. At a more simple level, dye penetrants can be used to reveal cracks in forgings by fluorescence when illuminated with ultra violet light.

The strain gauge is the traditional tool for quantifying some of the mechanical properties of components. A wire gauge attached to a surface undergoing loading experiences resistance changes that can be accurately detected and converted to surface strains. Siting of the strain gauge at critical points may be determined from structural calculations, from experience or with the brittle lacquer method. A lacquer applied to the surface and allowed to dry reveals crazing in the areas of high stress. The strain gauge method is well proven but like all measurement techniques has limitations. Time and skill are required for fixing the gauge in place and data is only provided at a single point. The surface is limited to that having a mass much greater than the gauge itself and which undergoes strains within the linear measurement range of the gauge, typically up to about $10,000 \mu\epsilon$.

In dynamic measurement, the accelerometer is the accepted engineering tool. A piezo crystal transducer attached to a small mass allows a large range of measurements of the accelerations of a surface to be made. Frequency and amplitude can be measured for sinusoidal or random movement. Like the strain gauge, the accelerometer gives quantified measurements at a point and is limited to a surface whose mass is much greater than its own. The accelerometer may reduce the frequency of a resonant mode due to the additional mass. The method of fixing to the surface also affects the frequency response of the accelerometer. Securing by drilling and tapping gives an extended linear frequency response compared with using beeswax. To detect the shape of a resonant mode over a large area, an array of accelerometers is required. The size of the mode determines the number in the array. As the frequency of the vibration mode increases, the spatial size of the mode decreases and the separation of accelerometers used to make the measurements must be reduced. For example, the testing of the wall of an internal combustion engine involves taking measurements at typically 100 points on a 5 cm grid (Davies et al 1985). Modes up to a frequency of 4.0 kHz can be analysed by this means. Higher frequencies involving measurements at more than 100 sites would be prohibitively time consuming. Another

limitation is that the grid array acts as a filter, where critical resonance modes could go undetected due to accelerometer sites falling on node positions.

The measurement of critical dimensions and shape is generally performed on the coordinate measuring machine, in one, two or three dimensions. In its simplest form the machine consists of one to three orthogonal rulers from which X, Y or Z coordinates can be read by positioning a sensor to the point on the component to be measured. Movement of the sensor may be motorised, giving a direct input of the coordinates to a computer. Accuracies of 20 μm are typical. Whether manual or automatic the time delay in moving the sensor introduces a fundamental limitation in the speed of data acquisition.

The traditional measurement methods described are limited in one way or another due to the fact that they are point contacting measurement techniques. The use of light on the other hand gives the potential of non-contact whole field analysis. Photoelasticity uses polarised light to visualise stress distributions in certain types of transparent material that become doubly refracting under stress. The method is generally restricted to the analysis of a two dimensional model of the component made from this material. Alternatively the actual component can be studied by coating the surface with a clear polymer and viewing the fringe pattern on the surface under reflected light.

Surface shape of specularly reflecting mirrors and lenses can be measured with classical methods of interferometry. The Fizeau interferometer is a typical instrument of this type making use of the laser. Many commercial measurement systems are now in use in the manufacture of optical components. Measurement is restricted to flats and convex and concave surfaces where simple wavefronts can be reproduced with standard optical components.

Holographic interferometry (HI) introduced in the mid 1960's allowed interferometry to be performed on non-specularly reflecting surfaces.

The significance of this advance was that interferometry was no longer restricted to smooth, simple surface shapes. Engineering components of complex shape and with an optically rough surface could be measured. Holographic reproduction of the surface shape was found to lead to interference effects upon movement of the surface. Powell and Stetson (1965) demonstrated how the vibration modes of the base of a tin could be visualised with time averaged holography, in the form of contours of the amplitude of vibration. Others measured quasi-static displacement, finding many applications in non-destructive testing. Metals, plastics, composite materials, rubbers and even the delicate paper cones of loudspeakers could be studied because ESPI is a non-contacting technique.

In the early days of holography it was thought that HI was the solution to many diagnostic analysis and inspection problems sought after by engineers throughout industry. In practice the growth of HI was restricted. One reason was the time and expense involved since a new hologram had to be made for each new component to be tested. The introduction of the thermoplastic hologram plate reduced the processing time from many minutes with conventional holography to 10 seconds using electrostatic and thermosetting processing. Commercial systems using thermoplastic plates are now available such as the "Instant Holographic Camera" from Newport Corporation which is finding widespread use in the United States. Nonetheless, the whole process remains a skilful technique limited to laboratory use. The second major limitation to HI has been the complexity of interpreting the interferogram since it usually contains components of out-of-plane, in-plane and rigid body motion.

Shortly after the introduction of HI, Rowe and Welford (1967) and Brookes and Heflinger (1969) showed how projected light grids could be used in shape and deformation measurement using moire techniques. New moire methods were developed rapidly with the addition of reference grids and many different ways of producing the gratings and viewing the contours. Until recently, moire techniques had lacked the resolution requirement of industrial measurement. The ability to

cope with different surface qualities, holes and edges are also problems to be overcome. Phase stepping techniques applied to moire topography by Reid et al (1984) now gives a resolution of 11 μm in height measurement on a 0.2m object. These results give some indication of the feasibility of using optical measurement techniques in industry.

In 1971 Electronic Speckle Pattern Interferometry (ESPI) was developed by Butters and Leendertz (1971). The annoying speckle effect accompanying holography and other laser techniques proved to be the means of a new interferometric measurement method. Speckle is formed when an optically rough surface is illuminated with coherent laser light. The light scattered from the surface forms a complex interference pattern, the intensity at any point being the resultant of the sum of the amplitudes of contributions from each point on the surface. The random variation in intensity is the speckle effect. If an image is formed of the surface, a random speckle pattern is also produced but the distribution of speckle intensities is modified by the aperture of the viewing system. Goodman (1975) determined the autocorrelation function for the intensity distribution of typical speckles in the image plane from which Jones and Wykes (1983) estimate the speckle size to be:

$$D_{ss} = \frac{2.44\lambda V}{A}$$

where λ = wavelength of illuminating laser light

V = distance from lens to image plane

A = diameter of viewing aperture.

The speckle "size" is the same as the diameter of the Airy disc, the resolution limit of the imaging system.

If a smooth reference beam is added to an image plane speckle pattern, interference modifies the intensity of each "speckle" due to

the object surface, giving a new phase-referenced speckle pattern. The pattern is said to be "phase-referenced" because any subsequent movement of the surface of the object causes the intensities of the speckles to vary cyclically due to a phase difference in the object beam compared with the stationary reference beam. A reference pattern of the surface at rest is *stored* in a video framestore. Subtraction of the live image reveals a dark field. Slight movement of the surface causes the intensity of each speckle to change. Where the phase changes by multiples of 2π , the speckle intensities are the same as in the phase referenced pattern, giving dark correlation fringes. Where the phase changes by some other value, the speckle intensity is different, yielding some intensity between dark and bright on subtraction. A bright fringe is formed. The dark and bright fringes are of the same form as classical interference fringes in marking out the loci of points of constant phase change. Because the method relies on the speckle effect, in-plane and out-of-plane displacement can be independently measured by varying the illuminating geometry. Like holography, ESPI can also be used in vibration and shape measurement.

The combination of the laser, video techniques and electronic signal processing in interferometry gives ESPI great potential for rapid data acquisition and automatic analysis in engineering measurement and testing. ESPI is a complementary technique to the traditional mechanical point measurement methods used throughout diagnostic analysis and inspection. The system has been used for testing samples and prototypes in the development laboratory and inspection room and could potentially be incorporated in automatic analysis on the assembly line. Some of the drawbacks of ESPI that have until recently limited its widespread use in industry are the practical use of the interferometer and the noisy output. This thesis consists of a report of the contributions made by the author in introducing a number of forward looking innovations in the development of ESPI as an industrial measurement and testing technique.

CHAPTER 1

ELECTRONIC SPECKLE PATTERN INTERFEROMETRY (ESPI)

The existence of speckle noise in coherent illumination in holography, was found to be an annoyance and a limitation to the resolution in the image detail. Early work in holography involved investigations into speckle reduction techniques (e.g. Martiensen and Spiller, 1967) but speckle remained a fundamental limitation in the recording of a single hologram. In holographic interferometry speckle reduced the fringe quality. There was also the additional problem of interpretation since components of in-plane, out-of-plane and rigid body motion could not be measured separately. The limitations of HI and a general interest in laser speckle led to the early work leading to the development of ESPI in the late 1960's.

Leendertz (1970) introduced speckle pattern correlation interferometry. Other workers used phase-referenced image plane speckle patterns to detect the presence of fatigue cracks. Leendertz was the first to show that the intensity at a point in the speckle pattern varied cyclically for a specific movement of the object surface if the speckle field interfered with a reference beam of a certain geometry. The first experiments involved the superposition of a negative of a speckle pattern for the surface at rest with a positive of the pattern for the displaced surface. Results did not simply indicate the presence of movement but gave quantified values of displacement throughout the field of view. What was more, the out-of-plane and in-plane displacement could be measured independently depending on the illumination geometry.

Being aware of some of the potential of speckle pattern correlation interferometry in engineering measurement, Butters and Leendertz (1971) at Loughborough replaced the photographic film with a video camera to give real time results. The use of an imaging system of suitable aperture in coherent imaging conveniently reduces the

speckle size to within the resolution range of the video camera. Instead of chemical processing, electronic processing of the video signal combined with analogue tape image memory was used to reveal the correlation pattern. Macovski et al (1971) proposed a similar video technique, but this was based more on smooth wavefront interference than speckle interference itself. Other research groups developed their own ESPI systems in the mid-1970's, the Norwegian group in Trondheim specialising in vibration measurement (e.g. Lokberg and Hogmoen⁽¹⁾, 1976). A paper by Lokberg (1980) gives a summary of ESPI, outlining its principles, different modes of operation and applications. Jones and Wykes (1983) have written a book on ESPI, comparing and contrasting it with holographic interferometry.

To provide further understanding of the ESPI technique, a summary of the basic theory of laser speckle and correlation fringe formation is given, together with a system description. This is followed with a survey of the literature written on ESPI from which the objectives and scope of the present work are drawn.

1.1 THEORY

1.1.1 Laser Speckle

The underlying mechanism of ESPI is the detection of image plane speckle. Laser speckle is the granular appearance of an optically rough surface illuminated with laser light. An optically rough surface in this case is one in which the variation in surface height is of the order of or greater than the wavelength of light i.e. standard deviation in surface height $\sigma \geq \lambda$. The speckle effect is found wherever a monochromatic source is used to illuminate a rough surface. Speckle is also found in coherent radar and ultrasonic imaging. Ennos (1975) termed the light scattered from a surface as "objective" speckle whereas that collected in the image plane of a lens is "subjective" speckle. The two forms of speckle are now described.

Objective Speckle

Objective speckle is the random spatial variation in intensity of the light in free space scattered from a rough surface illuminated with laser light. The surface can be thought of in terms of an array of points, each scattering the incident light. Each point acts as a source of spherical waves, rather like Huygens-Fresnel secondary waves. At any point above the surface the complex amplitude of the scattered light is given by the sum of the amplitudes of the contributions from each point. The resulting apparently random variation in intensity is the speckle effect. Ennos (1975) takes the "size" of the speckle to be the statistical average of the distance between adjacent regions of maximum and minimum brightness. The variation in speckle size falls within a narrow range, the mean speckle size at a chosen plane being related to the aperture angle subtended by the area of scattered light giving rise to it. The mean speckle size given by Ennos (1975) at a plane distance U from an illuminated area of diameter d is the radius of the Airy disc:

$$R_{os} \approx \frac{1.22\lambda U}{d}$$

In physical terms this means that in the viewing plane the speckle size increases as the size of the illuminated area decreases.

Subjective Speckle

When an image of a surface illuminated with laser light is formed, there is a similar random variation in intensity found in the image plane as in free-space above the surface. This is known as "subjective" speckle because the speckle size is modified by the viewing system. The spatial distribution of the speckle is determined by the diffraction limit of the imaging system. Goodman (1975) has derived an expression for the autocorrelation function $R(x)$ for image plane speckle intensities:

$$R(x) = \langle I \rangle^2 \left[1 + 2J_0 \left(\frac{\pi Ax}{\lambda V} \right) / \left(\frac{\pi Ax}{\lambda V} \right) \right]$$

where $\langle I \rangle$ = average light intensity over many speckles

J_1 = Bessel function

V = distance from lens to image plane

A = diameter of viewing aperture.

Jones and Wykes (1983) take the subjective speckle "size" to be the distance between the first two minima of the Bessel function, where $J_1(x) = 0$ for $x = 1.22\pi$ and the diameter of the speckle, D_{SS} is given by:

$$D_{SS} = \frac{2.44 \lambda V}{A}$$

This expression can also be derived from the geometry of the imaging system. Consider two points P_O and Q_O on the object surface illuminated with laser light shown in Figure 1.1.

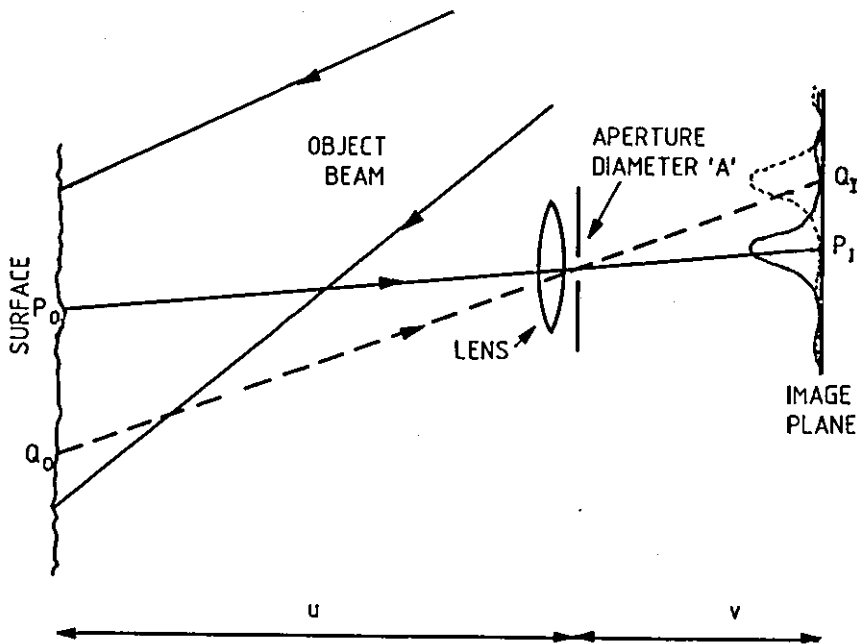


FIGURE 1.1 Optical geometry for estimation of speckle "size" in subjective speckle

Point P_O forms a diffraction pattern with a central maxima at P_I in the image plane of the lens. Point Q_O is positioned such that the first minima of the diffraction pattern at Q_I coincides with P_I . Each maxima at P_I and Q_I has a random phase associated with the random surface roughness on the object surface in the region of P_O and Q_O . The light at Q_I contributes nothing to P_I . Light scattered from points further from P_O and Q_O contribute a small but negligible amount to P_I since the secondary maxima are much smaller than the primary maxima. Therefore the light at P_I can be considered to be the mapping of the light from the region centred at P_O . From diffraction theory the distance $P_I Q_I$ is the distance from the centre of the diffraction maximum to the first minimum of the Bessel function, given by:

$$P_I Q_I \approx \frac{1.22 \lambda V}{A}$$

The speckle "size" D_{SS} is then twice this value, given by:

$$D_{SS} \approx \frac{2.44 \lambda V}{A} \quad (1.1)$$

The corresponding resolution element on the object surface has diameter D_{RE} :

$$D_{RE} \approx \frac{2.44 \lambda U}{A} \quad (1.2)$$

where U = object to lens distance.

The speckle "size" is therefore dependent on the aperture of the viewing lens, becoming larger for smaller apertures. The maximum spatial frequency, or speckle cut-off frequency, f_{max} is determined

by the aperture diameter A , and the lens to image plane distance, V the minimum speckle size, $g_{\min}$ according to Jones and Wykes (1983) being given by:

$$\frac{1}{f_{\max}} = g_{\min} \approx \frac{\lambda V}{A}$$

In ESPI the use of an imaging system maps a number of resolution elements of a surface onto the image plane in the form of a speckle pattern. A video camera placed in this plane resolves all or part of the speckle pattern depending on the speckle cut-off frequency set by the aperture. For example, a typical ESPI system uses a HeNe laser at a wavelength of 632.8 nm, with a 70 mm focal length lens and an object distance of 0.5m. At an aperture of $f/16$, the average speckle "size" is 28 μm with a minimum size of 12 μm . A 625 line video camera has a resolution limit of about 20 μm , which means that not all of the pattern is resolved. The corresponding average resolution element at the surface of the object is about 180 μm in diameter.

1.1.2 Correlation Fringes

ESPI correlation fringes can be formed with smooth or speckled reference beams, in the subtraction, addition or time averaged modes with in-plane or out-of-plane sensitivity. Jones and Wykes (1983) give a general account covering these different modes. The present work is largely limited to the use of a smooth reference beam system operating in the subtraction or time averaged mode for out-of-plane displacement sensitivity. The theory covered is limited to this system, following the results of Jones and Wykes.

The phase referenced speckle pattern in the image plane of an ESPI system is an interference pattern produced by the addition of two coherent laser wavefronts. One wavefront is the speckled image of the object surface and the other is a smooth reference wavefront.

For a linearly polarised laser with the plane of polarisation perpendicular to the plane of the optics, the reference beam is linearly polarised in the same direction. If the object surface is non-metallic (e.g. matt white surface), the image plane speckle pattern is randomly polarised with a preferred direction in the plane of polarisation of the laser. Interference occurs between the reference beam and those components of the image plane speckle with a similar polarisation. The complex amplitudes of the scattered object wavefront, U_S , and the smooth reference wavefront U_R , can be written as:

$$U_R = u_R \exp i \phi_R$$

$$U_S = u_S \exp i(\phi_S + \phi_{SP})$$

where u_R and u_S are the amplitudes of the components of the reference and object wavefronts that interfere. The object phase information is given by the phase ϕ_S . Superimposed is a random speckle pattern of phase ϕ_{SP} , which remains constant for small movements of the surface i.e. the object speckle pattern remains correlated. The total light amplitude U_T is given by:

$$U_T = U_R + U_S$$

Since the intensity is proportional to the square of the amplitude, the resultant light intensity is given by:

$$I_1 \propto U_T U_T^* = u_R^2 + u_S^2 + 2 u_R u_S \cos (\phi_S + \phi_{SP} - \phi_R)$$

$$I_1 = I_R + I_S + 2\sqrt{I_R I_S} \cos (\phi_C + \phi_{SP}) \quad (1.3)$$

$$\text{where } I_R = U_R U_R^* \\ I_S = U_S U_S^*$$

and the phase difference between the reference and object waves is defined as $\phi_C = \phi_S - \phi_R$.

Subtraction Mode

The phase-referenced speckle pattern, I_1 , of the surface at rest is detected by the video camera and stored in the video framestore as a voltage V_1 . The assumption is made that the speckle pattern is fully resolved. The effects of a partially resolved pattern, and the influence of optical and electronic noise are commented upon later. After deformation of the surface, the phase ϕ_S is changed by $\Delta\phi$, forming a new intensity I_2 :

$$I_2 = I_R + I_S + 2\sqrt{I_R I_S} \cos(\phi_C + \phi_{SP} + \Delta\phi)$$

Detection of the second pattern gives a signal of voltage V_2 . If the signals V_1 and V_2 are proportional to the input image intensities, the resultant voltage V_S on subtraction is:

$$V_S = (V_1 - V_2) \propto (I_1 - I_2) = 2\sqrt{I_R I_S} [\cos(\phi_C + \phi_{SP}) - \cos(\phi_C + \phi_{SP} + \Delta\phi)]$$

$$V_S = 4\sqrt{I_R I_S} \sin\left(\phi_C + \phi_{SP} + \frac{\Delta\phi}{2}\right) \sin\frac{\Delta\phi}{2}$$

On subtraction, V_S yields both negative and positive values, so the signal is rectified to retain the information contained in the negative part of the signal. The brightness of the picture^B of the resultant pattern on the monitor is proportional to $|V_S|$ given by:

$$B = 4K [I_R I_S \sin^2 (\phi_C + \phi_{SP} + \frac{\Delta\phi}{2}) \sin^2 \frac{\Delta\phi}{2}]^{\frac{1}{2}} \quad (1.4)$$

where $K = \text{constant}$. Although this equation gives the correct trend, the actual relationship between B and V_S is not linear and the brightness does not normally depend on the square root of the modulus.

For perfect subtraction, the points at which the pattern is fully correlated give a zero signal because the intensities are the same. Minimum correlation where the intensities are different give a non-zero signal. To interpret the functional form of the fringe pattern, Jones and Wykes suggest averaging along a line of constant $\Delta\phi$. The result is dark and bright fringes with a minimum brightness $B_{\min}$ given by:

$$B_{\min} = 0 \text{ for } \Delta\phi = 2n\pi \quad n = 0, 1, 2 \dots$$

and a maximum brightness $B_{\max}$ given by:

$$B_{\max} = 2K\sqrt{I_R I_S} \text{ for } \Delta\phi = (2n+1)\pi \quad n = 0, 1, 2, \dots$$

The correlation fringes follow a ^{squared} sine function intensity variation with a dark zero order fringe and dark higher order fringes corresponding to lines of 2π , 4π etc phase change. With normal illumination and viewing of the surface, these fringes indicate displacements of 0 , $\lambda/2$ and λ etc of the surface. For illumination at angle θ to the viewing direction, the displacement for the first order fringe for a 2π phase change is given by $\lambda/(1 + \cos\theta)$. As long as the illumination is within 10° of the viewing axis, the fringe separation is $\lambda/2$ to an accuracy of better than 0.8%.

Time Averaged Mode

Normally in ESPI, movement of the object during a single frame period is restricted because it tends to de-correlate the speckle pattern. In the time averaged mode the object is allowed to vibrate during a single frame period if the movement is small enough to retain

correlation of the basic object speckle pattern. A video framestore is not usually used since addition fringes are formed directly on the faceplate of the camera.

Consider an object surface vibrating sinusoidally at frequency ω where the period $2\pi/\omega$ is less than the frame period. The amplitude of vibration of the surface at time t is given by $a(t) = a_0 \sin \omega t$, where a_0 is the amplitude of vibration. The complex amplitude of the light scattered from the object in the image plane at time t is:

$$U_S(t) = U_S \exp i\left(\frac{4\pi}{\lambda} a_0 \sin \omega t\right)$$

The amplitude of the light scattered from the object at rest, U_S , and that of the reference wavefront, U_R is given by:

$$U_S = u_S \exp i(\phi_S + \phi_{Sp})$$

$$U_R = u_R \exp i \phi_R$$

The intensity in the image plane at time t is given by:

$$I(t) \propto U_R U_R^* + U_S(t) U_S(t)^* + U_R^* U_S(t) + U_R U_S(t)^*$$

Each video frame records addition fringes because the period of vibration $2\pi/\omega \ll \tau$ where τ is the frame period. The overall intensity, I , is given by the average of $I(t)$ over the frame period:

$$I = \frac{1}{\tau} \int_0^{\tau} I(t) dt$$

Jones and Wykes show the result to be:

$$I = I_R + I_S + 2\sqrt{I_R I_S} J_0 \left(\frac{4\pi}{\lambda} a_0 \right) \cos(\phi_C + \phi_{Sp}) \quad (1.5)$$

where J_0 is the zero order Bessel function.

Viewed directly on the monitor, the intensity variation appears as a variation in the contrast of the speckle pattern defining low contrast fringes. The contrast is improved by high pass filtering and rectifying the video signal before displaying on the monitor. The brightness B , is given by:

$$B = K[\sigma_S^2 + \sigma_R^2 + 2 \langle I_S \rangle \langle I_R \rangle J_0^2 \left(\frac{4\pi}{\lambda} a_0 \right)]^{\frac{1}{2}} \quad (1.6)$$

where σ_S = standard deviation of intensity of object wavefront

σ_R = standard deviation of intensity of reference wavefront.

Angular brackets denote average values taken along a line of constant vibration amplitude. Correlation fringes are observed, mapping the variation in the vibration amplitude across the surface. Areas of no movement are marked by a bright zero order fringe or node. Increasing vibration amplitude is marked by minima of the Bessel function, higher order maxima falling off rapidly in brightness. The minima occur at

$$a_0 \approx n \frac{\lambda}{4} \quad n = 1, 2, 3, \dots$$

Both subtraction and time averaged fringes are not smooth but are made of a speckle pattern in an attempt to define the underlying

correlation pattern. As indicated, Jones and Wykes suggest averaging along lines of constant phase change in order to define the fringe function. Bergquist (Bergquist and Mendoza-Santoyo, 1986) points out that these lines are difficult to locate in the case of high fringe densities where a fringe may be only 3 to 5 speckles wide. A slightly different approach is described by Slettemoen (1979). Taking an ensemble average is proposed as a means of defining the expected screen brightness. Normally this value is the resultant of averaging signals having random background noise. In practice this is realised by taking a local spatial average of the display from an area small compared with the fringes but large compared with the speckles. Slettemoen (1977) admits that this only works when a sufficient number of speckles are taken. Spatial averaging becomes questionable in the case of narrow fringes where the number of speckles gives a low sample count. Although these methods for defining fringe contrast may not be ideal, both of them predict the correct fringe positions.

Slettemoen (1979) has derived more complex expressions taking into account the finite resolution of the video camera, the effects of electronic filtering of the video signal and optical and electronic noise. The problem of noise is considered in more detail in Chapter 3. Slettemoen showed that an acceptable fringe contrast can be obtained even if the speckle pattern is not fully resolved and the same procedure for optimisation applies as for the fully resolved case. Optimisation of the fringe contrast for a fully resolved speckle pattern is now considered.

1.1.3 Optimisation Conditions

Light Levels

The speckle pattern imaged on the faceplate of the camera contains a range of intensities from zero to some maximum value. Video cameras have a typical sensitivity range of 10^2 to 10^3 . The minimum detectable intensity is fixed by the background electronic noise N_e , and the maximum intensity I_{sat} by the maximum discharge current from

the photoconductive layer. Varying the intensity levels of the object and reference beams affects the speckle contrast which in turn affects the fringe contrast. Optimum values for the light levels can be found from calculating the signal to noise ratio of the fringe pattern.

Subtraction Fringes

For subtraction fringes, averaging along a line of constant $\Delta\phi$, and adding the electronic noise, N_e , the monitor brightness is given by equation (1.4):

$$B = C\sqrt{R} \langle I_S \rangle \left| \sin^2 \frac{\Delta\phi}{2} \right|^{\frac{1}{2}} + N_e$$

where $C = 4K = \text{constant}$

$$R = \frac{\langle I_R \rangle}{\langle I_S \rangle}$$

The signal to noise ratio can be defined as:

$$\text{SNR} = \frac{C\sqrt{R} \langle I_S \rangle}{N_e}$$

Jones and Wykes (1983) calculate that in a working system where the total intensity is some proportion, P , of the maximum intensity, I_{sat} , the SNR is:

$$\text{SNR} = \frac{C\sqrt{R} P I_{\text{sat}}}{(1 + R + 2 (\gamma_S^2 + R^2 \gamma_R^2 + 2R)^{\frac{1}{2}})}$$

where $\gamma_S = \frac{\sigma_S}{\langle I_S \rangle} = \text{rms contrast of object wave}$

$\gamma_R = \frac{\sigma_R}{\langle I_R \rangle} = \text{rms contrast of reference wave.}$

For a speckled object wave the rms contrast γ_S is unity, and for a smooth reference beam γ_R is much smaller than unity e.g. $\gamma_R = 0.02$. The SNR is then a maximum when $P = 1$ and $R = 2$ i.e. when the camera is near saturation and the average reference beam intensity is twice the object beam intensity. This equation also demonstrates that the fringe visibility is relatively insensitive to variations in R and γ_R i.e. if the beam ratio is not optimised and the reference beam is noisy. For example, when the ratio R is 20, the SNR is 70% that of the optimised value at $R = 2$. This result is useful in showing that when there is not much laser power available, it is preferable to have a high intensity reference beam to operate the camera near to I_{sat} i.e. $R > 2$. In practice $\langle I_R \rangle$ can be made large because the reference beam is formed by direct illumination of the camera and requires a much smaller proportion of the total beam intensity than the object beam. Most of the light from the object beam is lost in the scattering process, as little as 0.02% reaching the camera faceplate. Recent work by Bergquist and Mendoza (1986) confirms the tolerance of the fringe contrast of subtraction fringes to large variations in beam ratios.

Time Averaged Fringes

Time averaged fringes are a form of the addition mode. Jones and Wykes calculate the SNR for addition fringes to be:

$$\text{SNR} = \frac{\sqrt{8R}}{(1 + R^2 \gamma_R^2)^{\frac{1}{2}} + N_e / C \langle I_S \rangle}$$

The SNR has a maximum value when $R \gamma_R = 1$ and $\langle I_S \rangle = \sigma_R$. This result was originally derived by Slettemoen (1977). Optimum time averaged fringes are obtained by satisfying the following conditions:

1. The reference beam should be as noise free as possible
2. The mean value of the intensity of the object beam, $\langle I_S \rangle$ should equal the standard deviation of the rms noise in the reference beam, σ_R .

3. The sum of the intensities of the reference and object beams should give total peak values at I_{sat} .

Because the time average mode is additive, the time invariant noise components are not removed as in the subtraction mode, and so the noise has to be minimised by optimising the SNR. Optimisation usually involves having a high intensity beam illuminating the object, a reduced aperture diameter (e.g. $< f/22$) and a reduced reference beam intensity.

Conjugacy

The previous calculations assume that the origin of the reference beam is in the centre of the imaging aperture. In practice the origin may be displaced laterally or longitudinally with respect to the imaging axis, causing the two interfering wavefronts to shear. Greater shear causes the phase difference between the object wave ϕ_S and the reference wave ϕ_R to vary rapidly across the faceplate of the camera. Jones and Wykes discuss this problem in terms of the need for conjugacy between the reference and object beams at the camera faceplate for maximum fringe visibility. Too great a shear and the interference pattern is too fine to be resolved by the camera. Calculations of the tolerance to shear are made on the basis of an extra phase component added due to the shear. The phase difference ϕ is then:

$$\phi = \phi_S + \phi_{SP} - \phi_R + \frac{2\pi}{\lambda} (d_{1C} - d_{0C})$$

where d_{1C} and d_{0C} are the distances from the lens aperture and the reference beam origin to a point "P" on the camera. If ϕ varies by more than 2π across a resolution cell of the camera, information is lost and the fringe contrast deteriorates. The variation of the phase due to the object ($\phi_S + \phi_{SP}$) is controlled by the aperture size. Choosing a small enough aperture limits the speckle cut-off frequency. If the reference beam origin coincides with the centre of

the aperture, the last term due to shear is zero. Displacement of the reference beam origin increases this term until eventually no fringe pattern is resolved at all. Jones and Wykes (1983) calculated the departure from conjugacy that can be tolerated to be:

$$\text{Lateral displacement } \Delta x \ll \frac{V\lambda}{x_r}$$

$$\text{Longitudinal displacement } \Delta l \ll \frac{V^2\lambda}{Wx_r}$$

where V = distance from centre of aperture to camera

x_r = diameter of resolution cell of camera

W = width of active area of camera tube.

For example, using HeNe laser light at a wavelength of 632.8 nm with an aperture to camera distance of $V = 80$ mm, and a 625 line camera with an active area width of $W = 12$ mm and resolution cell size of $x_s = 20$ μm some typical values are:

$$\Delta x \ll 2.5 \text{ mm}$$

$$\Delta l \ll 17.0 \text{ mm}$$

The conclusions made by Jones and Wykes are that the displacement in the lateral direction gives more rapid variation in ϕ than equivalent displacements in the longitudinal direction. Experimental work carried out by Bergquist and Mendoza-Santoyo (1986) confirms the need for co-linearity of the reference beam origin and the optical axis, but suggests there is a greater tolerance to departure from axial conjugacy than that calculated by Jones and Wykes.

De-correlation

Another factor affecting fringe visibility is correlation of the basic speckle pattern imaged from the object. In the theory described for the subtraction mode, it is assumed that the object speckle pattern remains exactly the same form in the image plane between undeformed and deformed states of the object. If there is a gross phase change in the speckle pattern then the two patterns become two unrelated speckle fields. Lines of constant phase change do not exist across the field. If there is only a slight change in the pattern, the two patterns are still statistically related but with the addition of a random phase error at each point. On subtraction the fringes are of reduced contrast. De-correlation may occur due to changes in phase of the illuminating wavefront or due to movement of the surface itself. The pattern is defined as being just de-correlated when a phase change of 2π is introduced across the diameter of a speckle in the image plane corresponding to a resolution element of the imaging system.

For de-correlation due to out-of-plane displacement or rotation, Jones and Wykes calculate the displacement ΔZ that can be tolerated to be:

$$\Delta Z = \sqrt{2U \lambda}$$

where U = object to lens distance.

For example, with $\lambda = 632.8 \text{ nm}$ and an object distance of $U = 0.5\text{m}$, an object displacement of $\Delta Z = 700 \text{ }\mu\text{m}$ along the viewing axis causes the speckle pattern to just fully de-correlate. This result shows a high tolerance to out-of-plane displacement related de-correlation since displacements of only a few microns are usually measured in one interferogram.

With in-plane displacement and rotation, the image plane speckle pattern becomes fully de-correlated when a point on the surface moves through a distance of Δx , the size of the resolution element at the

surface. From equation (1.2) for the same values as above, Δx is typically of the order of 100 μm . The tolerance to in-plane related de-correlation is less than that due to out-of-plane movement.

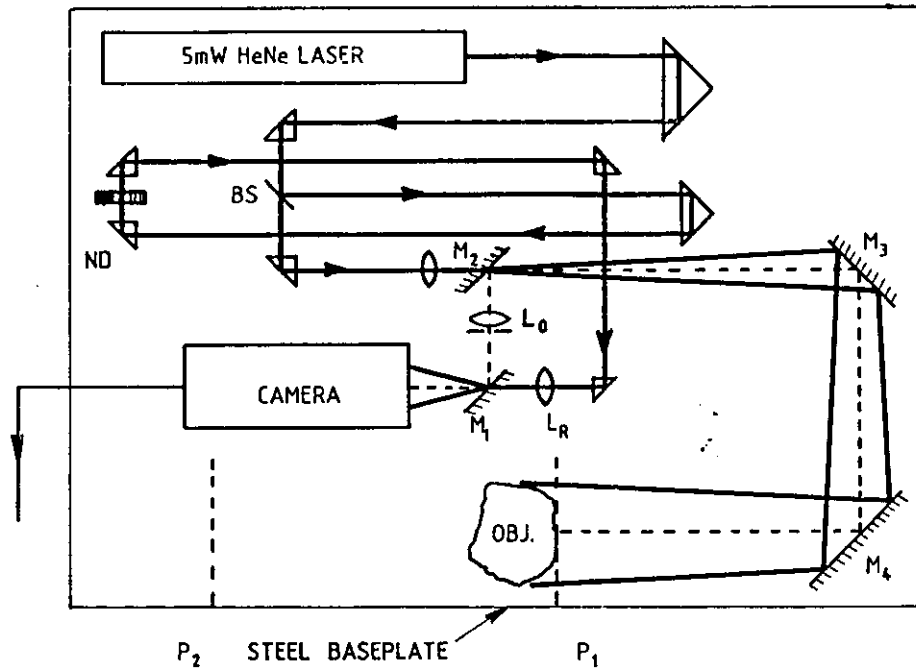
1.2 SYSTEM DESCRIPTION

The theory outlined gives some appreciation of the basic mechanism of ESPI and the complexity of the technique where attention has to be paid to the effects of image resolution, beam intensities, conjugacy and de-correlation. Realisation of the theory in a working system involves taking all these factors into account. The ESPI systems used in this work are the result of ten years of development at Loughborough. An outline is now given of two optical designs available in 1981, followed by a description of the electronic processing system used throughout this work.

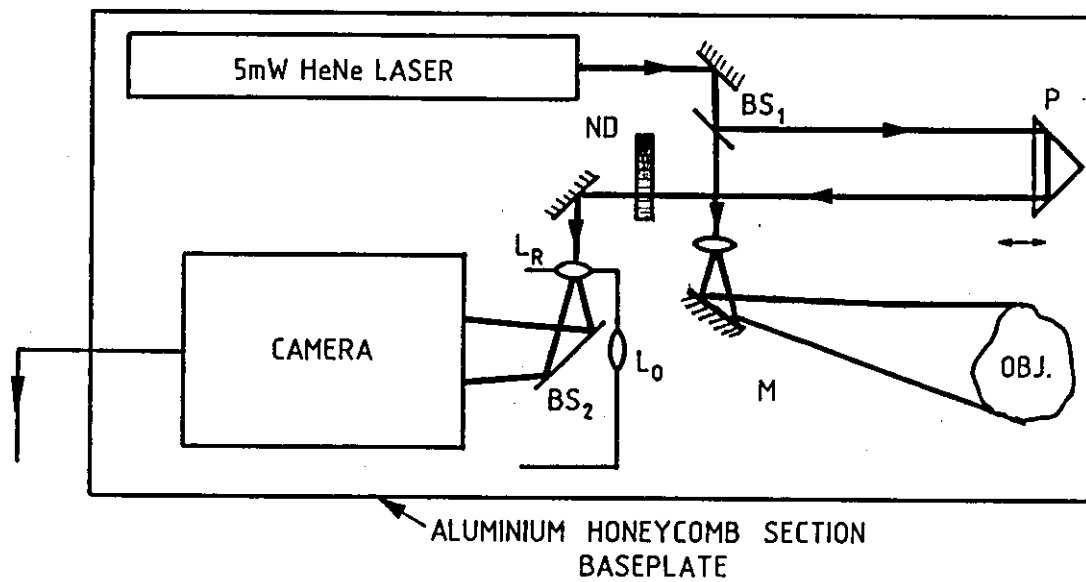
1.2.1 Vintens System

The critical point of any ESPI optical interferometer is the head where the object and reference waves are combined at the camera faceplate. A favoured design at the time for attaining a high degree of conjugacy was the pierced mirror arrangement, shown in Figure 1.2(a). A mirror M_1 placed at 45° to the optical axis combines the light from the image through lens L_O and the smooth reference beam passed through a small hole in the middle of the mirror. The reference beam is focussed by lens L_R onto a pinhole glued over the hole, acting as a spatial filter. This design was initially made for two wavelength ESPI contouring *to remove optical dispersion introduced by the wedge.* A second pierced mirror M_2 gives on-line viewing and illumination.

The other major design consideration is compactness, leading to the use of a lot of prisms and folded beams. A 5 mW HeNe laser is used, dividing the beam at the beam splitter BS into the reference and object beams. The reference beam has a fixed path length, passing through a variable neutral density filter, ND, to give an adjustment



a) Vintens System



b) Loughborough demonstration rig

FIGURE 1.2: Layout of two ESPI interferometer designs from Loughborough in 1981

to the intensity. Mirrors M_3 and M_4 direct the expanded object beam onto the object and also collect the light scattered back from the object surface. The object surface is placed in coherence planes P_1 or P_2 , plane P_1 giving an object beam path distance equal to the reference beam path, and plane P_2 being a laser cavity length further from the camera. Illumination areas of 150 mm and 300 mm are available in the two planes, with a choice of two interchangeable lenses for different fields of view. Simple lenses are used for imaging, focussing being achieved by moving the camera. An adjustable iris diaphragm on the camera side of the lens acts as an aperture. The camera used is the standard vidicon tube. All the components are mounted on a heavy metal baseplate, with an open area for the object, giving a total weight of 90 kg.

1.2.2 Loughborough Demonstration Rig

The Loughborough demonstration rig was built initially for showing to visitors to the research facility at Loughborough. The layout (Figure 1.2(b)) is very different to the Vintens system, using a glass wedge in the head to combine reference and object beams, and being of a simpler overall design. A 5 mW HeNe laser provides the laser light, the reference beam from BS_1 being directed into a retro reflecting prism, P , mounted on an optical rail parallel to the viewing axis. After spatial filtering and expanding by lens L_R , the reference beam is directed into the camera with beam splitter BS_2 which is wedged shaped and anti-reflection coated on the rear surface. This reduces the effects of interference fringes formed from front and rear reflections. Mirror M reflects the expanded object beam onto the object which is mounted anywhere within the focussing range of the system. Positioning the retro prism P in line with the object ensures that the object and reference beam path lengths are equalised. Illumination is within 10° of the viewing axis. Like the Vintens system, a fixed simple lens, L_O , is used for imaging, moving the camera backwards and forwards for focussing. The video camera uses the higher sensitivity Chalnicon tube. All the components are

mounted on an aluminium honeycomb section baseplate. A photograph of the system is shown in Figure 5.1.

Many of the experiments in this work were carried out with breadboard systems like those in holography using discrete components magnetically clamped to an air damped heavy steel table. The optical layouts were based on the design of the Loughborough demonstration rig using an optical head with a glass wedge for combining the reference and object beams. Reference and object path lengths were equalised and kept as short as possible to reduce instability and drift caused by air currents.

1.2.3 Electronic Processing

A layout of the video signal processing system used throughout this work is shown in Figure 1.3. The video camera used is a 1" Chalnicon

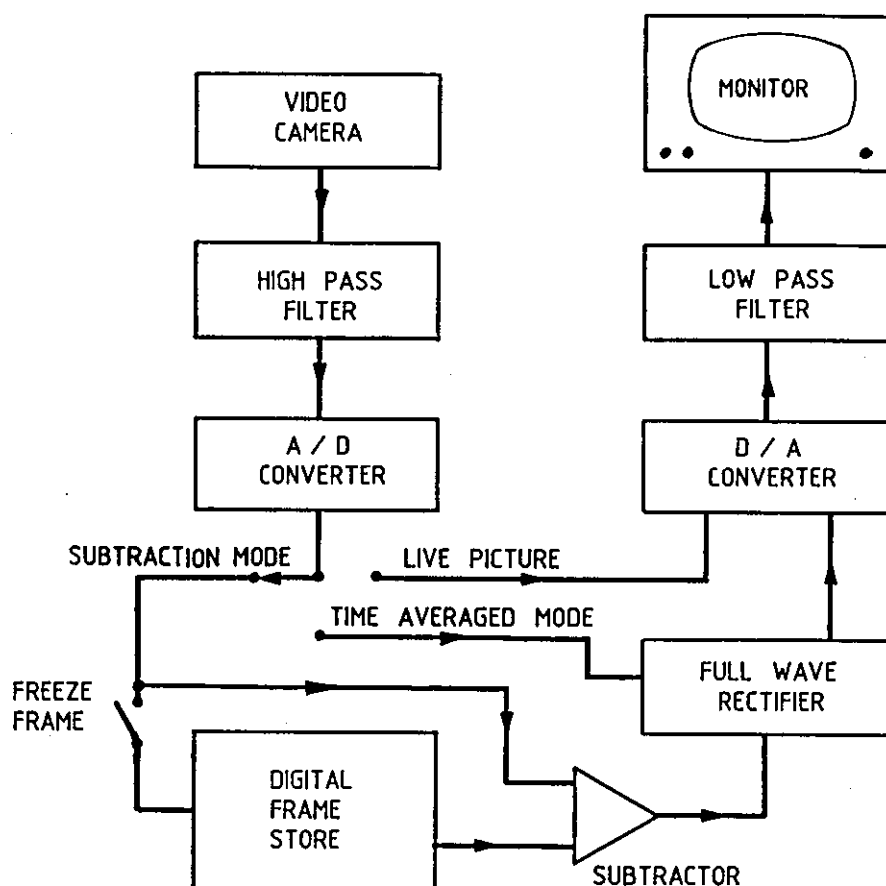


FIGURE 1.3: Block diagram of video signal processing system for ESPI subtraction and time averaged mode

tube which has a higher sensitivity and higher photometric accuracy than the standard vidicon. The active area of the camera faceplate is approximately 12 x 9 mm with the photo-conductive layer having a persistence time of about 0.1 seconds. Using the standard 625 line format, the vertical resolution is 20 μm . The horizontal resolution is set by the frequency response of the camera electronics, which is fairly uniform up to about 4.0 MHz, falling to a low value at 10.0 MHz, giving a resolution limit in the region of 20 μm . A critical section of the video signal processing is the head amplifier. To avoid unnecessary noise, the output signal is DC coupled into a high impedance FET (Field Effect Transistor) connected directly to the faceplate of the camera.

The output of the camera processing unit is high pass filtered to remove low frequency intensity changes across the image. In the systems used at Loughborough, the filter has been modified to differentiate the signal at each edge. The effect is to give the appearance of finer speckle and a subjective improvement in fringe quality.

After filtering, the video signal is digitised and for the subtraction mode stored in a digital frame store as a 512 x 512 pixel image with a 4 to 6 bit grey scale depending on the store used (see Appendix B for details). On subtraction, the signal contains both positive and negative values. Since a negative signal is displayed as black on the monitor, it is full-wave rectified to preserve the information. After digital to analogue conversion, the signal is low pass filtered at 3.5 MHz to remove D/A noise and to provide a moderate amount of speckle noise filtering without unduly reducing the horizontal resolution. Image plane speckles of 70 μm or smaller are removed, leaving a horizontal resolution of 180 lines per TV picture width.

For the standard time averaged mode the digital store and subtraction section is bypassed. The digitised signal is full wave rectified, re-converted to an analogue signal and low pass filtered.

In the units used at Loughborough the components for filtering and subtraction are incorporated in the same cabinet as the digital store to keep signal connections short and to reduce noise.

1.3 THE STATE OF ESPI IN 1981

A critical review of ESPI as it was in 1981 when the author began working in the field is now given to reveal weaknesses then seen. ESPI was first reported in 1971 and although it has aroused interest in industry, early attempts at exploitation were unsuccessful and at the beginning of this decade it remained essentially a laboratory technique. Problems arise from the practical operation of the instrument due to the complexity of maintaining optimisation, and the nature of the output. ESPI fringes are interferometric but intrinsically noisy, restricting the measurement range as well as interpretation whether by eye or digital processing. For clarification the review is divided into four sections: the design and overall construction of the system, the modes of operation available in 1981, the range of applications and analysis of the fringe pattern.

1.3.1 Design

From the description of ESPI given in Section 1.2 it can be seen that the design of the interferometer is similar to that of a focussed image holographic system. Brandt (1969) reports such a holographic system, where the image of an object is formed on a hologram plate and combined with a reference beam. The reference beam may be derived externally or locally from unfocussed light scattered from the object, in an off axis direction so as not to obscure image detail. The large angle between object and reference rays produces a fine interference pattern with a spatial frequency in the region of 2000 to 3000 $\frac{\text{line pairs per mm}}{\lambda}$. A high resolution photographic emulsion is able to resolve the pattern and reproduce the image of the object in the holographic process when re-illuminated with the reference beam. With ESPI, the object image is formed on the faceplate of a video

camera which has a much lower resolution than photographic emulsions, in the region of 30 to 40 ^{line pairs per mm} λ . As indicated in the description of ESPI, the use of an imaging aperture and an on-line reference beam reduces the spatial frequency of the interference pattern to within the resolution capability of the camera. The first ESPI design by Butters and Leendertz (1971) used a smooth reference beam. Other designs that followed proposed a variety of methods for producing smooth and speckled reference beams and different ways of combining it with the speckled image. Two current designs at Loughborough in 1981, the Vintens system and demonstration system described in Section 1.2 are now discussed.

The Vintens system is described in full by Jones and Wykes (1983) and by Hurden (1982). This early commercial design was based on the work carried out at Loughborough in the mid-1970's but it saw no real success as an industrial instrument. There are many reasons for this. The initial high price of £50,000 to £60,000 and the inevitable reluctance of management to test new technology cannot have helped in establishing the instrument. As far as is known only two systems were sold in total to educational establishments.

From the design point of view a major problem is the complexity of the optical layout arising from beam-folding. Mechanical instability is introduced by the many lenses, prisms and mirrors, causing fringe drift. There is a greater likelihood of optical noise from the numerous air-glass surfaces and a reduction in the beam power available due to absorption and reflection losses. The combination of all these factors reduces the fringe contrast. The pierced mirror device for beam combining *removes optical dispersion*, but is difficult to use in practice, making realignment a time-consuming and frustrating procedure. The author gained some experience in operating the Vintens system in helping to carry out modifications to the two systems sold, to improve the quality of the output. The overall conclusion made was that it is an unattractive instrument to use, requiring a high degree of skill and patience. Note must be taken though of the use of multi-laser cavity path length

compensation, a redeeming feature of the system. The provision of two positions for the object spaced a laser cavity length apart gives a useful choice of viewing areas.

The Loughborough demonstration rig on the other hand is of a simpler design. Using fewer optical components reduces the susceptibility to optical noise and light losses. Operation and maintenance is simplified with the wedge beam combiner. The moveable retro-prism for changing the reference beam path length provides a continuous range of object positions. A problem with the wedge is that it introduces astigmatism, making it impossible to bring horizontal and vertical image detail into focus in the same plane at apertures larger than $f/8$. This problem has gone unnoticed probably because apertures smaller than $f/22$ were generally used in the past. With the use of the higher resolution Chalnicon tube and larger apertures in the subtraction mode, a non-focussed image is unpleasant to work with and impedes analysis. Nonetheless, the system has proved stable and reliable and is still providing demonstrations to visitors at Loughborough at the time of writing (December 1986). Simplicity is a key feature in an ESPI system designed and built by the Norwegian group at Trondheim for use in industrial testing (Lokberg and Svenke, 1981). A single interferometer was purpose built for time averaged use in turbine blade vibration analysis. The reference beam path length is fixed and the two beams are combined with a wedge. A silicon vidicon camera is used for its high sensitivity in low light levels and tolerance to high levels of illumination, a useful feature where the careless introduction of stray light could otherwise damage the tube. A selection of lenses are available for different viewing areas, focussing by adjusting both the camera and lens positions. The system has been operating successfully in a Norwegian turbine manufacturing company since 1976 with few serious maintenance problems.

In the three systems cited, simple objective lenses or at the most a doublet have been used for imaging. Optical aberrations are not severe at the small apertures of $f/16$ to $f/70$ used in the time

averaged mode but for larger apertures it is a noticeable problem. No reports have been found in the literature discussing the problem of aberrations when using the simple lens/wedge combination. Having to move the camera for focussing when using a fixed focus lens adds further complications with the need for a high quality optical rail to hold the camera firmly in place.

Most authors quote an aperture of between $f/16$ and $f/70$ for general ESPI work (e.g. Lokberg, 1980). Reducing the diameter of the aperture of the imaging system reduces the speckle cut-off frequency to within the resolution limit of the video camera. At that time it was generally thought necessary to fully resolve the speckle pattern. Slettemoen (1979) shows that adequate fringe contrast is achieved even when all the details of the speckle pattern are not resolved. Other workers have also confirmed this (Jones and Wykes, 1981).

Little comment is made in the literature on the effect of the quality of the optical components on the fringe contrast. Slettemoen (1979) demonstrates theoretically the need for minimal optical noise when using a smooth reference beam in the time averaged mode, but the type of components used is left to the discretion of individual ESPI designers. Another source of noise to be taken into account is the *wedge* fringes produced by internal reflections of the smooth reference beam in the parallel faceplate of the camera tube. A circular interference fringe pattern results, the contrast varying from tube to tube. The general solution has been to glue a glass wedge onto the faceplate. Lokberg and Svenke (1981) reported having to test 15 camera tubes before finding one that was adequately noise free.

By 1981 digital frame stores and digital subtraction were in general use at Loughborough, replacing the older type of analogue frame store used in the early years of development. Jones and Wykes (1981) report that the use of digital stores with analogue high pass filtering of the input and low pass filtering of the output give high contrast correlation fringes, as described in Section 1.2.3. Digital

frame storage gives more stable and accurate image subtraction than analogue storage where mechanical speed or mains drift can lead to synchronisation errors between stored and live images. Nakadate et al⁽¹⁾ (1980) also reported using digital storage, advocating digital non-linear processing throughout as being superior to the partial analogue processing used at Loughborough. Claims were made that high contrast fringe patterns were more easily obtained with the all-digital system. In reply to this paper, Wykes et al (1981) wrote that optimisation of the optical parameters has a greater influence on the maximum fringe contrast attainable than the form of the signal processing. While the quality of ESPI fringe patterns tends to be subjective, the results of Nakadate certainly do not appear to be any better than those of Wykes et al.

In 1981 ESPI systems were largely laboratory designs that could be used by skilled operators but had not been fully adapted for commercial use. A simplified layout of the interferometer was the favoured design for industrial use.

1.3.2 Modes of Operation

Many of the operation modes available in HI such as time averaged, double exposure and double pulsed modes had been successfully applied to ESPI by 1981. The time averaged mode received the most interest in the literature after having been introduced by Butters and Leendertz (1971). New methods were applied to extend the possible range of amplitude and phase measurements. Lokberg and Hogmoen⁽¹⁾ (1976) reported a method for the phase detection of vibration modes by phase modulating the reference beam. The method was incorporated in the commercial ESPI system from Vintens, known as "Electronic Speckle Pattern Analyser of Mode Structure", or ESPAMS (Hurden, 1982). Using phase modulation, Lokberg and Hogmoen⁽²⁾ (1976) extended the range of measurement of vibration amplitude upwards to $8.4 \mu\text{m}$ and downwards to $0.1 \text{ \AA}$ (Hogmoen and Lokberg, 1977). Large amplitude vibration is measured by cycling the reference beam phase relative to the object beam phase at the same frequency as the

object. By this means the bright zero order fringe can be moved to the positions occupied by higher fringe orders with higher amplitude phase modulation. Counting the fringe order yields the amplitude. The upper limit of measurement is fixed by the spatial resolution of the video system since the fringe width at higher orders becomes very narrow. Small amplitude vibration is measured using a photo-detector on the monitor screen to register small cyclic changes in intensity caused by low frequency phase modulation of the reference beam phase at 6 Hz. The lower limit of 0.1 Å is determined by the minimum detectable intensity change of the video system.

Beam chopping introduced to ESPI by Lokberg (1979) gives a simple method of improving the quality of vibration fringes by converting the J_0^2 intensity profile into $\cos^2$ fringes. Pulsing the laser beam at the extremes of vibration of the object gives straightforward addition of two speckle fields instead of a combination of fields due to movement in between the extremes. Using very short duration pulses, erratic or non-sinusoidal movement can be detected. At a standard video frame rate of 25 Hz, the exposure time under continuous illumination is 40 ms. Compared with HI, ESPI can tolerate more environmental instability where typical holographic exposures are of the order of 0.5 to 5 seconds. Reducing the exposure time to 0.4 ms by beam chopping gives ESPI a tolerance of up to 0.2 mms^{-1} rigid body motion (Lokberg, 1979). This degree of object stability can easily be achieved without having to take special precautions. A problem with beam chopping is that the illumination energy in each exposure is reduced due to the short duration, leading to poorer contrast fringes. Improvement in contrast is provided by using a pulsed laser where a much higher energy level per pulse is achieved. Cookson et al (1978) used a double pulsed ruby laser to investigate loudspeaker vibrations and transient events in the side of a steel cabinet. With a pulse width of 20-50 ns, object movements of up to 2 ms^{-1} could be tolerated. Preater (1980) used a similar laser with double pulsed ESPI to measure in-plane strain of a flat surface rotating with a tangential velocity of up to 3.4 ms^{-1} .

The subtraction mode includes measurement of in-plane and out-of-plane displacement, two wavelength contouring, image shearing and fluid flow. Out-of-plane measurement systems are well documented by Jones and Wykes (1981). Details of optimisation conditions have been discussed in Section 1.1.3. The maximum number of measurable fringes is 40 to 50 per screen width. At larger displacements, de-correlation and a fringe width approaching the speckle size reduces the fringe contrast. An alternative approach at larger displacements is to re-reference with the digital frame store, returning the fringe count to zero. The picture can be re-referenced as soon as the fringe visibility begins to fall. Recording the results on video tape allows post examination of continuous loading conditions in the study of non-elastic behaviour.

A significant advantage of ESPI compared with HI is that the system can be made independently sensitive to out-of-plane and in-plane displacement, depending on the illumination and viewing geometry. When measuring in-plane strain with HI there is always an out-of-plane component included in the fringe pattern. With ESPI, normal illumination and viewing gives out-of-plane sensitivity. Illumination with two object wavefronts at equal angles on either side of the viewing axis gives in-plane sensitivity, one beam acting as a reference to the other. Derby et al (1974) discuss a method for in-plane strain measurement. There are a number of conditions that have to be met if out-of-plane sensitivity is to be removed altogether. Measurement is limited to flat or gently curving surfaces, ^{although} non-normal viewing of the surface ^{is allowed.} The need for plane wavefront illumination limits the object size to that of the collimating components. Attention must also be paid to the design of the stressing rig to reduce the effects of de-correlation caused by rigid body motion.

For total strain measurement of complex surface shapes, it is necessary to know the form of the surface, as well as the displacement. Macovski et al (1971) suggested using moire methods

combined with video to measure shape and displacement. Denby et al (1975) proposed a system of two wavelength ESPI contouring, subsequently developed further by Jones and Wykes (1978). The surface to be measured is compared with a reference wavefront produced with conventional optical components or with a holographic element, giving a fringe pattern representing the difference in shape. Two wavelength ESPI contouring is discussed further in Chapter 4. The technique is interesting but requires complex apparatus and a high degree of skill to operate successfully, giving poor contrast fringes. In its present state it is unlikely to arouse much interest commercially.

Image shearing is an ESPI mode for measuring the first differential of displacement. Nakadate et al⁽²⁾ (1980) describe a technique using a Fresnel biprism in front of the objective lens to produce two sheared images. The method was stimulated by earlier work on speckle pattern shearing interferometers by Leendertz and Butters (1973) at Loughborough. Some favourable characteristics compared with other modes are that it is simple to perform and less sensitive to rigid body motion. In practice the fringes are of poorer contrast and easily de-correlate.

The final mode worth mentioning is the detection of fluid flow, making use of the sensitivity to variations in the refractive index of the medium in the path of the object beam (Butters et al, 1972). If an image of a back illuminated ground glass plate is combined with a smooth reference beam at the camera, convection currents in front of the plate give a swirling fringe pattern on subtraction. High density fluid flow gives the same effect. Results of better quality are obtained using smooth wavefronts in a Mach-Zehnder interferometer, but with the necessity of high grade optical components to produce matched wavefronts. The ESPI technique has the advantage that subtraction gives a dark reference field, allowing changes in refractive index to be detected.

This short review of operation modes demonstrates something of the versatility of ESPI in measurement and testing. The use of a video system and the direct sensitivity to in-plane strain gives ESPI certain advantages compared with holographic interferometry.

1.3.3 Applications

The applications of ESPI are similar to those of holographic interferometry. Butters (1977) presents a comparison of the two methods in non-destructive testing, a popular application for these kind of interferometric techniques. Examples are given of using HI for detecting de-bonds in car tyres and regions of poor bonding in diaphragms shown up by discontinuities in the fringe pattern. In each case loading was performed by applying pressure to produce a stress gradient across the surface. Working on the same principle of detecting fringe discontinuities, ESPI results are shown using forced vibration to reveal cell sites in honeycomb section panels. Surface heating with a warm air blower was used successfully to reveal variations in structural strength of reinforced plastic components, non-uniformities appearing as "V" shaped ESPI fringes. Very often a test rig is required for testing particular types of components. One example given is a rig for testing the bonding of brake shoe linings by applying a mechanical load. Faulty bonding was detected by comparing the ESPI pattern of the test component with an accurate pattern of a well bonded component produced holographically. In summary, Butters points out that ESPI has the advantages of speed and convenience compared with HI where rapid comparison of components is an attractive feature in NDT.

Bergquist (unpublished) has carried out work to quantify the type and size of defects that can be detected with ESPI. Discontinuities in the fringe pattern *corresponding to defects, vary in appearance* between soft rubbers, medium stiffness epoxy and carbon fibre composites, and stiffer metallic materials. Results showed that ESPI can be used to detect de-bonds in honeycomb section panels as small as 1/20 of the width of the viewing area. For example, on a panel with a width of

200 mm, an area of 10 mm diameter can be detected where the honeycomb is not glued to the front panel. The limit is fixed by the minimum area of speckle pattern required for the eye to be able to detect a difference in contrast of the fringes due to a differential surface displacement in the region of the de-bond.

Lokberg (1980) reported similar results in NDT of laminated skis with ESPI used at Eumig (Wiener Neudorf). The Norwegian group have an impressive list of applications made in the area of vibration analysis. Results have been obtained on underwater sonar transducers, the ear drum of a living person, turbine wheels and blades at a temperature of over 800°C, optical fibres vibrating in the Megahertz region and the traditional loudspeaker. The ESPI system installed in a Norwegian turbine blade manufacturing company (Lokberg, op cit) is one of the few examples of ESPI being used successfully in production testing. Turbine wheels of 20-70 kg are force vibrated and frequency scanned to detect the presence of dangerous resonant modes. Resonance frequencies are measured to an accuracy of $\pm 1\%$, the results being comparable to within 1-2% of measurements made using strain gauges under real working conditions. Quality checking of this nature ensures that vibration failure does not occur due to resonance within the operating speeds of the turbine wheels. The system was also used successfully in the development of new turbine wheels for a new power generation plant. ESPI was used to analyse a prototype wheel which was modified by adding or removing material to damp or frequency shift dangerous resonant modes. Results of the vibration mode being immediately available on the monitor made the process of modification very effective.

1.3.4 Fringe Analysis

Many of the applications described are qualitative in nature, with the exception of vibration analysis where amplitude and phase can be accurately measured using phase modulation. Making measurements of strain from a fringe field is more difficult. Consequently little mention has been found in the literature concerning quantified

results of strain measurement. At the beginning of this decade, digital processing techniques had only just been introduced in ESPI. Without digitisation of an image in a store accessible by a computer, analysis has to be performed by eye. Denby et al (1974) made measurements of in-plane strain by tracing the fringes from the monitor screen. Fringe positions were estimated to within a quarter of a fringe for closely spaced fringes. An accuracy of strain measurement of 5% was obtained, comparable with the accuracies of strain gauge measurements. Another factor affecting the accuracy is the variation in fringe sensitivity across the field of view due to the change in the angle of illumination in the case of non-collimated illumination. Calibration of the field must be made.

The more serious difficulty in fringe analysis is relating a point on the interferogram to a point on the surface of the object. Positional errors are introduced in the imaging system and during electronic processing of the video signal. The objective lens introduces optical aberrations, depending on how well corrected it is, and the camera tube itself is not able to ^{perfectly} monitor the image field due to registration errors in the field scan. Digitisation of the video signal ~~can introduce~~ aliasing and distortion. Analysis of the 2D field introduces perspective errors for off-axis points on the object surface not in the plane at which the field width is measured (discussed further in Chapter 5). Some of these aspects are currently being investigated at Loughborough.

1.3.5 Summary

Butters and Leendertz (1971) foresaw some of the potential of ESPI in engineering measurement and testing. Real time analysis, robustness and the availability of an electrical signal for automatic processing gave ESPI advantages in applications work compared with the HI technique. Over the following decade some of the potential was exploited by a few but not to any great extent by industry. In 1981, ten years after its introduction, ESPI was a well developed laboratory technique, outperforming HI in its ease of use, but giving

Footnote: Amendment - page 39 does not exist

poorer quality interferograms. The technique was thought to be well understood and documented theoretically. Little work had been carried out in fringe analysis due to the difficulties encountered. Shape measurement could be made with ESPI but the two wavelength contouring technique was too impractical for industrial use. A commercial ESPI system was available in Britain but experienced much less success than a one-off design installed in a Norwegian manufacturing company. The key to success was in some part due to the simplicity of the design.

1.4 DEVELOPMENTS SINCE 1981

During the period of the author's own work, there have been some important advances made in ESPI. In this section a survey is given of some of the more significant literature published by other workers in the field between 1981 and 1986.

1.4.1 Design

One of the most important developments in ESPI in this period is that two major optical companies have bought licences to manufacture their own ESPI instruments. The original patents by Butters and Leendertz for the basic ESPI principle, are held by the British Technology Group (BTG). Through the work of Tyrer and co-workers at Loughborough, a British company, Ealing Electro-Optics plc have designed a prototype based on a Loughborough design which they began marketing as the "Vidispec" in September 1985. An American company, Newport Corporation, are currently building a prototype based on a similar Loughborough design. Unlike the Vintens and Loughborough demonstration rigs which accommodate the object on the same baseplate as the interferometer, the Vidispec is a "point and shoot" system. The interferometer is built on a separate baseplate and pointed at the object, as shown in Figure 2.5, giving great versatility in object distances, positions and sizes. Retro prisms used in variable path length compensation in the Loughborough demonstration rig is developed further in the Vidispec by folding the beam five times

(Figure 2.1). Moving one of the prisms alters the reference beam path length, giving a choice of object distances of 0.3 to 1.2m in front of the viewing lens. While providing a large range of object positions, beam folding introduces 20 extra air-glass surfaces into the path of the reference beam, adding optical noise. The result after spatial filtering is a rather patchy, non-gaussian intensity distribution. A 5 mW HeNe laser is used, giving a maximum viewing area of 0.3m. A conventional 35 mm format photographic zoom lens introduced by the author, gives an easily accessible range of field views depending on the focal length. The remainder of the optical design is similar to the Loughborough demonstration rig, using off axis illumination and a wedge beam splitter for combining the object and reference beams. A Chalnicon video camera is connected to a newly designed processing section and digital framestore (see Appendix B for details). Further analysis of the Vidispec is given in Chapter 2 as it is relevant to the author's work. The importance of the collaboration between Loughborough and two major optical manufacturing companies is that it shows there is renewed interest in ESPI and that there now exists the means for producing a more successful commercial design.

The use of a glass wedge for beam combining inevitably introduces optical noise and aberrations in the phase referenced speckle pattern. A solution to this problem is elegantly provided by Creath and Slettemoen (1985) using a single mode optical fibre.

Instead of combining the reference and object waves with a beam splitter, the reference wave is introduced from the end of the fibre placed at the centre of the imaging aperture. The fibre is so small that it spatially filters the reference beam giving a smooth gaussian intensity profile. One problem encountered is slight phase changes due to air currents moving the fibre. No comment is made on how the fibre is mounted in the aperture.

In the same paper by Creath and Slettemoen, a second design improvement is the use of a CCD array camera in place of the

traditional camera tube. High scanning speeds can be attained, a frame period of 5 mS being used in the application discussed. Because of the use of individual photodiode elements, the picture registration accuracy is high. In principle the CCD camera is an improvement on the camera tube but with a low resolution 100×100 array used, the results shown are poor. Only the first order dark fringe in the vibration pattern is visible by eye. A higher resolution array would give significant improvements.

Bergquist and Mendoza-Santoyo (1986) have recently reported experimental results challenging earlier theoretical work on the importance of conjugacy on fringe visibility. Tests are reported using diverging, plane and converging smooth reference wavefronts in a conventional out-of-plane ESPI system. Initial results confirm the need for colinearity of the reference and object beam axes, but indicate that axial conjugacy is not as critical as that calculated by Jones and Wykes (1983). Results show that a slightly diverging beam would give optimum fringe contrast at an aperture of $f/25$ used in the experiments. No results are given for other apertures. In the author's experience, axial conjugacy depends on the aperture, becoming more critical at apertures of $f/32$ or greater. In this case, a slightly diverging reference beam would give a circular area of fringes in the centre of the field of view surrounded by an area of zero fringe contrast, indicating a definite cut-off point in conjugacy.

Apart from these individual cases discussed concerning the design of the interferometer, no serious analysis of the optical design has been found in the literature.

1.4.2 Modes of Operation

Further application of the methods used in HI have been made in ESPI, developing the modes of operation beyond that which was possible in 1981. Particular success has been gained with the use of new laser

sources. The period has also seen the emergence of a new method of contouring.

A method for removing the effects of the fluid in a cell while studying a sample in the fluid is reported by Rowland and Mendoza-Santoyo (1986). The aim of the work was to measure the dynamic bulk properties of elastomer samples by cyclically pressurising them in a pressure cell and measuring the amplitude of deformation with ESPI. Pressurising the fluid alters the effective path length of the object beam as it illuminates the sample, adding an extra component to the fringe field. The solution is to pass the reference beam through the same depth of fluid as the object beam by reflecting it from a mirror positioned next to the sample. The effects of the fluid are cancelled, allowing the sample displacements to be measured independently.

There are certain advantages to be gained in using alternative lasers to the HeNe and Ar Ion lasers traditionally used in ESPI. For example, the CO₂ laser produces light of 10.6 μm wavelength, giving a corresponding fringe sensitivity in the range of 5-20 μm , bridging the gap between ESPI and moire sensitivities. Lokberg and Kwon (1984) discuss the difficulties involved in using a 5W continuous wave CO₂ laser in ESPI. Some of the problems to be overcome are the non-optical wavelength, the large speckle size, the low resolution of the "Pyrricon" detector and the different operating principle of the detector. Instead of detecting integrated energy as with an ordinary vidicon tube, the "Pyrricon" detects changes in incident radiation during a single TV frame. Time averaged results are shown with 2 to 4 fringes on objects oscillating at 5 Hz and 30 Hz. Although the results are of poor quality the work indicates some of the possibilities of using infra red laser light.

A significant step forward for using pulsed ESPI in industrial measurement is the application of the Nd YAG laser by Tyrer (1985). Improvements in this laser in recent years are such that a double pulsed frequency doubled laser beam can now be produced at repetition

rates comparable with video frame rates. Operating at a wavelength of 530 nm, results have been obtained in loudspeaker vibration analysis. The system is more reliable, easier to maintain and has a more portable power supply than the pulsed ruby laser. Pulsed ESPI is particularly useful for analysing components and machinery in real operating conditions as the short exposure time removes the requirement for interferometric stability.

After the difficulties encountered with two wavelength ESPI contouring, a new method of single wavelength contouring using wavefront shearing has been introduced by Winther and Slettemoen (1984) and Bergquist and Montgomery (1985). Winther and Slettemoen use the displacement of the end of a single mode optical fibre carrying the illumination beam to produce projected grid contours. No stationary reference fringe is formed, limiting the potential of the method. Bergquist and Montgomery on the other hand rotate a mirror in the path of the object beam, which gives an identifiable zero order fringe, and greater potential for contouring. The development of this mode is the subject of Chapter 4. The conclusion of both papers is that the method gives potential for an ESPI system with a combined displacement and shape measurement facility.

1.4.3 Applications

In the area of applications, the range of field widths and object temperatures that can be studied with ESPI has been increased. Herbert (1983) has studied out-of-plane deformation on areas as small as 1 mm^2 with a fringe density of 20 fringes per screen width. On a field width of $300 \mu\text{m}$ the fringe density is reduced to 7 per screen width due to de-correlation. At high magnifications, in-plane movement of the surface is of the order of the diameter of the resolution element at the object surface. For object widths of less than 1 mm, Herbert found that the resolution element was of the order of $1 \mu\text{m}$, the same order as the in-plane movement caused by the out-of-plane displacement resulting in de-correlation.

At the opposite extreme of field size, Bergquist (1982) reports results on a 1.25m target with a 15 mW HeNe laser and Chalnicon camera. Forty measurable fringes and up to seventy ^{discernible} fringes by eye were obtained. These exceptional results were achieved by careful optimisation of the system parameters for the case of low laser power available when it is not possible to have ideal optimisation conditions. The scattered object light collected at the lens is increased by opening the aperture to $f/4.5$, and the reference beam intensity is increased to run the camera near to the saturation level. Even though the speckle cut-off frequency is theoretically below the resolution limit of the camera at this large aperture, measurable fringes were obtained. These results suggest that the cut-off is not absolute but that there is enough resolvable speckle information remaining for the system to work.

Most ESPI applications are carried out on objects at or near to room temperature. Lokberg et al (1985) has successfully demonstrated the use of ESPI on objects at 1700°C . The use of beam chopping and careful filtering using multiple layers of absorbing filters removes unwanted infra red heat.

Extending the range of sample sizes opens up many new industrial applications, from the study of precision engineering components to aircraft panels. The ability to study high temperature objects opens up new applications in deformation studies in rolling, extrusion, forging and general material forming.

1.4.4 Fringe Analysis

The introduction of digital processing to ESPI at the beginning of this decade has resulted in fervent activity in fringe processing and analysis. Some interesting and significant advances have been made in the processing of traditional correlation fringe patterns and in calculating complete phase change maps using phase stepping.

Different approaches have been taken in the area of processing traditional correlation fringe patterns. The aim of processing fringes is to identify the positions of the maxima and minima. Varman and Wykes (1982) suggest the totally automatic approach using digital processing routines to reduce the speckle noise sufficiently for a simple algorithm to be used to detect peaks and troughs in the intensity. Polynomial smoothing of an image by performing a least squares fit of a Chebyshev polynomial over a series of overlapping grids gives an improved image, taking a few minutes on the Texas 990 microcomputer. Smoothing by passing a 3 x 3 pixel "window" across the image and modifying the central intensity takes half a minute. Digital filtering is used with a Fast Fourier Transform (FFT) subroutine to convert a line at a time into a spatial frequency distribution. Applying a filter to the spectrum and transforming back into an intensity distribution gives a smoothed pattern. Improved results were obtained by repeating the procedure in the orthogonal direction giving 2D filtering. On a mainframe computer, 2D filtering of a 256 x 256 x 8 bit image takes 5 to 6 hours. More recently, Henry (Montgomery, Bergquist and Henry, 1986) has performed 2D filtering on a 256 x 256 x 6 bit image of an ESPI fringe pattern using a DEC PDP 11/03 microcomputer in 10 hours.

Nakadate et al (1983) also report advanced digital image processing using contrast stretching, thresholding and skeletonising to reduce a speckle fringe pattern to a set of solid contour lines. Results shown have a fringe density of 16 fringes per picture width, starting from a high quality ESPI fringe pattern. In the author's experience, processing fringe patterns to give unbroken contour lines in this way works well on high contrast fringes with a normalised overall intensity profile across the image and low noise contributions. If there are sharp changes in intensity, or noise from the reference beam or object detail, contour information is lost and a confused pattern of broken lines results. An alternative is to use the man-machine interactive mode proposed in the same paper by Nakadate et al. Moderate smoothing is followed by the operator using a light pen to define working areas and initiate automatic marking of fringe

minima. Erroneous positions are corrected by the operator, fringe numbers inserted and a polynomial function fitted to the contours. Differentiation of the function gives the slope, strain and bending moment of the deformation. Combining the intelligence of the operator in deciding what is and is not useful information, and the data processing speed of the computer results in a successful fringe analysis system for analysing realistic results.

Hurden (1982) suggests an even simpler method for analysing vibration fringe patterns. No processing is carried out, as it relies on the fact that the bright zero order fringe is fairly definable by eye. The operator tracks the position of the zero order fringe with a light pen. Using the reference beam phase modulation technique proposed by Lokberg and Hogmoen⁽¹⁾ (1976), the bright fringe is moved to the position formerly occupied by the first higher order fringe. This process is repeated for all the higher order fringes, marking each with the light pen. Knowing the phase modulation, and counting the fringe orders allows calculations to be made on a small computer to yield an isometric view of the vibration mode, displayed on the monitor screen. The interactive mode provides a simple but effective method of producing full field quantified results.

Two interesting methods for improving the quality of time averaged fringes to help in fringe analysis have been reported during this period of work. The author has subsequently developed these methods further, reported in Chapter 3. The first method is the subtraction of time invariant noise related to the reference and object beams. Nakadate et al⁽²⁾ (1980) suggested subtracting the speckle pattern of the object at rest from the speckle pattern of the vibrating object. Creath and Slettemoen (1985) followed with a theoretical analysis of this and other noise subtraction modes which they named as follows:

- CASE I - standard time average mode
- CASE II - subtraction of the combined speckle pattern of the object at rest from that of the vibration object (method of Nakadate et al)

- CASE III - subtraction of a reference frame formed from the object at rest and the reference beam phase oscillating at a large amplitude from the combined pattern formed by the object vibrating and a normal reference beam
- CASE IV - subtraction of a reference frame formed by the object vibrating from a pattern of the same object vibrating but with a π phase change introduced between the object and reference beams
- CASE V - like CASE II but with a π phase change introduced between the two beams after subtraction.

All the methods summarised give a bright zero order fringe except for CASE II in which it is dark. The paper reports that CASES II, IV and V give improved results with lower noise values but that they are also sensitive to out-of-plane displacement. In the case of unstable objects, the effect is to add displacement fringes, confusing the vibration pattern. CASE III proposed by Creath and Slettemoen is suggested as being superior as it is only sensitive to vibration and is therefore suitable for objects that may drift or slowly distort with time. Fringe pattern results are only shown for CASE I and CASE III. The results are of poor quality because a low resolution CCD array is used. CASE IV is a method that has been commonly used at Loughborough since the introduction of digital framestores.

The second technique proposed in the literature involves averaging the time variant electronic and speckle noise. In the time averaged mode addition fringes are formed on the camera faceplate due to many vibration cycles of the object during a single frame period. If the amplitude of vibration is unaltered, the fringe pattern remains the same over successive frames. The electronic noise associated with the camera and processing electronics on the other hand varies between frames. Nakadate et al (1980) used this fact to reduce the random electronic noise by averaging 60 frames. This technique is a common method of noise reduction in thermal imaging, long distance

radio communication etc. The speckle pattern due to the object is normally stationary between frames. Slettemoen (1980) suggested a method of changing the basic speckle pattern by rotating a double slit aperture, thereby altering the viewing direction. A long exposure photograph of the picture on the monitor with the speckle pattern slowly varying between frames produces a photograph with reduced speckle noise. Further examples of photographic speckle averaging are given by Lokberg and Slettemoen (1984), de-correlating the speckle pattern by changing the direction of illumination of the object surface. The method is proposed as being useful for the presentation of results. The limitations of the technique are that the results are photographic, involving a time delay in chemical processing and they are not immediately accessible for automatic analysis by computer. The de-correlation method also restricts the results to low amplitude vibration measurement since at high amplitudes the fine fringes "wash out" due to the change in interferometric sensitivity.

Both the methods of noise subtraction and speckle averaging give results that more closely approximate the underlying correlation pattern. The images are clearer and of a higher resolution, reducing the need for post-image smoothing before fringe analysis.

One of the most significant advances made towards successful automatic fringe analysis in ESPI has been the application of phase-stepping techniques. Instead of forming dark and bright speckled fringes indicating lines of constant phase change in the traditional subtraction mode, a map is produced of numerical values of the phase change that includes the sense of the change. Phase-stepping has already been successfully applied to both HI (e.g. see Hariharan, 1982) and moire techniques (Reid, 1984). An ESPI phase map is produced in the following manner. The first step is to form a map of arbitrary phase values for each pixel in the digitised image of the speckle pattern of the object at rest. This map is calculated from three or more images containing slightly different speckle intensities formed by stepping the reference beam phase through three

or more divisions of a 2π phase change. The object is deformed and the process repeated to form a second phase map. Subtraction of the two phase maps reveals the phase change in steps of 2π across the image. Removal of these 2π phase discontinuities reveals an absolute phase change map from which the magnitude and sense of displacement are calculated. The main drawback to the technique reducing the resolution is the presence of speckle noise. Speckle de-correlation, points of low or zero intensity modulation and camera saturation give a random array of erroneous phase values. The effect of this "salt and pepper noise" as it is termed, can be reduced by smoothing.

Three papers were published at about the same time on the subject of phase-stepped ESPI, the results showing varying degrees of success. Nakadate et al (1985) give an impressive set of results in the form of isometric views of deformation for out-of-plane, in-plane and image shearing modes. A Chalnicon video camera is used with a slightly different approach taken to that just described, initially storing only one image of the speckle pattern in the undeformed state. The object is deformed and four images are stored for phase changes of 0 , $\pi/2$, π and $3\pi/2$. These images are subtracted from the pattern stored before deformation and the result squared to give four new images. The phase map is then calculated. Creath (1985) follows the standard phase-stepping method described, storing four images before and after deformation. Results are shown for out-of-plane displacement measurement using a 100×100 CCD array.

In both the examples by Nakadate et al and Creath, the accuracy of displacement measurement was determined experimentally to be $\lambda/10$. The main problem found in each case was the large number of erroneous phase measurements due to speckle noise. Both resort to using multiple iterations of median window smoothing with arrays of 3×3 to 11×11 pixels to reduce the problem. In the case of Nakadate et al, a speckled reference beam is used, adding unnecessary optical noise. Using a smooth reference beam would reduce the number of "bad points". With the method by Creath, the main problem is the low resolution detector array, giving aliasing and a loss of information.

Creath suggests that further problems are caused by de-correlation due to the tilt of the object during deformation at the small aperture of $f/40$. The solution proposed is to enlarge the aperture if the detector resolution had permitted it. From Section 1.1.3 for out-of-plane related de-correlation, the pattern de-correlates when the surface moves through an angle θ (Jones and Wykes, 1983), is given by:

$$\theta \approx \frac{MA}{f}$$

where M = magnification
 A = aperture diameter
 f = focal length

According to this estimation, de-correlation could be reduced by moving the object closer to the object lens to increase the magnification.

A third report on ESPI phase stepping is covered in a paper on "Electrooptic Holography" by Stetson et al (1985) in which some sort of novel technique is claimed in applying digital processing to speckle pattern correlation interferometry. In reality, it is a theoretical discussion of the advantages of ESPI combined with digital processing techniques applied to NDT. Butters and Leendertz pointed out the advantages of having a direct video signal available for processing in 1971 and Nakadate et al were performing all-digital processing of ESPI results in 1980. The phase stepping technique suggested by Stetson uses N images before and after deformation. No results of phase map calculations are given. The method takes no account of the speckle noise, which the previous two methods found to be the greatest limitation in practice. On the other hand, the previous two methods give little indication of the processing time involved, which would probably amount to tens of minutes on the microcomputers used. Stetson calculates that with an MC 68000 microprocessor at a clock rate of 12 MHz, the processing time could be reduced to a few seconds with multichannel processing, suggesting the use of a parallel processor.

The success in developing digital processing techniques for the analysis of ESPI results gives some indication that there is a renewed interest in ESPI, particularly with the advent of phase stepping techniques. During the period of the author's work there has been a growth in the appreciation of the potential of using a video system in this kind of speckle interferometric measurement technique.

1.5 SCOPE OF THE THESIS

1.5.1 Conclusions of Literature Survey

A number of conclusions can be made from the literature survey in Sections 1.3 and 1.4:

- Complex optical designs of the interferometer give a poorer quality output than simple designs due to a susceptibility to optical noise and light losses through the use of a large number of optical components. The system is made less attractive to use because of fringe drift and the difficulty of operating the system. No serious analysis of the efficiency of the optical system or the aberrations introduced by the wedge beam combiner and simple lens has been published. For operating the interferometer larger apertures may be used and the positioning of the reference beam origin along the optical axis is not as critical as at first thought.
- The noisy output is improved by digital image processing techniques such as smoothing, FFT's and contrast stretching. Processing a $256 \times 256 \times 6$ bit image takes many minutes or even hours on a microcomputer. Semi-automatic fringe analysis can be performed with an operator using a light pen. Time averaged fringes are improved by the use of noise subtraction and speckle averaging techniques. Little work has been published on the problem of relating image points on the interferogram to points on the object.

- Two wavelength ESPI contouring is difficult to perform and yields poor contrast results. The new mode of wavefront shearing or Electronic Speckle Contouring (ESC) shows greater potential for ESPI shape measurement.
- In 1981 ESPI remained essentially a laboratory technique, the main problems being the practical operation and the noisy output. Subsequent work has led to a more successful commercial design of ESPI than the earlier Vintens system. Renewed interest in developing ESPI has resulted from improvements in digital image processing techniques, particularly with the application of phase stepping. The versatility of ESPI as an interferometric measurement technique is becoming more widely appreciated, the video system providing speed and ease of analysis. Preliminary results using solid state cameras, optical fibres, and the Nd YAG double pulsed laser indicate ESPI has potential for further development and more widespread use in industrial testing and measurement.

1.5.2 Objectives

In the light of the conclusions made from the literature survey and the work carried out by the author, the main objectives of this thesis are:

1. To show how the ESPI instrument can be made more attractive to use by simplifying the optical interferometer and improving the quality of the output.
2. To lay the foundation for a total ESPI measurement system capable of measuring shape as well as displacement by developing ESC.
3. To demonstrate that ESPI is a viable industrial testing and measurement technique that is worth developing, by illustrating the work with practical applications and by comparing it with other optical techniques.

1.5.3 Chapter Summaries

The chapters include the following work:

Chapter 2: Optical Design - An analysis of the optical design of the interferometer is carried out by the author, and a number of ideas are investigated for improving the light efficiency, reducing the optical noise and aberrations and making the system more flexible to use. Multi laser cavity path length compensation, optical coatings, component quality, a cube beam combiner and multi element zoom lens are considered.

Chapter 3: Noise Reduction - The problem of noise and signal quality in the ESPI output is discussed, giving three levels of noise reduction: simple analogue processing of the video signal; time invariant noise subtraction in the time averaged mode and ensemble averaging of speckle noise.

Chapter 4: Electronic Speckle Contouring (ESC) - Following the theory proposed by Bergquist, the new method of ESPI contouring is developed empirically using various techniques of wavefront shearing. Noise reduction methods developed in Chapter 3 are applied to improve the results, and a design is suggested, combining some of the latest techniques developed by other workers to give a system capable of measuring shape as well as displacement.

Chapter 5: Comparison of ESPI with Other Optical Techniques - Justification of the development of ESPI as a useful technique for engineering measurement is given by comparing the technique with speckle pattern photography, holographic interferometry and moire techniques. The section on moire includes a white light projected grid technique developed by the author to demonstrate some of the potential of ESC in shape measurement.

Chapter 6: Discussion and Conclusions - The work is completed with a discussion of the contributions made to the development of ESPI by the author and other workers in the field. Ideas for future work are recommended. The conclusions summarise the main findings of the work.

The thesis is a presentation of forward looking innovations that are already benefitting ESPI systems now in use and lay the foundations for future systems giving new and better quality results than are possible at present. The innovations described are accompanied, where possible, with applications carried out by the author to demonstrate some of the potential of ESPI as an industrial testing and measurement technique. Examples are given throughout the body of the work to elucidate the ideas as they are developed.

CHAPTER 2

OPTICAL DESIGN

Commercial interferometers have attained high standards of manufacture through a long history of development. When a video system and electronic processing are added in ESPI to form a new type of interferometer in which the fringe pattern is pseudo-interferometric, further complications are added. The interference of two wavefronts in the image plane is affected by many factors: the image resolution limit, speckle distribution, de-correlation, conjugacy, coherence length, focussing, polarisation, beam ratios, optical path stability and perhaps other factors as well. Matching these to the camera and frame store introduces further resolution limits, aliasing and an assortment of other parameters that must be taken into consideration.

The problem of optimising an ESPI system is demonstrated by the variation in quality of the results shown in the literature. In a paper by Nakadate et al⁽¹⁾ (1980) claims are made that non-linear digital processing in ESPI gives certain improvements. Using a 50 mW HeNe laser to inspect a target area of 70 x 60 mm a maximum of ten fringes are shown in the results.

Although fringe visibility is perhaps subjective, a reply to this paper by Wykes et al (1981) suggests that the results are of poor quality due to lack of optimisation. They indicate that high contrast fringes over an area of 100 x 100 mm are easily obtained with a 5 mW laser in the Vinten's system and summarise the procedure for optimising using correct beam ratios and apertures. The original paper by Butters and Leendertz (1971) shows 80 discernible fringes in the subtraction mode with what looks like a 15 mW HeNe laser (details are not given). If the number of fringes gives some indication of performance, recent papers on phase stepping techniques show poor quality results compared with these early results. Nakadate et al (1985) show phase maps made up of 15 fringes and Creath (1985), 8 fringes, claiming that it is possible to obtain up to 10 using the

100 x 100 diode array used in her particular arrangement. Bergquist (1982) on the other hand reports an ESPI system capable of giving 40 measurable and 70 discernible fringes on an object 1.25m square with a 15 mW laser and an aperture of $f/4.5$.

A good paper on optimisation by Slettemoen (1979) describes the influence of beam ratios, camera resolution, imaging aperture size, and optical and electronic noise on the fringe visibility. Jones and Wykes (1977) quantify de-correlation effects and in a later paper discuss mechanical stability, coherence, and other general parameters for optimising an ESPI system (Jones and Wykes, 1981). Although it is thought that conjugacy and system resolution are well understood, these aspects are receiving renewed attention at Loughborough (Bergquist and Mendoza-Santoyo, 1986).

There is not a lot reported on the hardware of ESPI systems. Jones and Wykes (1983, pp 189-190) analyse the standard Vidicon, Newvicon, Silicon Vidicon and other tubes but already this is out-of-date with the Chalnicon and Super-Chalnicon having since become available. Recent work at Loughborough has suggested improvements could be made with the store and electronics by optimising each part of the processing sequence to reduce the problem of drift (e.g. see Chapter 3 on speckle averaging) and to preserve the full information content of the video signal. A full development programme concerning the application of new sensors, memory chips, A/D D/A converters etc is ideally required. This particular aspect is outside the scope of the present work.

In this chapter, some aspects of the quality of optical components in the interferometer are considered. The limitations of laser coherence length and the place of path length compensation are also discussed. These factors are of fundamental importance to the formation of high visibility correlation fringes. The work is restricted to the use of out-of-plane sensitive systems using a smooth reference beam, the principles being true for most modes of operation.

2.1 DESIGN CRITERIA

2.1.1 Introduction

The design of classical interferometers such as the Michelson or the Fizeau interferometer are aided by modern computer techniques and new processes of forming precise surface shapes where wavefront geometry and optical path lengths require accuracies of a fraction of the wavelength of light. With ESPI this is not so much the case. The conditions of coherence length and conjugacy typically require accuracies of fractions of a millimetre since measurement depends on phase changes rather than absolute phase. It is surprising how reasonable results can be achieved with the use of laboratory quality optics, and a piece of string for measuring path lengths.

Component instability can make the need for continual readjustment quite bothersome, a factor which is unacceptable in an industrial instrument. A fixed field of view also imposes a limitation where interactive analysis is enhanced by the ability to consider detail as well as the general view. Aspects of quality of data, simplicity of design and flexibility of use are significant considerations in designing any ESPI system. To meet these requirements, investigations have been carried out into the following areas:

2.1.2 Quality

The proportion of light from the laser available to illuminate the object depends on the efficiency of the optical components used to produce the object and reference beams. The quality of the materials used in these components and the presence of surface dirt affects the amount of optical noise added to the beams. Although spatial filtering is effective in noise reduction, noise of low spatial frequency and that which is added after filtering still remains a problem. The beam combiner between the camera and lens has been found to be a critical component in this respect. Where a glass wedge has been used, optical aberrations are also introduced which affect the image quality. Some of these aspects are considered.

2.1.3 Simplicity

In both the Vinten's system and the Vidispec, a large number of components are used in the path of the reference beam to make it equivalent in length to that of the object beam. This increases the susceptibility to optical noise and air turbulence which affects the quality and phase of the reference beam. Simplification in the design is suggested, with the use of a reference beam path that is shorter than the object beam path by an integral number of laser cavity lengths to operate within one of the coherence planes.

2.1.4 Flexibility

A simple lens restricts the field of view and is prone to optical aberrations. A multi-element zoom lens is suggested to reduce aberrations and give an adjustable field of view.

The effectiveness of these changes is now discussed.

2.2 OPTICAL COMPONENT QUALITY

2.2.1 Efficiency

The reflection and transmission characteristics of optical components is a parameter not quantified in the literature but left to the consideration of individual ESPI operators.

Low power HeNe lasers are convenient light sources for portable ESPI systems such as the Vidispec, and the Loughborough demonstration rig. The power of the light illuminating the target sets an upper limit on the area that can be studied. Early versions of the Vidispec quote a target width of 0.3m with a 10 mW laser. Obviously the surface preparation of the target and the sensitivity of the camera affect this limit, but it is related to the useful output power.

A simple test was carried out to determine the efficiencies of optical components.

2.2.1.1 Investigation of optical efficiency of an Ealing Optics Vidispec ESPI system

The power of the laser beam was measured at a number of points in the Vidispec Interferometer using a "Coherent Model 212" power meter. The silicon photo cell was suspended perpendicularly to the beam being measured, the laser blanked off and the meter set to zero to compensate for background light levels, subdued light being used in the laboratory. The meter range giving the maximum reading was used each time, with a worst reading error of $\pm 3\%$. In the case of components that reflect an expanded laser beam that is larger than the detector area, an unexpanded laser beam was used to measure the efficiency of the component and the power calculated accordingly.

A diagram of the layout is shown in Figure 2.1 with the light power given at each point. The figures quoted for the reference beam are typical of that used in the subtraction mode. Table 2.1 gives a list of the efficiencies of each component.

The main point of interest is that from these figures only 5.3 mW or 51% of the original 10.4 mW is used to illuminate the object. This is remarkably low considering that only 0.5 μ W is required for the reference beam at the camera faceplate. Similar measurements made on the Loughborough demonstration rig indicated similar results with only 49% of the original 5 mW beam available for illuminating the object.

The use of specialised optical coatings would reduce these losses. For example, over-coated silver mirror coatings increases the reflectivity to 96% and broadband multi-layer coatings reduces reflections at 45° to 0.5% to give the theoretical results in the third column of Table 2.1.

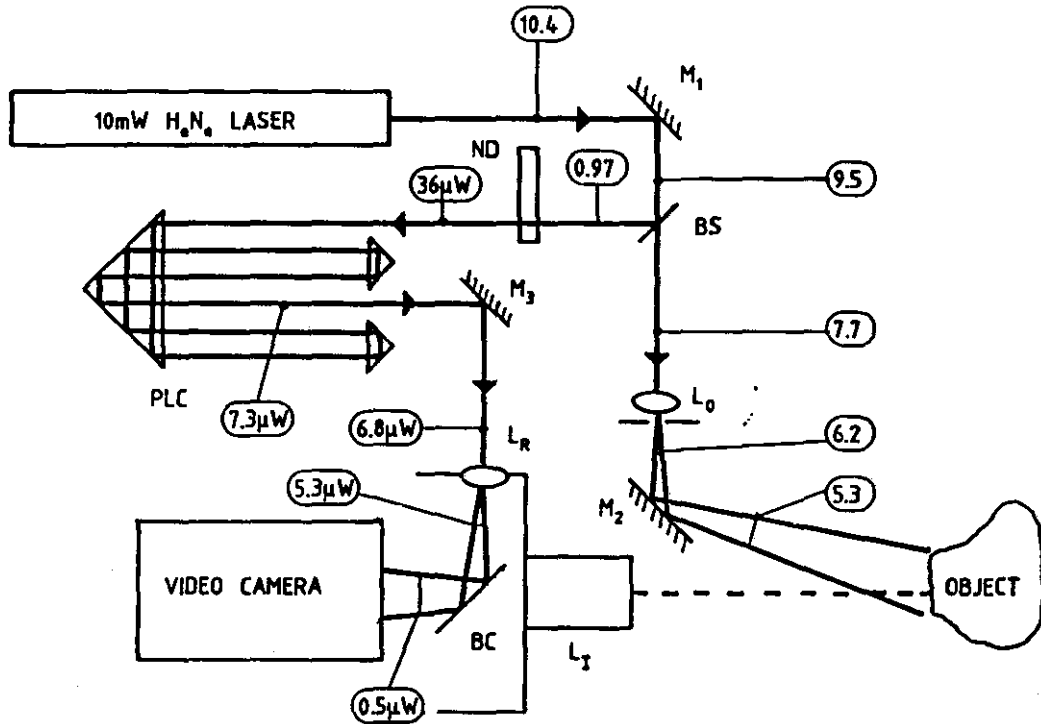


FIGURE 2.1: Laser beam power at different points in the Vidispec interferometer - power in mW unless otherwise stated

Component	Efficiency	
	Measured	Theoretical After Coating
M1 Main mirror	91%R	96.%R
M2 Object mirror	86%R	96%R
M3 Reference mirror	93%R	96%R
BS Beam splitter	10%R 81%T	2%R 94%T
BC Beam combiner	10%R 82%T	4%R 94%T
ND Variable ND filter	4%T	25%T
PLC Path length compensator	20%T	62%T
LO Object beam lens	81%T	86%T
LR Reference beam lens	78%T	86%T
LI Imaging lens	86%T	86%T

TABLE 2.1: Efficiency of optical components in the Vidispec, measured and theoretical, after special coatings applied
R - Reflection, T - Transmission

On this basis, the light available in the object beam is increased by 2.4 mW from 5.3 to 7.7 mW, an improvement of 45%. This gives an increase of 20% of the diameter of the target area. Judicious use of coatings and high efficiency dichromate gelatin holographic elements may give further improvements. As well as saving light power, unwanted reflections are reduced that minimise optical noise from scattering, diffraction and interference effects that are always a problem when using coherent laser light.

2.2.2 Optical Noise

Optical noise introduced into the reference and object beams by the optical elements deteriorates the quality of ESPI fringes. Slettemoen (1977) shows that the optimum contrast of time averaged fringes is achieved when the reference noise is at a minimum. With subtraction fringes the reference noise is removed to a certain degree, in the process of subtraction. The problem of noise has been highlighted in the present work by speckle averaging reported in Chapter 3, in which optical noise not known about before was discovered. These were revealed as the signal to noise ratio of the basic ESPI process was increased. In this section, some aspects of the origin of optical noise and how it can be reduced at source are discussed.

Optical noise consists of any signal that is not wanted. In an interferometer using smooth reference and object beams it is any perturbation from the smooth Gaussian intensity profile of the beam formed by a laser running in the TEM_{00} transverse mode. The laser cavity itself is a source of optical noise that is usually of high spatial frequency and can be removed by spatial filtering. Each optical surface that the beam passes through or is reflected from adds noise by absorption or diffraction effects due to microscopic imperfections, grease or dirt. Spatial filtering removes most of the noise but more light is lost the smaller the pinhole that is used to remove the lower spatial frequencies.

A speck of dust on a mirror demonstrates this problem. The dust forms a circular diffraction pattern in a beam reflected from the mirror. If the central rings are of a low enough spatial frequency, a dark circular shadow is formed when the beam is spatially filtered, while the finer higher orders are removed.

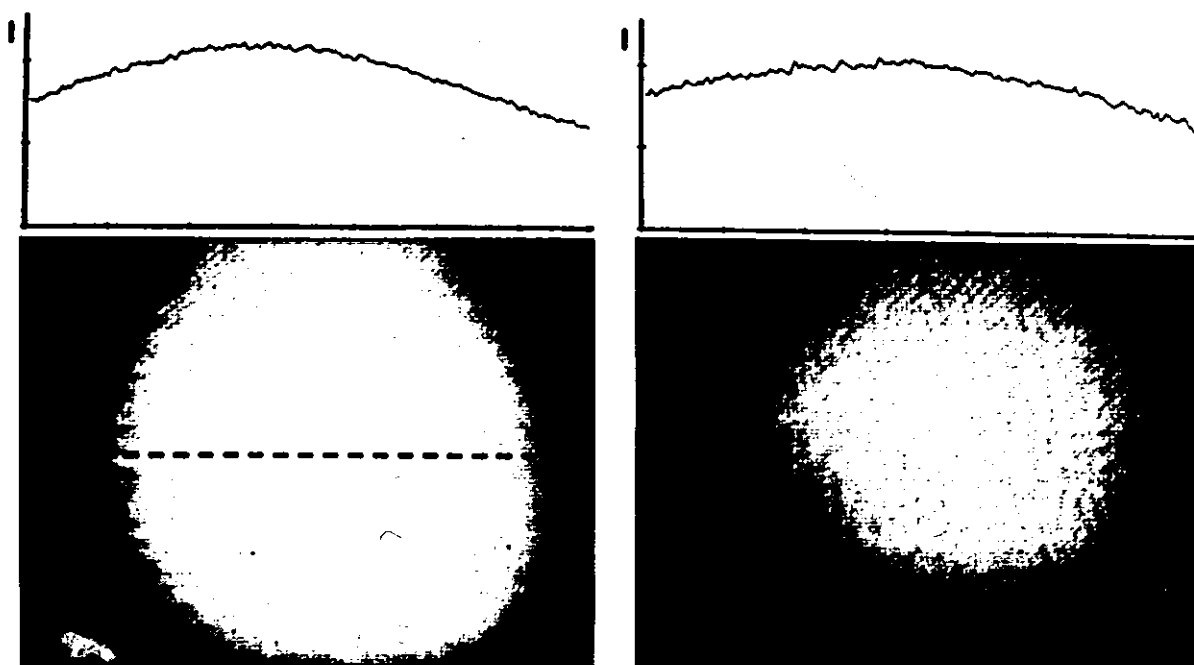
Any optical element placed in the path of the beam after the spatial filter is a likely source of noise. In practice the beam combining wedge in front of the camera is particularly troublesome in this respect. A selection of photographs of reference beams reflected from different beam combining elements at 45° are shown in Figure 2.3. They may appear at first to be similar, but the intensity profiles given show some of the differences. The best profiles are given by the uncoated glass wedge in (a) and the $\lambda/10$ optical flat in (c).

The picture in (b) shows regular undulations in the intensity, or "blotches" which are possibly caused by a faulty anti-reflection coating. This wedge was used in the ESPI system from which some of the speckle averaged interferograms were made, giving them a mottled appearance (e.g. see Figure 3.20(b)). A different sort of noise is observed in Figure 2.3(d) in which the profile falls off rapidly towards the edges. This is suspected ~~as~~ being due to noise from the path length compensator in the Vidispec due to the beam striking 20 boundaries in the prisms. More noise is added with each surface and it is not completely removed after spatial filtering.

In all four cases there are very faint regularly spaced lines. The diagonal lines in (a) and (b) may be interference fringes from multiple internal reflections. In (c) and (d) there is a set of faint vertical lines. This is suspected ~~as~~ being due to a fault in the camera from crossover noise from the timing circuits.

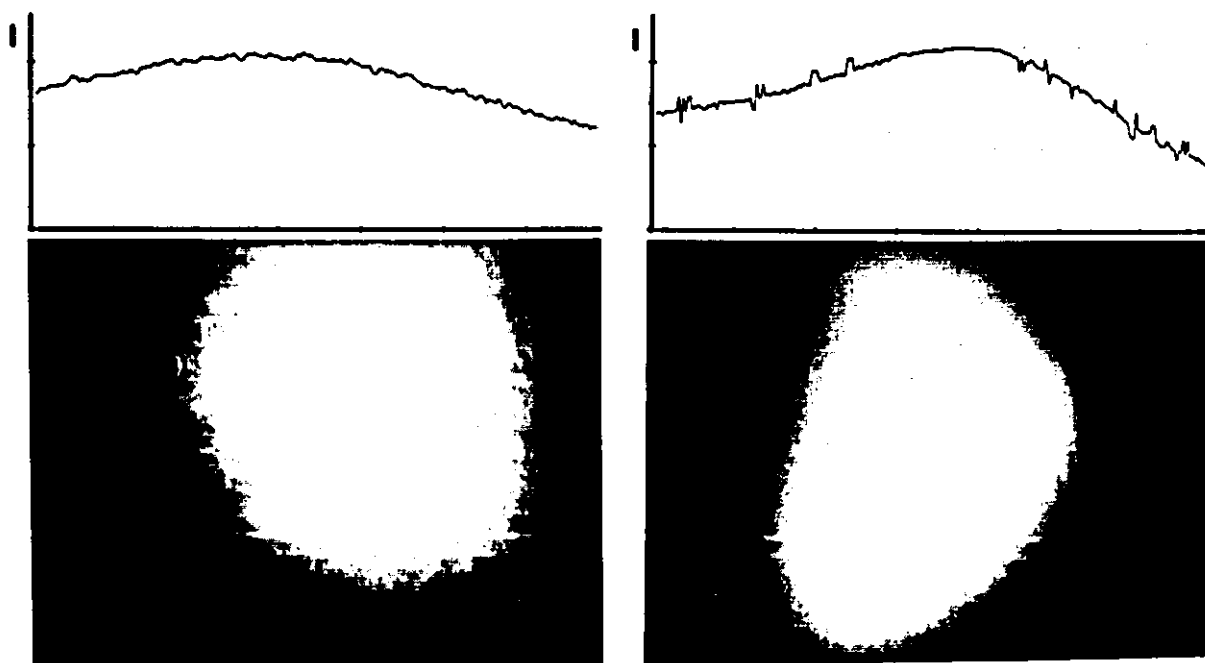
The conclusion from this investigation is that the reference beam is particularly susceptible to optical noise from dirty or poor quality optics. It shows the importance of using as few optical components as possible, and keeping them clean. An alternative idea is to dispense

Footnote: Amendment - what was Figure 2.2 is now combined with Figure 2.3.



(a) Uncoated wedge

(b) Anti-reflection coated wedge

(c) $\lambda/10$ optical flat

(d) Vidispec wedge

FIGURE 2.3: Comparison of spatially filtered reference beams reflected from different beam combiners placed at 45° in front of the video camera

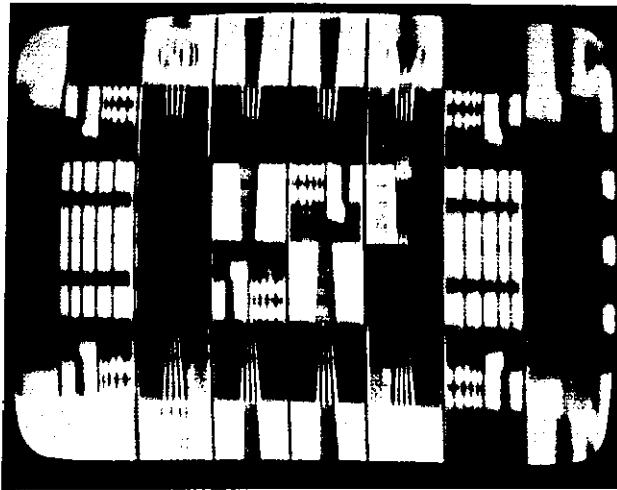
with the beam combiner and use a single mode optical fibre to introduce the reference beam as used by Creath et al (1985).

2.2.3 Optical Aberrations

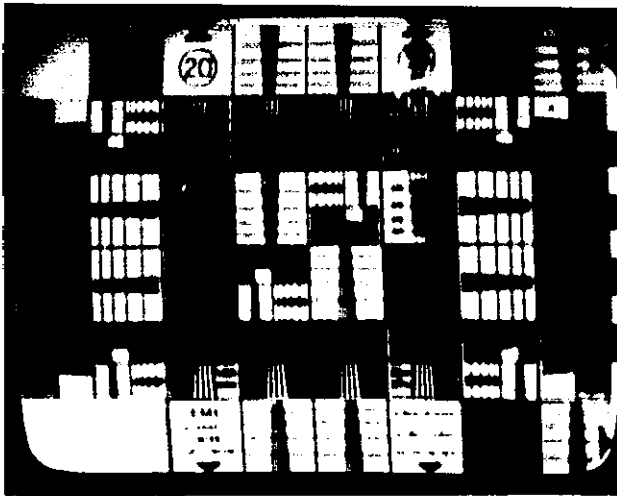
The use of a wedge beam combiner placed at 45° between the imaging lens and video camera introduces astigmatism, spherical aberration and coma. The most noticeable aberration is astigmatism, in which the vertical lines come to a focus in a different plane to the horizontal lines. Figure 2.4(a) shows a photograph from the television screen of a white light back-illuminated test target imaged with a 60 mm focal length simple lens at an aperture of $f/8$ onto a Chalnicon camera tube (Jackson). The vertical lines have been brought into focus to show the extent of blurring of the horizontal lines due to the wedge. Hurden (1982) recommends that the wedge should be chosen to minimise these aberrations. In the past this problem has probably been neglected because the use of small apertures of $f/16$ to $f/70$ have reduced the effects. With the use of higher resolution television cameras and larger apertures, as in the Vidispec, the problem is particularly noticeable in setting up the target. On the live display it is difficult to identify sharp details. The effect of blurring on the fringe contrast is being investigated at Loughborough at present by other workers.

The second most apparent aberration is the tilting of the optical axis in the plane of the optics. In practice this results in the camera having to be positioned slightly to one side of the normal optical axis and the target placed on the other side. This is slightly off-putting and introduces geometrical distortion in the image.

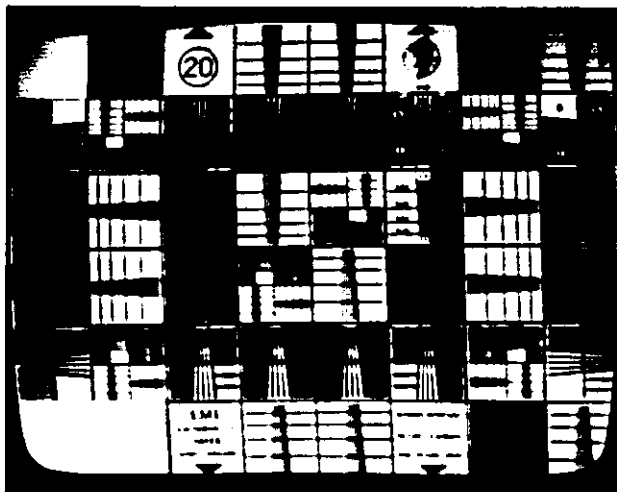
There are a number of solutions to these problems. A theoretical study of these optical aberrations is given in a book by Smith (1966). One solution is to use a thin wedge, bearing in mind that it should not be so thin as to produce Fabry-Perot fringes that can be resolved by the camera.



(a) Severe astigmatism with a 60 mm FL simple lens and wedge beam combiner



(b) Reduced astigmatism with a 67 mm FL zoom lens and wedge beam combiner



(c) Improved image with a 67 mm FL zoom lens and cube beam combiner

FIGURE 2.4: Lens aberrations of different optical elements. Television test chart back-illuminated with white light; aperture = $f/8$, imaged on a 1" Chalnicon video camera

Well corrected multi-element lenses show a reduced susceptibility to optical aberrations. This is demonstrated in Figure 2.4(b) with the use of a zoom lens in which more horizontal detail is visible. To reduce astigmatism and optical axis rotation further, a cube beam combiner is used, Figure 2.4(c) showing the result. The system reported by Bergquist (1982) uses such a cube. The disadvantages are that spherical aberration is present and an extra air/glass interface is introduced into the path of the reference beam compared with the wedge. Special anti-reflection coatings and blacking should be used to minimise unwanted internal reflections. A novel feature of the cube is that it displaces the image plane further back from the lens. For a cube of thickness t and refractive index N , the displacement d is given by:

$$d = \frac{(N-1) t}{N}$$

For a crown glass cube of 20 mm side d is about 7 mm. This may be useful in providing more room between the camera and lens for the reference beam spatial filter. Being symmetrical, the cube gives an optical axis in line with the optical axis of the imaging lens.

2.2.4 Conclusions

From these investigations into some aspects of the quality of the optical components, the following conclusions are made:

- As much as 51% of the available laser light is lost through using uncoated laboratory grade mirrors, prisms and lenses. By using special optical coatings the useful output of the object beam can be increased by 45%.
- The larger the number of optical components in the system, the greater is the amount of optical noise introduced. A simple layout is preferred. Attention should also be paid to the quality

of the beam combining element as this is particularly susceptible to airborne dust and dirt.

- A wedge beam combiner introduces severe astigmatism and optical axis rotation that leads to a poor quality image. The use of a multi-element lens and a cube element reduces both these problems, although spherical aberration is introduced but equally in both beams.

In general, it has been found that a simplified design is preferred with high grade coated optics. Alternatively combined optics, in the imaging lens/beam combining element would be of considerable help.

2.3 PATH LENGTH COMPENSATOR

2.3.1 Limitations Imposed by the Laser Coherence Length

At present the most common lasers used in ESPI are HeNe and Ar Ion lasers with typical coherence lengths of about 0.1m and over 1m respectively (when an etalon is used). The relatively short coherence length of the light from a HeNe laser has in the past meant equalising the reference and object beam paths to the nearest centimetre to ensure spatial coherence. To achieve this involves using more optical components, requiring more light and introducing noise. A greater path length also allows the possibility of fringe drift due to air turbulence. The depth of view is also restricted by the short coherence length, although this has not been reported as a limitation in ESPI as yet.

2.3.2 Path Length Compensation Methods

In early ESPI systems the reference beam path is fixed, as in the Vinten's system for example (Hurden, 1982), in which it is wrapped round in a loop using 4 prisms. The new Vidispec uses an adjustable path length based on a Loughborough design using multiple folded paths (see Figure 2.1) and a moving prism arrangement. By this means a working range of 0.94m is available in front of the instrument. With 5

folds, 20 surfaces are traversed by the beam. The arrangement is flexible but it is expensive and susceptible to noise and fringe drift.

2.3.3 Multi-Laser Cavity Length Path Length Compensation

The Vinten's design provides space for mounting the target in the second coherence plane at a distance of a laser cavity length further away from the imaging lens. How this affects the fringe contrast does not appear to have been investigated in the literature. Because this method may provide simplifications to the path length compensation, two experiments were performed to measure the fringe contrast at different coherence planes.

The Vidispec system with a square plate as the target was used in each experiment (Figure 2.5). By adding a weight to the bar, projecting at the rear, the plate twists and a standard ESPI test pattern is formed. The fringe contrast was measured by computer using the method described in Appendix C. A vertical line spanning about 8 fringes is sampled and after smoothing, is measured to find an average value of the fringe contrast C_f , given by:

$$C_f = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

(Jones and Wykes, 1981). This gives a quantified value of the fringe contrast after smoothing, that is not an absolute value but one that can be compared with other results if the same number of smoothing cycles is used.

In the first experiment, the plate was fixed at a distance of 0.34m from the lens mount, with the zoom lens set to a focal length of 70 mm and an aperture of f/16. The path length compensator was then moved from 0.3m to 1.2m and a new fringe pattern formed at increments of 0.05m. In each case the reference beam intensity was adjusted to just

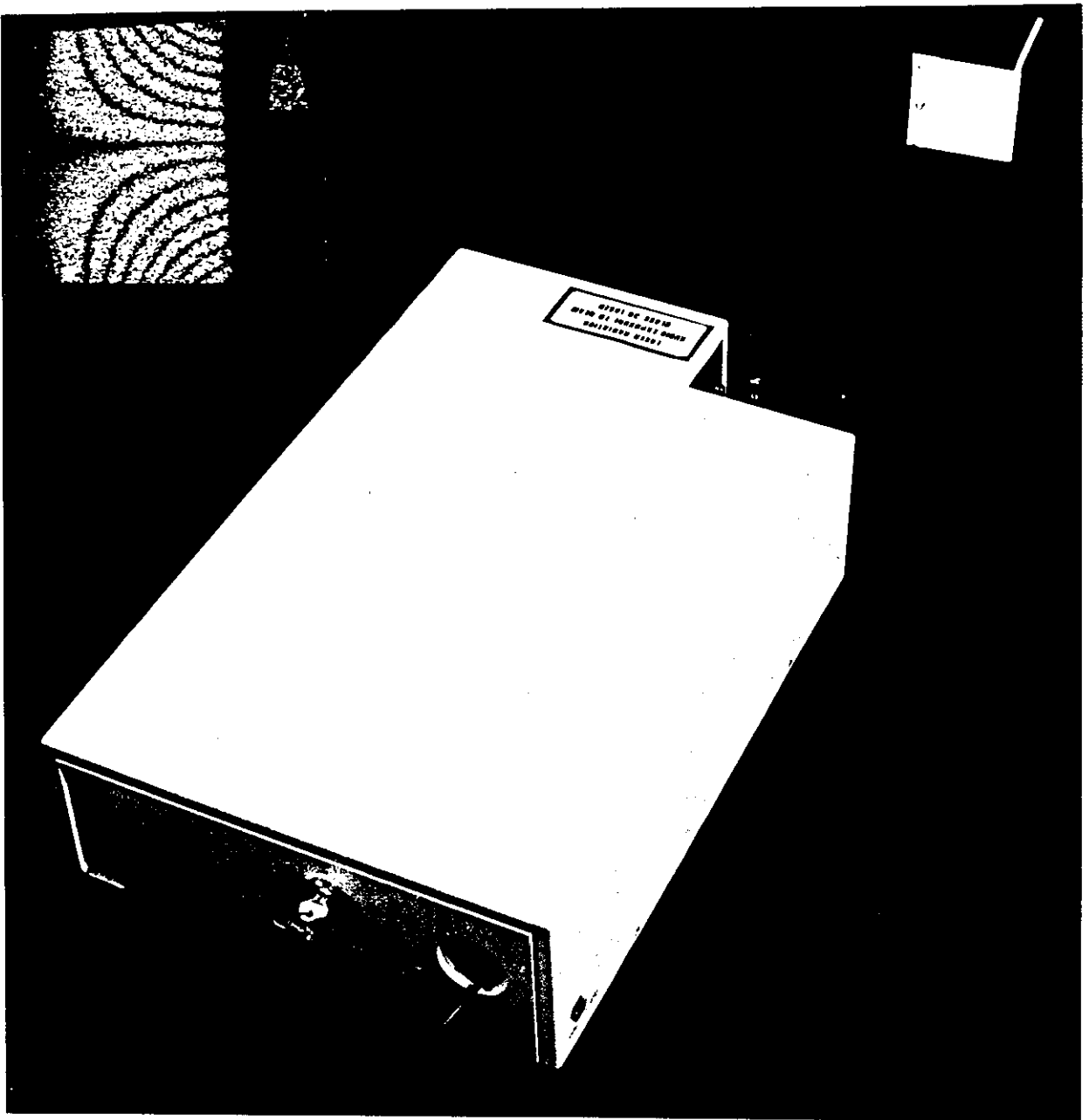


FIGURE 2.5: Vidispec interferometer pointed at a 100 mm wide metal plate
Typical results in subtraction mode showing torsion when a
weight is added

below saturation level of the camera. By this means, most parameters were kept reasonably constant except for the change in path length of the reference beam. The fringe contrast was measured at each point.

For the second experiment, the reference beam path length was kept constant and the plate moved. The fringe contrast was measured from the first to the fifth coherence planes, moving the plate a cavity length further from the Vidispec each time. The object beam divergence was reduced with a converging lens to cover the same object area and the 70-210 mm zoom lens enabled the same size of area to be viewed.

Results

The variation of fringe contrast with increasing reference beam path length is shown in Figure 2.6. In the process of making measurements, the change in path length was made by measuring the distance between prisms as the scale (a metal tape provided on the Vidispec) was found to have an error of -4%. The peaks in the fringe contrast values at each coherence plane are equal within experimental error. The distance between peaks is approximately 0.46m which is in agreement with the laser cavity length of 0.456m.

From the results viewed on the television screen, fringe contrasts in the range of 0.4 to 0.5 give fringes of acceptable quality. On this basis, the target can be placed to within about $\pm 0.1\text{m}$ of the optimum point of the coherence plane.

The results of the second experiment are given in Table 2.2. These too indicate no detectable change in the fringe contrast at different coherence planes even in the fifth plane.

It is concluded that there is no detectable deterioration in the fringe contrast even up to the fifth coherence plane. At each coherence plane there is a working distance of at least 0.1m when using a 10 mW HeNe laser. These results have been confirmed by other workers (Bergquist, 1981 unpublished).

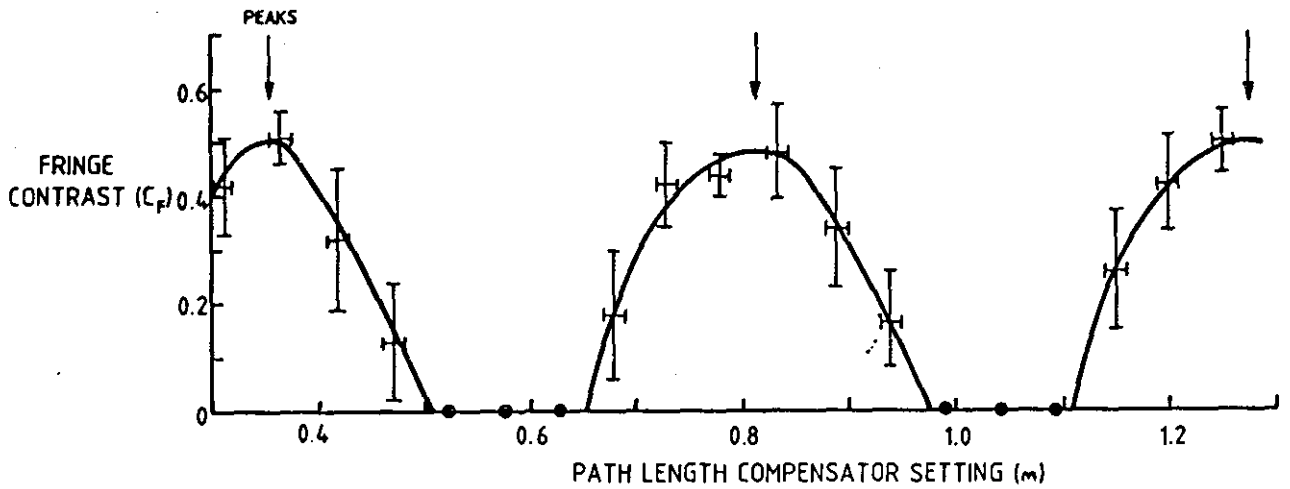


FIGURE 2.6: Variation of fringe contrast with reference beam path length compensator setting

Coherence Plane	Distance from First Coherence Plane (m)	Fringe Contrast
1	0	0.53
2	0.46	0.41
3	0.92	0.50
4	1.38	0.47
5	1.84	0.56

TABLE 2.2: Fringe contrast with target at different coherence planes

The consequences for this are that the optics in the reference beam path can be simplified. This is discussed the end of the chapter.

2.4 ZOOM LENS

2.4.1 Imaging with a Simple Lens

Simple lenses have been used in ESPI systems from the earliest designs, probably because at the small numerical apertures used then aberrations were not a significant problem. The Vinten's system uses two interchangeable simple lenses of different focal lengths to give a choice of magnifications. Lokberg and Svenke (1981) also mention the use of interchangeable lenses. Focussing involves moving the camera backwards and forwards. This sort of arrangement makes a system inflexible when it is to be used in interactive analysis where it is desirable to change the viewing area *quickly*.

As mentioned previously, a simple lens in combination with a wedge beam combiner suffers from astigmatism. A single element spherical lens also displays spherical aberration unless an aperture of $f/22-60$ is used, in which case it is reduced as the geometrical limit is approached.

2.4.2 Imaging with a Multi-element Zoom Lens

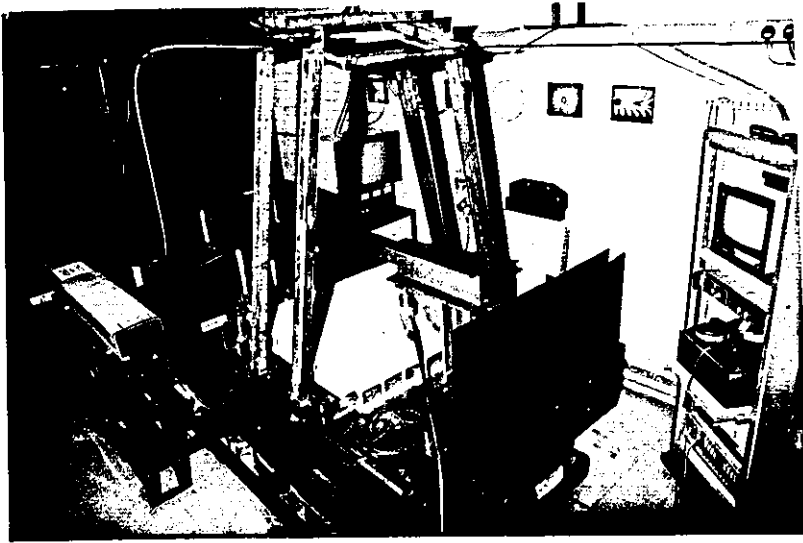
The use of a multi-element zoom lens for imaging solves some of the problems encountered with simple lenses. From the literature, it does not appear to have been used with ESPI, probably because it was thought that a variable focal length lens would fall outside the constraints on the position of the reference beam origin then thought to be imposed by conjugacy (e.g. see Jones and Wykes, 1983, p.176). During the course of the present work, the idea of using a zoom lens was generally known at Loughborough, but not applied. The author took up the idea as it seemed favourable for general use.

One consideration in choosing a zoom lens is the space needed between the camera and imaging lens for the beam combining elements. Space for the wedge and the spatial filter assembly for the reference beam requires a gap of at least 30 to 35 mm. With the camera faceplate being some way inside the camera, a minimum of 42 mm is required. This

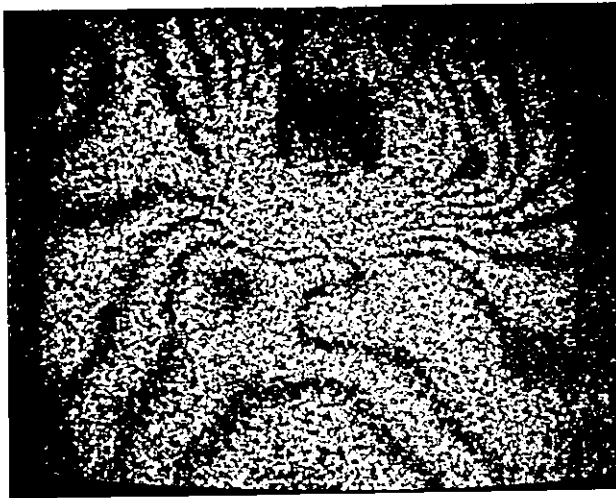
eliminates the use of a standard CCTV zoom lens because they usually have a short back focal length of 25 to 30 mm. Photographic zoom lenses are more suitable, with a minimum back focal length in the region of 45 mm. Although normally used for a 35 mm image format, they are just as suitable for a video format of 12 mm (with a 1" vidicon). Their low cost and availability make them ideal for use with ESPI.

Some of the first work using a zoom lens was carried out while assisting a final year student project for investigating the deflection of a 1m slab of plastic flooring while under point load. The design was undergoing development for use in computer rooms, in which cables could easily be passed beneath the slabs. It was necessary to see an overall view of the slab under load, and then look at close-up areas round the point of loading and the support pins below the plastic sheet.

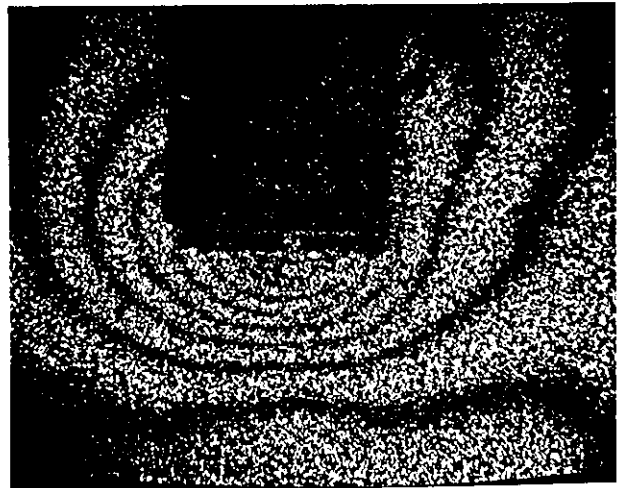
The apparatus used is shown in Figure 2.7(a). This application demonstrates some of the considerations that need to be made in applying ESPI. To remove rigid body motion the whole slab is clamped to the table. Loading is done hydraulically with the ram placed between the slab and an "L" shaped girder overhanging the slab and fixed to the table. Using an overhead mirror, and a correcting mirror in front of the imaging lens, the whole of the slab can be viewed at once using a horizontal breadboard ESPI system made up from components magnetically clamped to the table. Both mirrors are also used for illumination with an Ar Ion laser at a wavelength of 514 nm and typical power of 250 mW. The range of loading was 0.5 to 2 kN on a 25mm x 25mm block. Typical results are shown in Figure 2.7(b) and (c) to show the benefits of the zoom facility. In each case the fringe pattern was formed with an additional load of 10 to 40 N. Exact measurements were not taken as the analysis was more qualitative to determine the effect of supporting studs underneath the slab. A short focal length of 35 mm gives an overall picture of the deflection in 2.7(b) but detail is lost near the loading point. Increasing to a focal length of 80 mm and re-referencing and loading gives a higher



(a) General view of apparatus showing optical table, loading assembly and ESPI system



(b) General view of deflection with 35 mm zoom lens
(0.98 m x 0.74 m field)



(c) Fringe detail revealed with 80 mm FL zoom lens
(0.42 m x 0.32 m field)

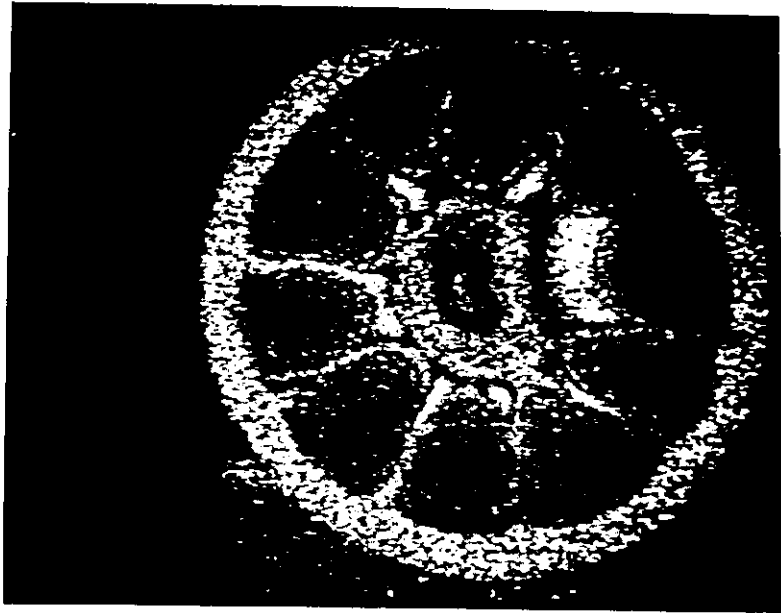
FIGURE 2.7: Use of the zoom lens in a typical ESPI application - deflection of 1 m² plastic computer flooring under a point load

resolution in 2.7(e). Of course, it is not possible to use the zoom facility to study detail in each interferogram as changing the image size de-correlates the speckle pattern. A new image must be stored at each focal length.

The use of a 70-210 mm zoom and re-positioning the correcting mirror on the optical table enables any area of interest down to $0.16 \times 0.12\text{m}$ to be studied. By this means it was possible to investigate the deformation patterns for various loading points and areas over which the load was applied.

In the time averaged mode it is possible to use the zoom facility while the object remains vibrating because de-correlation effects do not apply when no reference image is stored. If noise subtraction is employed (see Section 3.3) then the image has to be re-stored at each focal length and a phase shift introduced. This is demonstrated in Figure 2.8 with a 50 mm diameter loudspeaker vibrating sinusoidally at 4.0 kHz. The overall view in 2.8(a) gives the general mode, which is predominantly the 5th diametral (5D) mode, and a close up reveals the subtle detail of the fringes in 2.8(b). This was carried out with the Vidispec. While ESPI may be restricted in resolution, this clearly shows that with the use of a zoom lens, it is possible to pick out detail quickly.

In both these examples, the origin of the reference beam remained in the same place for each focal length, with no apparent loss of fringe contrast due to lack of conjugacy. Jones and Wykes (1983, pp 175-178) determine that the optimum position of the origin is in the centre of the imaging aperture. Using a zoom lens, the optimum position therefore changes with a change in the focal length. In practice it has been found that conjugacy conditions are related to the aperture, and that the position of the origin along the optical axis is more critical at smaller apertures (e.g. $f/22$). For a small aperture and a large departure from conjugacy, the interference term between the reference and object waves becomes too small to be resolved by the camera. Work in progress at Loughborough by Bergquist



(a) General view of resonant mode at 70 mm FL



(b) Fringe detail of an anti-node revealed at 210 mm FL

FIGURE 2.8: Use of zoom lens in time averaged mode - resonance of a 50 mm loudspeaker vibrating at 4.0 kHz. Object and reference noise subtracted and a π phase shift introduced

and Mendoza-Santoyo (1986) indicates that tolerance to longitudinal shifts of the origin are much greater than that first estimated by Jones and Wykes (1981), and that a collimated or converging reference wavefront may give improved results under certain conditions. On the other hand colinearity is found to be critical.

Placing the origin at a distance along the optical axis equal to the middle of the focal length range has been found to give adequate results. With a 35-80 mm range, a distance of 55 to 60 mm gives good results at all apertures over the available range of $f/32$ to $f/2$. With the 70-210 range, and the reference beam in this same position (as in the Vidispec) good results were obtained for apertures larger than $f/5.6$. This indicates remarkable tolerance to longitudinal errors.

It has been found that using a multi-element zoom lens optical aberrations are reduced and the flexibility in the viewing area enhances the use of ESPI in interactive analysis in both the subtraction and time averaged modes. The position of the origin of the reference beam should be optimised, though it is probably more tolerant to longitudinal errors along the optical axis than was at first thought.

2.5 IMPROVED INTERFEROMETER DESIGN

2.5.1 Conclusions

From the series of experiments carried out, the general conclusion is that recent designs of ESPI interferometers suffer from unnecessary light losses, optical noise and aberrations due to the use of low grade optical components and complex design. The reduction in quality and flexibility of the output data detracts from its use as an industrial instrument. Two important design principles can be put forward:

1. The design should be kept as simple as possible; every extra lens, mirror and path length adds optical noise and reduces beam power.

2. High grade optical components should be used to make the most efficient use of the laser power, and minimise optical noise and aberrations.

Using these principles and the ideas suggested in this chapter, an improved interferometer design is proposed, shown in Figure 2.9. The overall layout is based on the Loughborough demonstration rig.

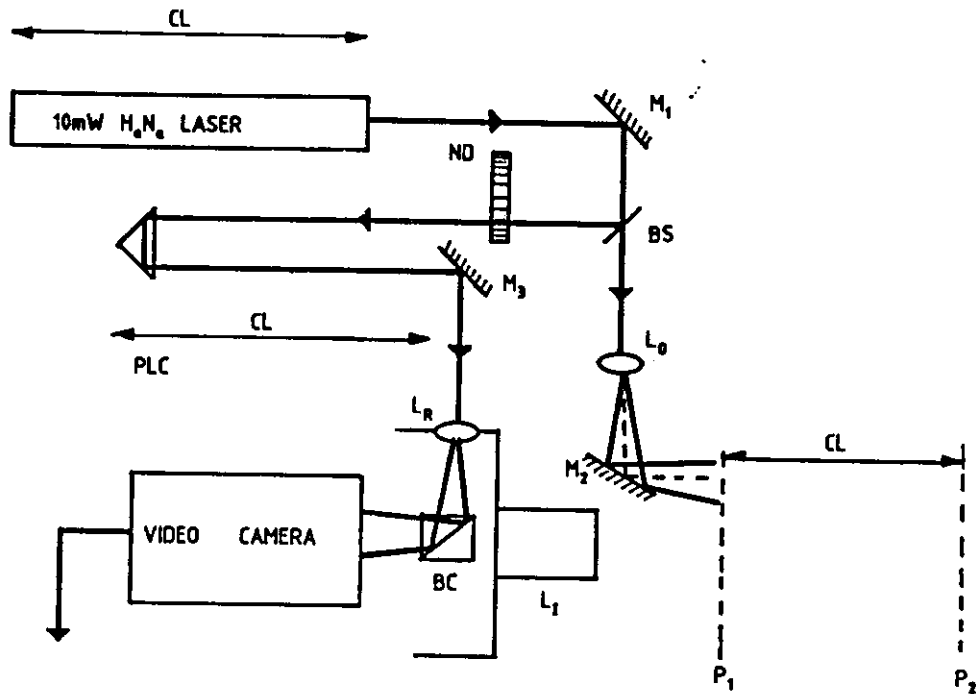


FIGURE 2.9: Improved design of ESPI interferometer

This has proved to be an efficient layout in the use of the available space while retaining flexibility of operation. The features are now discussed.

2.5.2 Minimum Number of Optics

The number of optical components has been reduced by simplifying the path length compensator. An object placed at any distance in front of the imaging lens will fall on or near a coherence plane P_1 , P_2 etc. With the prism being adjustable over a distance of a whole laser

cavity length, the nearest coherence plane can be brought into line with the plane of the object. If further simplification is required, the prism is removed, the mirror M3 is rotated and the reference beam is directed straight into L_R . The object is then placed in one of the specified coherence planes which are fixed.

2.5.3 High Grade Coated Optics

Each optical component is ideally of high grade material and suitably coated. If possible, interferometer quality optical surfaces with a flatness to $\lambda/20$ should be used. The mirrors M1 to M3 and the reflective surfaces of the prism in PLC are treated with overcoated silver for efficient reflection (96%). The wedge BS is anti-reflection coated to give 0.5% reflection at 45° and to maximise the transmission for the object beam. A narrowband anti-reflection coating can be used on the transmission surfaces of the prism and the relevant faces of the beam combiner BC.

2.5.4 Cube Beam Combiner

The beam combiner consists of a specially prepared double prism cube giving about 4% reflection and 94% transmission, blacked on non-transmission faces and AR coated on the others to minimise internal reflections.

2.5.5 Zoom Lens

A multi-element photographic zoom lens L_I is used for imaging. The focal point of L_R is positioned at a distance along the optical axis from the camera faceplate midway in the range of focal lengths of the zoom. The two lenses that have proved useful in practice are the Tamron SP 28-80 mm and the 70-210 mm zoom lenses.

2.5.6 Variable Neutral Density Filter

A rotating variable ND filter is used to adjust the intensity of the reference beam. It is worth finding a high quality filter as a poor quality coating can easily add optical noise to the reference beam.

Further improvements may be made with the use of combined optics. The ESPI head for combining the beams may be simplified by using a single mode optical fibre for introducing the reference beam from within the imaging lens. Alternatively the lenses L_R and L_I , beam combiner BC and camera faceplate could be connected and optically matched to minimise the number of air/glass surfaces.

CHAPTER 3

NOISE REDUCTION

3.1 THE PROBLEM OF NOISE

3.1.1 Introduction

Having considered some aspects of the optical design of the interferometer, the next step is to explore some methods of improving the general appearance of correlation fringes and, if possible, increase the resolution. A noisy output is a fundamental drawback in ESPI. As well as being offputting, it makes it more difficult to extract useful information by eye or by automatic computer analysis. One of the advantages of ESPI is that it can make use of a number of electro-optical techniques to help with this problem, as will become clear in this chapter.

To determine the extent to which the noise can be reduced, it is necessary to look at some of the sources of noise.

3.1.2 Theory

The time averaged mode is the most susceptible mode to noise, being additive, and so it is helpful to consider some of the theory describing a vibration pattern displayed on a television monitor. In this way, most of the noise terms will be considered and fully dealt with for the subtraction mode.

From equation 1.6 in Chapter 1 and following Slettemoen (1977), if the total electronic noise, σ_T is added, the total variance $\sigma_T^2 (M)$ of the signal on the monitor is given by:

$$\sigma_T^2 (M) = \sigma_S^2 + \sigma_R^2 + 2|M|^2 \langle I_S \rangle \langle I_R \rangle + \sigma_E^2$$

where: $M(x,y)$ = fringe function due to object movement
 I_R = reference intensity
 I_S = object intensity
 σ_R = standard deviation of reference intensity
 σ_S = standard deviation of object intensity

This can then be written as:

$$\sigma_T^2(M) = \langle I_S \rangle^2 \gamma_S^2 + \langle I_R \rangle^2 \gamma_R^2 + 2|M|^2 \langle I_S \rangle \langle I_R \rangle + \sigma_E^2 \dots (3.1)$$

where: $\gamma_R = \frac{\sigma_R}{\langle I_R \rangle}$ = rms contrast of reference intensity

$\gamma_S = \frac{\sigma_S}{\langle I_S \rangle}$ = rms contrast of object intensity

σ_E = total electronic noise

Angular brackets $\langle \rangle$ denote ensemble averages. This implies the expected value over many similar surfaces with the same set up. It is not an exact value but a theoretical average intensity. While this does not give a precise description of the noise terms, it is helpful in providing a general description suitable for dealing with the separate terms. The final interferogram consists of four terms, the reference noise term, object noise term, interference term and electronic noise term.

1. Reference Noise Term - $\langle I_R \rangle^2 \gamma_R^2$

For a smooth reference beam, the reference contrast $\gamma_R \ll 1$ but as indicated in Chapter 2, it can be a significant term for a working system where optical surfaces readily pick up airborne dust and dirt. The reference beam noise is normally time invariant.

2. Object Noise Term - $\langle I_S \rangle^2 \gamma_S^2$

For a fully resolved speckle pattern the object intensity contrast $\gamma_O = 1$, and for a partially resolved speckle pattern, such as for small apertures, $\gamma_O < 1$. It is a function of the nature of the illuminating wavefront and surface being illuminated and the system resolution. Again, this is normally time invariant.

3. Interference Term - $2|M|^2 \langle I_S \rangle \langle I_R \rangle$

The interference term is the signal that is required, modulated by the so called fringe function, M . It is detected by high pass filtering and square law detection (rectification). The expression given is for ensemble averaged values of the object and reference beam intensities, but in practice it is modulated by a speckle pattern. This too is time invariant and has been lost by "ensemble" averaging.

4. Electronic Noise Term - $\sigma_E^2 = \sigma_{ED}^2 + k(\langle I_S \rangle + \langle I_R \rangle)$

The total electronic noise term consists of two parts:

σ_{ED}^2 = signal independent mean square electronic noise

$k(\langle I_S \rangle + \langle I_R \rangle)$ = mean square noise proportional to the optical signal level (k = constant).

The first ^{part} is time variant, due to noise within the electronics and the second part is time invariant due to the video signal from the image on the camera.

The first step in improving the output is by optimising the system. For a standard time averaged ESPI system where the laser power is limited, this is achieved by:

- i) Minimising the electronic noise
- ii) Making the reference beam as noise free as possible
- iii) Making the standard deviation of the reference intensity equal to the standard deviation of the object intensity
- iv) Setting the reference and object intensities such that the peak intensities are approximately at the saturation level of the camera (Section 1.1).

In the subtraction mode, most of the noise terms are removed in the process of subtraction and the procedure for optimisation is far less stringent. The optimum beam ratio is about 1:2 object to reference intensity, but fringe contrast is not significantly reduced for ratios of 1:20 or more.

After optimising, any further improvement to the output must involve other noise reduction techniques. It is suggested that this can be achieved at three distinct levels.

The first level involves simple image processing of the final interferogram to improve the fringe visibility. Both subtraction and time averaged fringes can be processed where the fringes are considerably broader than the background speckle pattern. The second level improves the resolution of time averaged fringes using noise subtraction, as used in the subtraction mode. The third and final level gives a fundamental improvement in resolution by averaging the random speckle noise to approach the underlying correlation pattern. These are now described.

3.2 SIMPLE IMAGE PROCESSING

3.2.1 Introduction

A photograph of a typical subtraction pattern is shown in Figure 3.1(a). The speckles vary in size from one to a few pixels of the 625 x 512 pixel digital frame store used to store the phase referenced speckle pattern. These are generally smaller than the fringe size, which varies from 30 to 100 pixels. At the simplest level, filtering

techniques can be used to reduce the speckle content of a fringe pattern, together with other image processing techniques such as contrast stretching. In this section, some typical digital techniques are described briefly to introduce some work carried out on analogue processing techniques which would be suitable for use in a low cost industrial system.

3.2.2 Digital Processing

Some of the principal digital image processing techniques applicable to ESPI are given by Varman and Wykes (1982). Smoothing involves the removal of the higher spatial frequencies of the image containing the speckle information, by either fast Fourier transform filtering or by local averaging. Thresholding is one example of the broader technique of contrast stretching, passing the signal through a look-up table to highlight high intensities and reduce the lower intensities. While it is fairly easy to perform some of these techniques, the time required to do so on low cost image processing equipment can be excessive. For example on a 16 bit micro such as the DEC LSI 11/03 used at Loughborough, typical times for processing a 256 x 256 x 6 bit image are:

2D Discrete Fourier Transform and Filtering	10 hrs
Smoothing	40 sec per pass
Binarising	15 sec

The 2D FFT includes calculating the transform, filtering and then the inverse transform first in the X direction and then in the Y direction. Smoothing consists of passing a 3 x 3 or larger array "window" over the image to carry out local averaging. Examples of these two methods are mentioned in a paper by Montgomery, Bergquist and Henry (1986). Binarising is the result of setting a threshold value from the histogram of intensity distributions and forming a binary image with two intensity values.

More sophisticated image processing hardware using a 32 bit pipeline processor reduces these times to two minutes for FFT's and 0.1 sec for smoothing or binarising. With further developments in array processing, frame rates will be achieved, but at a high price. Until these digital processing techniques become cost effective for use with a commercial ESPI system, it is worth investigating some of the possibilities with analogue processing. Most of these techniques can be performed on low cost electronic hardware devices at video frame rates. One dimensional smoothing can be achieved with a low pass video filter, two dimensional smoothing by image blurring and thresholding using a home-built circuit to produce a binary image.

3.2.3 Analogue Smoothing

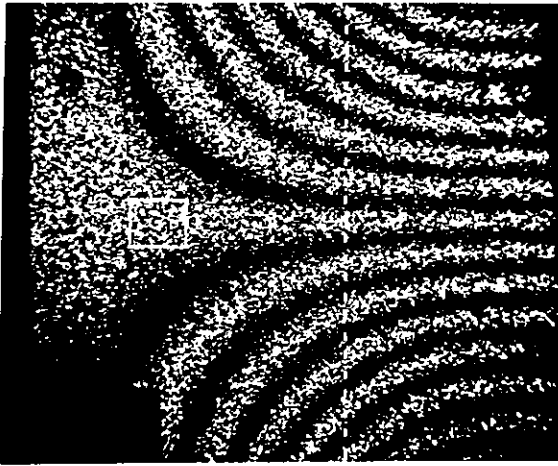
Experimental

A torsion plate similar to the one in Figure 2.5 was chosen to give a standard test pattern of vertical and horizontal fringes so that results from different techniques could be compared. The plate measures 70 x 60 mm and is painted matt white with a fine cellulose aerosol paint. A breadboard bench system with magnetically clamped components was used with a 15 mW HeNe laser, sensitive only to out-of-plane movement. The Pantak (EMI) store was used to give results like those shown in Figure 3.1(a) which were stored on $\frac{1}{2}$ " Sony video tape. More fringes are formed by placing the weight on the bar further from the plate.

Contrast measurements of the speckles are made on the DEC LSI 11/03 computer connected to the CVI store, 512 x 512 x 6 bit in size. A sample area of 50 x 40 pixels in the bright fringe in Figure 3.1(a) is taken and the contrast, C_s , is calculated (Appendix C) where:

$$C_s = \frac{\text{Standard deviation of pixel intensities}}{\text{Average pixel intensity}}$$

This gives a measure of the speckle noise, a maximum for $C_s=1$ and a



(a) Unprocessed - $C_s = 0.70$
in boxed region. Intensity
profiles taken along dotted line

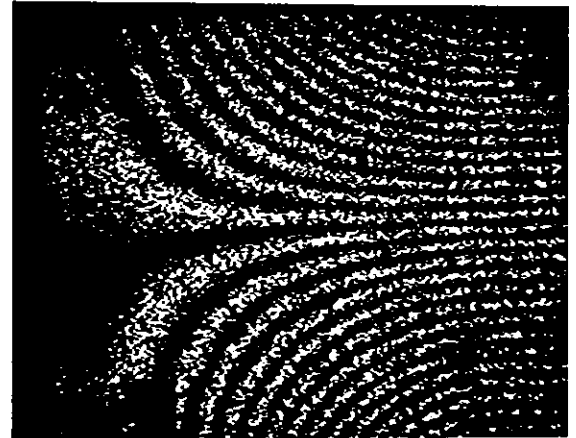


(b) Low pass filtered at
0.5 MHz. $C_s = 0.31$

FIGURE 3.1: Smoothing of coarse ESPI fringes by low pass filtering horizontally



(a) Unprocessed



(b) 2.0 MHz



(c) 1.0 MHz



(d) 0.5 MHz

FIGURE 3.2: Smoothing of fine ESPI fringes by low pass filtering at different cut-off frequencies

minimum for $C_5=0$. A Texas 990 computer, Matrox video store and XY plotter were used to plot out the cross-sections of the image intensities.

1D Filtering

A commercially available range of low pass video filters was used to perform one dimensional filtering (see Appendix B for details) of the composite video signal. The filter was connected between the ESPI output and the monitor.

The greatest reduction in speckle contrast is obtained with the 0.5 MHz filter, being reduced from a value of 0.70 to 0.31 as in Figure 3.1. For such a restricted bandwidth any signal changes of $2\mu\text{S}$ or less are removed. In a 625 line system the active line period is $52\mu\text{S}$ which gives a maximum horizontal resolution of 26 fringes. The speckles remaining in Figure 3.1(b) are largely the result of 1D filtering, since the vertical resolution stays the same. The results in Figure 3.2 show the effect of different cut-off values on higher density fringes, in (d) showing the resolution limit at 0.5 MHz.

From results in ESPI shown in the literature it is very rare to observe more than 50 fringes in one image and it is questionable whether one would ever want to, since re-referencing allows continuous monitoring of displacement. However, a range of filters from 0.4 MHz to 3.8 MHz would give a choice of the degree of smoothing with a vertical fringe resolution limit of 20 to 200 fringes.

2D Filtering

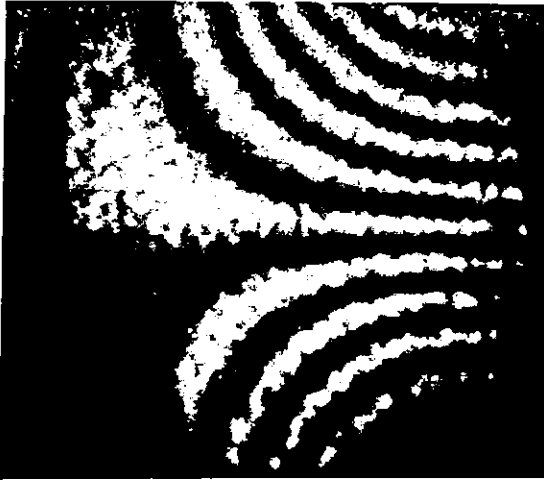
A better method of smoothing is to filter the interferogram in two dimensions. At the time this work was carried out, electronic 2D

video filters were not available, so the technique of image blurring was used instead. Two methods were tested. In the first, a video camera with a standard 50 mm CCTV lens was set up at a distance of 1.0m from the interferogram displayed on the monitor. The effect of slightly blurring this image is shown in Figure 3.3. Full 2D filtering reduces the speckle contrast to 0.23, but the intensity roll off towards the edges and image distortion is quite apparent.

The second method is to use a Vidicon Storage Tube to filter the interferogram. This is a frame store consisting of a segmented silicon wafer target scanned with an electron beam. It differs from a conventional vidicon tube in that an image can be written onto the target as well as read from it. By slightly de-focussing the scanning electron beam, the image can be blurred. Smoothing of ESPI fringes is quite effective, Figure 3.4 showing the results where the speckle contrast is reduced to 0.09. By means of the zoom facility the close up shows how effectively the speckles have been filtered. Controlling the size of the electron beam gives precise control over the spatial resolution. With this particular device the frame rate is reduced to 8 Hz since image writing takes 80 mS and image reading 40 mS. This demonstrates the effectiveness of 2D filtering.

Comparison of results

In order to compare these different methods of smoothing, intensity profiles of the fringes are given in Figure 3.5. Line $x = 180$ (shown in Figure 3.1 (a)) of the 256×256 image are shown. The unprocessed fringes are almost indistinguishable because of the speckle noise, which causes considerable problems in automatic fringe tracking. When compared with the smoothed patterns to identify the fringe positions it is seen that there is virtually complete subtraction to zero in the troughs where the speckles are fully correlated, and the peaks consist of high contrast black and white speckles. 1D filtering produces identifiable fringes but these are still noisy because no filtering in the vertical direction is taking place. With 2D filtering, the desired ^{squared} sine intensity profile is approached.



(a) Coarse fringes
 $C_s = 0.23$

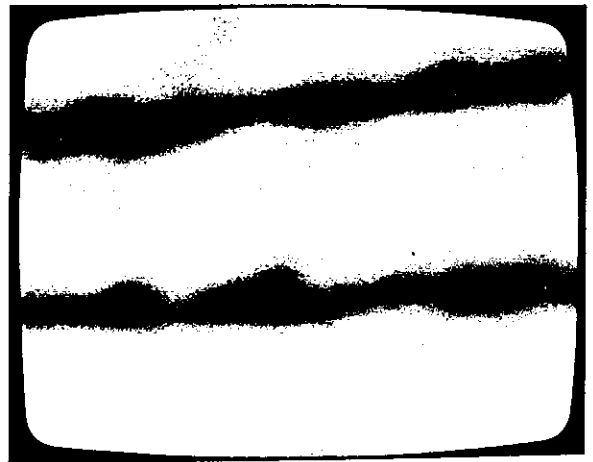


(b) Fine fringes

FIGURE 3.3: Smoothing in two dimensions using a de-focussed video camera



(a) Coarse fringes
 $C_s = 0.09$



(b) x6 magnification

FIGURE 3.4: Smoothing in two dimensions using a Vidicon Storage Tube with a de-focussed electron beam

While the speckle contrast decreases from 0.70 to 0.09, making the fringes subjectively clearer, the fringe visibility may decrease where the troughs become greater than zero.

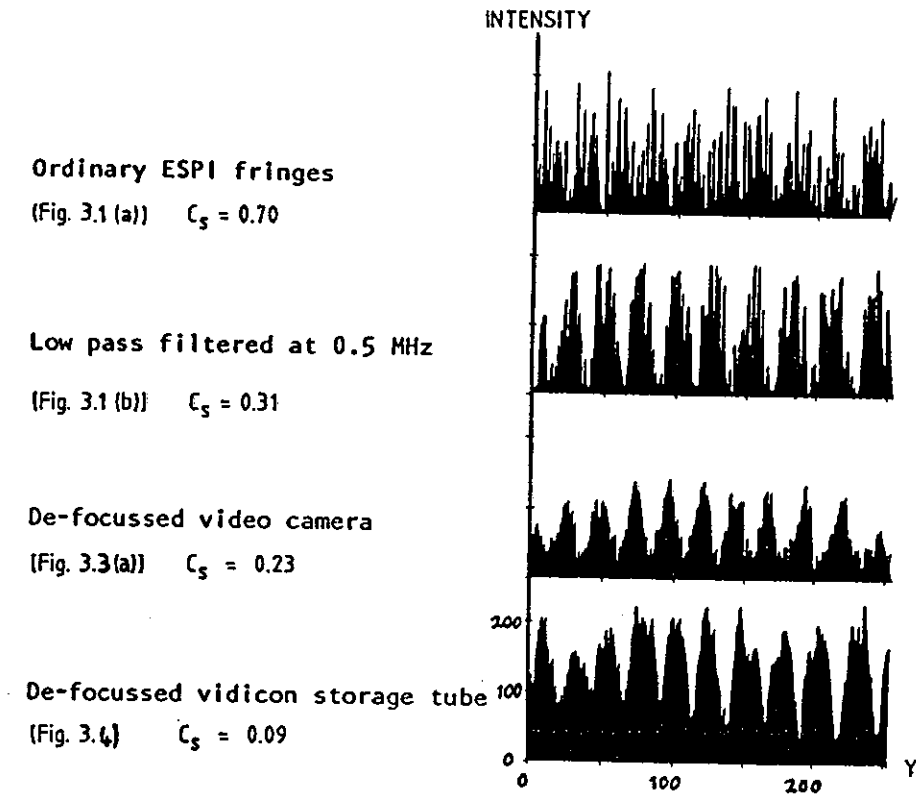
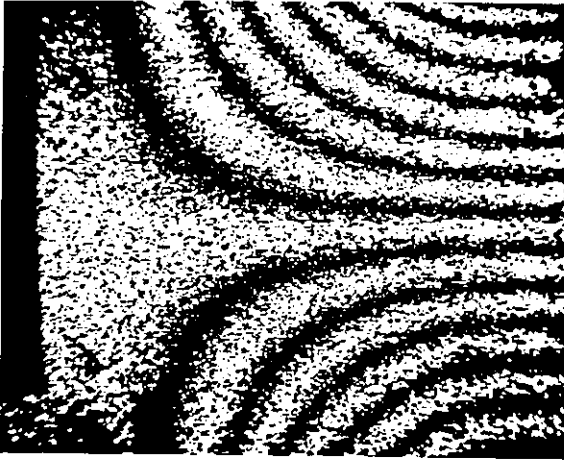


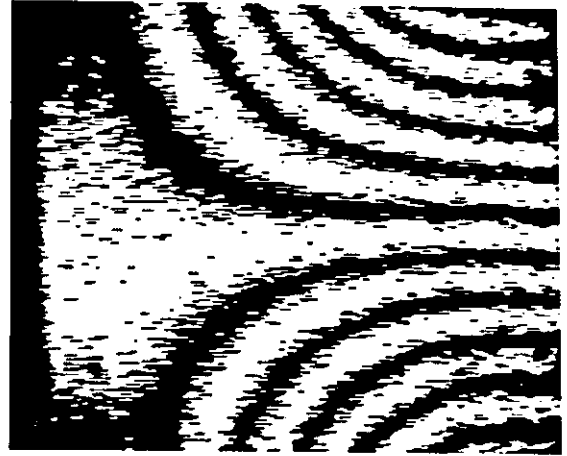
FIGURE 3.5 Comparison of intensity profiles of smoothed fringes for line $x = 180$, C_s = speckle contrast in bright fringe

3.2.4 Analogue Thresholding

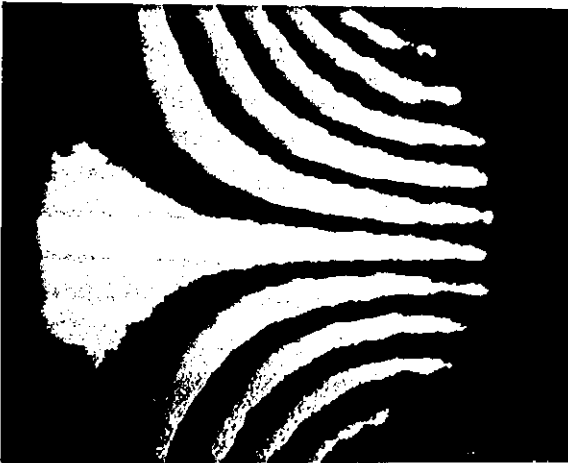
The grey scale of an image is reproduced by the voltage of a video signal. Binarising the image consists of setting a threshold, below which the signal is reduced to one level and above which it is



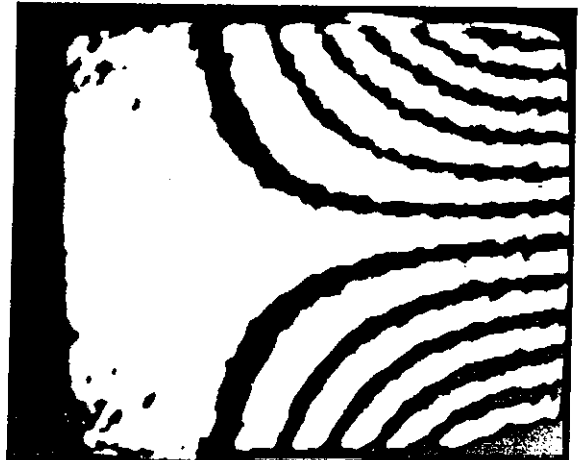
(a) Unprocessed (Fig. 3.1(a))
 $C_s = 0.61$



(b) Low pass filtered at
0.5 MHz (Fig. 3.1(b))
 $C_s = 0.24$



(c) De-focussed video camera
(Fig. 3.3(a))
 $C_s = 0.14$



(d) De-focussed VST (Fig. 3.4)
 $C_s = 0.04$

FIGURE 3.6: Binary images produced by thresholding the video signal after smoothing

increased to a higher level. A home-built circuit was available to perform thresholding. The images obtained by smoothing were passed through the circuit and an optimum threshold set to obtain the images shown in Figure 3.6.

In all four examples, the speckle contrast, C_s is reduced, to the extent that black and white fringes are formed in (c) and (d). Where the image intensity falls off towards the edges in (c), fringe information is lost. High pass filtering of the input signal to the frame store largely normalises the Gaussian intensity distribution produced by the reference and object beams. In this case, the use of a second video system causes severe roll off towards the edges.

A comparison of the intensity profiles of the binarised images is shown in Figure 3.7. In all four cases the fringe visibility is improved, approaching a value of 1.0 since the troughs are nearly zero. The spikes and uneven black and white levels show the imperfections of the analogue circuit used.

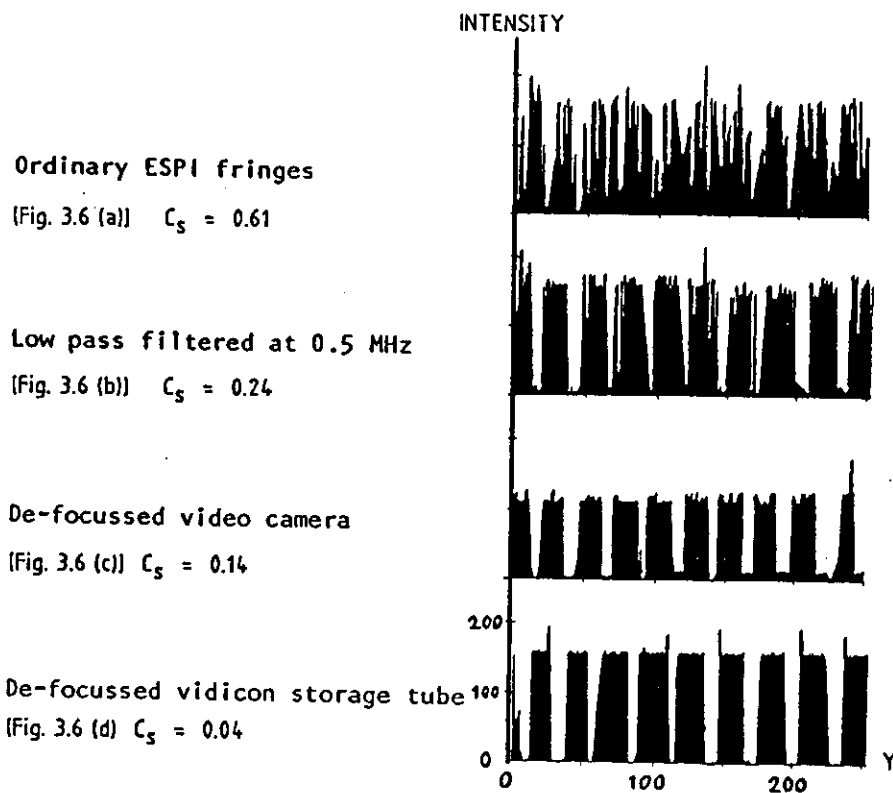


FIGURE 3.7: Comparison of intensity profiles of binarised fringes for line $x = 180$. C_s = speckle contrast in bright fringe.

While the appearance of the fringes is improved, the formation of square function fringe profiles is not conducive for precise fringe location. Localised variations in intensity lead to an alteration in fringe width on thresholding, which introduces an error in the precise position of the fringe.

3.2.5 Summary of Analogue Processing Techniques

A number of experiments have been performed demonstrating the use of analogue devices for video signal processing. One dimensional filtering in the horizontal direction of the image can be achieved with low pass video filters. The cut off value chosen sets a limit on the maximum resolvable fringe density. Two dimensional smoothing using image blurring gives greater reductions in speckle contrast but introduces a degree of image distortion. Smoothing followed by thresholding produces high visibility fringes with a very low speckle contrast. This is more suitable for presentation of results than precise measurement since an error is introduced in the fringe positions.

Image processing can be carried out more precisely with digital techniques but at present these are expensive. Analogue processing techniques by comparison have two distinct advantages:

- operation at or near to video frame rate
- low cost.

Suggestions for suitable processing equipment are given at the end of this chapter.

3.3 TIME INVARIANT NOISE SUBTRACTION

3.3.1 Introduction

The second level of noise reduction involves the subtraction of the optical noise terms due to the object and reference intensities and

the electronic noise associated with these terms. In the subtraction mode this automatically takes place on subtraction of the stored image from the live image. With the time averaged mode the optical noise terms take on a significant value in comparison with the fringe function signal.

By making use of the digital frame store normally used in subtraction, Nakadate et al⁽²⁾ (1980) describe a method of subtracting the optical noise to improve the quality of time averaged fringes. This method is improved by Creath and Slettemoen (1985) but without the provision of a full set of results. In this section, a technique is described whereby only the reference noise is subtracted. This has not been reported before, to the author's knowledge, although it has been generally used at Loughborough since digital subtraction became available. The subtraction of reference and object noise while the object is vibrating, corresponding to CASE IV in the paper by Creath and Slettemoen (1985), is also described with corresponding visual results to show the improvement that is possible. These two techniques provide a convenient method of gaining a modest increase in resolution with a working ESPI system that is susceptible to the degrading effects of dust and dirt on the optics.

3.3.2 Reference Noise Subtraction

The source of the noise in a smooth reference beam has been discussed in Chapter 2. In equation (3.1) the reference noise $\langle I_R \rangle^2 \gamma_R^2$ is a separate term which can be subtracted. This can be achieved by storing an image of the reference beam in the digital frame store and subtracting it from the live image. In practice, the ESPI system is optimised for ordinary time averaged fringes and the reference intensity is increased until the total signal almost saturates the camera. By blanking off the object beam, the image of the reference beam can be frozen in the frame store. Returning the object beam, the stored reference intensity is subtracted from the live time averaged pattern as in the subtraction mode.

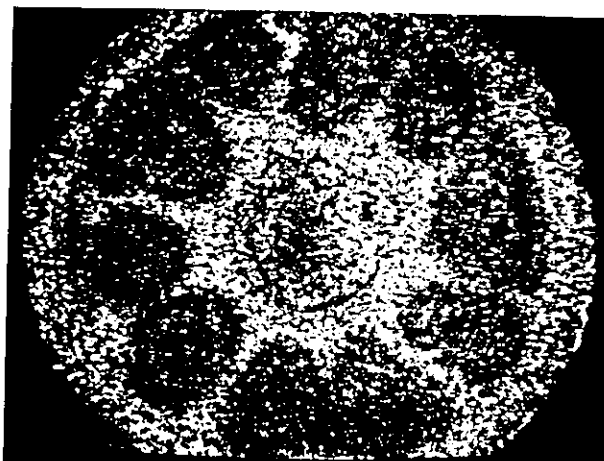
This was performed on the Loughborough demonstration rig, using a simple lens and a wedge beam combiner that had not been cleaned for some months. Figure 3.8(a) shows the standard time averaged pattern of a 50 mm loudspeaker vibrating at 4.0 kHz, where even the first order fringe is barely visible. Subtraction of the reference noise in Figure 3.8(b) reveals the first order fringes. Because the system is operating purely in the time averaged mode, the frequency of vibration can be altered at will without having to refresh the store at each new frequency.

3.3.3 Reference and Object Noise Subtraction

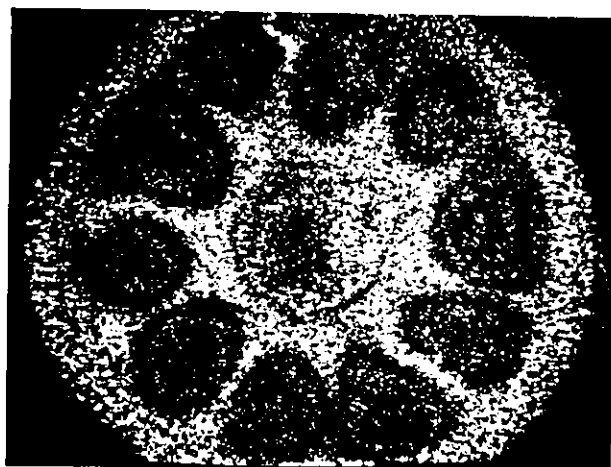
This method corresponds to CASE IV in the paper by Creath and Slettemoen (1985) in which they describe the theory but do not show any results. The aim is to subtract the reference noise term $\langle I_R \rangle^2 \gamma_R^2$, the object noise term $\langle I_S \rangle^2 \gamma_S^2$ and the electronic noise term $k(\langle I_S \rangle + \langle I_R \rangle)$ associated with the optical signal. Because both the reference and object intensities are included this time, subtraction is no longer a straightforward amplitude subtraction, but involves the complex terms.

With the object vibrating at a set frequency, the phase referenced speckle pattern is stored in a single frame store and subtracted from the live image. As with the subtraction mode, a dark image is formed. When a phase change of π is introduced between the object and reference beams, a bright zero order fringe is formed where the object movement is zero. Dark fringes are formed on the moving areas where the speckle contrast is low due to addition fringes on the camera faceplate. A high contrast vibration pattern is formed.

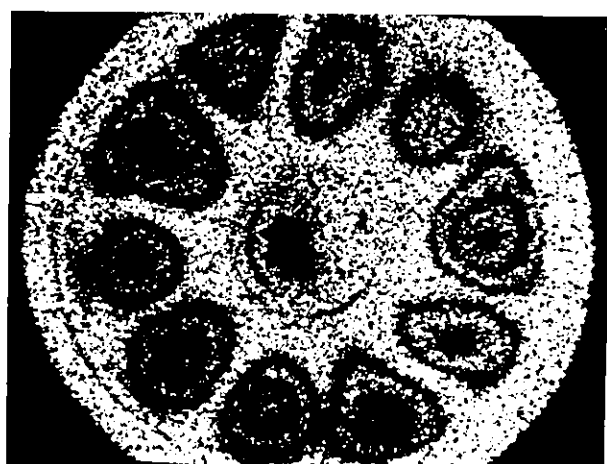
With the same arrangement and system parameters used in the previous experiment, this procedure was carried out on the vibrating loudspeaker to give the results in Figure 3.8(c). A π phase change was introduced quite crudely by slightly bending the optical table, sufficient to reveal the pattern.



(a) Poor time averaged fringes due to noisy reference beam



(b) Reference noise subtracted



(c) Reference and object noise subtracted and π phase change introduced

FIGURE 3.8: Modest improvement in resolution by subtraction of optical noise terms. 50 mm loudspeaker vibrating at 4.0 kHz

A useful feature of this technique is that because the object noise term is subtracted, the system does not have to be optimised in the usual way for the time averaged mode. Altering the object/reference beam ratio or the aperture does not significantly affect the fringe contrast. It appears to be of more importance to have the highest overall signal level. The main drawbacks are that the system is sensitive to out-of-plane displacement and the frame store must be refreshed for each new frequency together with the associated phase change.

The importance of this technique is that it ruggedises the time averaged mode, in that noisy beam profiles and a non-optimised system are tolerated, making it more suitable for unskilled use.

3.4 ENSEMBLE AVERAGING OF TIME VARIANT NOISE

3.4.1 Introduction

The third level of noise reduction deals with the fundamental problems of the speckle noise in the object intensity, I_S , and to a lesser extent, the electronic noise. While the time variant electronic noise term, σ_{ED}^2 continuously changes between frames, the object speckle pattern is time invariant since it is dependent on the optical geometry and the imaging resolution. Speckle noise severely limits the resolution in ESPI.

Speckle noise in ESPI is very similar to the granulation problem in holography where the use of coherent light introduces granulation in both the recording process and reconstruction. Martienssen and Spiller (1967) discuss the problem and conclude that speckle reduction is not possible at the recording process of one hologram by de-correlating the speckle pattern continuously, for example with a moving diffuser plate, because the granulation is the carrier of the information. A way round this is to take a number of holograms of an object scattering a different speckle pattern for each exposure, and to add these photographically at the reconstruction stage. They use Fraunhofer holograms to ensemble average the speckle content of the

image and reduce it by a factor of $\sqrt{N}$ for N images.

With ESPI the situation is slightly different, but similar results can be achieved. If the speckle pattern is de-correlated at a rate significantly greater than the camera frame rate, the speckle content of the image from the camera is reduced to that of incoherent imaging. Because of the persistence of the photo sensitive detector, the speckle content is ensemble averaged. In this situation ESPI fringes cannot be formed because there is no speckle pattern to detect. As in holography, ensemble averaging must take place after reconstruction. This can be done by averaging a number of interferograms with identical fringe patterns but with a randomly different speckle content.

Slettemoen (1980) introduced this idea to ESPI, using a rotating double slit aperture to ^{slowly,} de-correlate the focussed speckle pattern, causing a twinkling effect on the screen. A photographic camera exposed for a few seconds to this produces an interferogram with reduced speckle content. This photographic method was further developed by Lokberg and Slettemoen (1984) by changing the angle of illumination.

Ensemble averaging of successive video frames also reduces the time variant electronic noise term. Nakadate et al⁽²⁾ (1980) use this method, averaging the same time averaged fringe pattern for 60 successive frames using a summation function on an image processing system to increase the SNR of the video output.

The principle of ensemble averaging of random noise to increase the SNR of a signal is a common technique in radar and telecommunications, but has only been applied to ESPI quite recently. This section explores some of the methods of de-correlating and averaging the pattern in video frame stores to make the technique entirely electro-optical in nature. While the author has developed this technique experimentally, the principle has also been proposed independently by Tyrer, also at Loughborough, to lead to a joint

patent application (16 September 1985, patent No. 8522820).

3.4.2 Speckle De-correlation Methods

Speckle de-correlation is a well-documented aspect of ESPI, particularly in relation to the quality of the output which is dependent on the stability of the speckle field in the image plane. Wykes (1977) discusses wavelength related de-correlation and Jones and Wykes (1977) displacement dependence. A small change in the form of the phase referenced speckle pattern due to cyclic intensity changes of individual speckles is not adequate for speckle averaging. This simply averages out to the non-complex addition of I_S and I_R , leaving the background object speckle pattern. What is required is a gross change in the speckle distribution in the image plane.

The object speckle pattern can be changed by altering a number of parameters:

1. Viewing direction
2. Illumination direction
3. Wavelength of laser light
4. Gross phase changes of illuminating wavefront
5. Phase of the light scattered from the object.

Slettemoen (1980) suggests changing the viewing direction using a rotating double slit aperture, moving the aperture its own width to completely de-correlate the pattern (Figure 3.9(a)). This is a special case for a tuned imaging system, giving a limited number of randomly different patterns and restricted availability of light due to the small aperture. Lokberg and Slettemoen (1984) make the comment that this method is complicated to perform in practice. An easier method is described in this latter paper, changing the illumination direction by tilting a mirror in the path of the illuminating beam (Figure 3.9(b)). A drawback of this method is that the finer higher order time averaged fringes may be lost as the direction of interferometric sensitivity is changed.

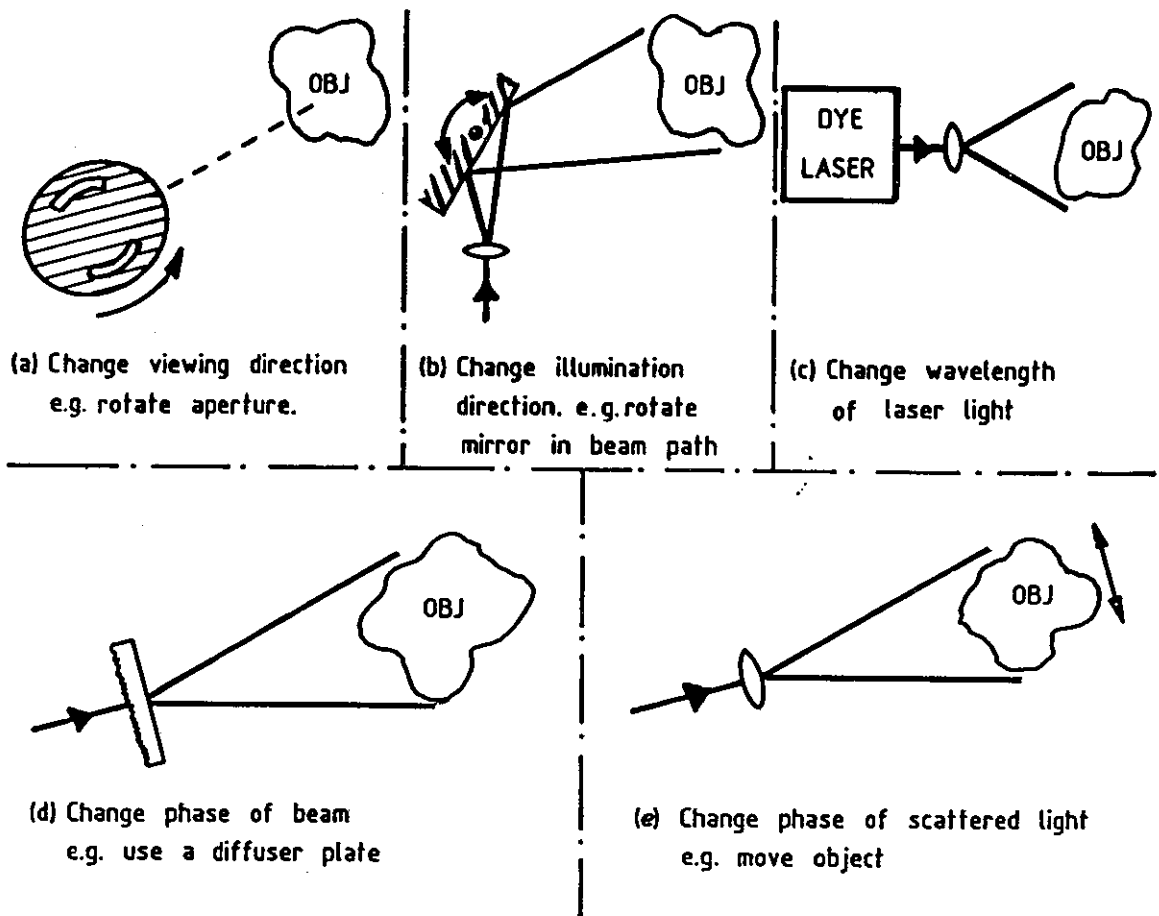


FIGURE 3.9 Five methods of de-correlating the speckle pattern in the image plane

Following Wykes (1977), a wavelength change of 20 to 50 nm is required to alter the temporal phase of the illuminating wavefront sufficiently to de-correlate the speckle pattern from a surface having a standard deviation in surface height of over $1\text{ }\mu\text{m}$. Such a large wavelength change for each new speckle pattern necessitates the use of a dye laser (Figure 3.9(c)). Because of its expense and problems in maintenance, the use of a dye laser at present is not an attractive option for an industrial test instrument. There is also a change in interferometric sensitivity with wavelength. Changing the phase of the illuminating wavefront with a moving diffuser plate is suggested by Lokberg and Slettemoen (1984). In this method (Figure 3.9(d)) a random phase change is introduced into the light scattered from the object surface.

Finally, the phase of the scattered light can also be changed by altering the nature or position of the scattering surface. Since the surface roughness is usually fixed, it is easier to give the object a small displacement.

From Section 1.1.1, for a typical ESPI system the resolution element at the object surface is $180\text{ }\mu\text{m}$. This requires a linear translation of 0.2 mm of the object surface for each new speckle pattern. With this technique the position of the vibration fringes also moves, limiting the resolution.

3.4.3 Discrete and Continuous De-correlation

Most, if not all of the methods just described can be successfully used to produce complete de-correlation of the speckle pattern to form discrete images that can be individually added. Because of the interferometric sensitivity, continuous de-correlation may lead to the fringes "washing out". For example, it has been found that in testing the object translation method with an object mounted on a motorised linear translation stage, even at a rate of $1\text{ micron per second}$, the fringe quality is seriously impaired. This is probably due to the jolting action of the servo motor, stepping 1 micron at a time. A smooth running translation system may overcome this problem. In practice it is quite difficult to obtain a smoothly changing speckle pattern.

A second problem encountered with continuous de-correlation is the formation of fringes when using the optical noise subtraction method described earlier in the chapter. This is most noticeable in using the change in angle of illumination method when tilt fringes are formed (see Chapter 4). In the light of these initial trials it was decided to make use of moving diffuser plates to de-correlate the speckle pattern as they show distinct advantages over the other techniques.

3.4.4 Use of a Diffuser Plate

A number of methods of using a diffuser plate for speckle decorrelation were investigated (Figure 3.10). The first successful method proved to be the use of a galvanometer mirror in the path of the object beam to scan the beam across a stationary diffuser plate (Figure 3.10(a)). This consists of a 2 mm thick glass plate ground on one side.

The light scattered by the plate acts as a speckled object wavefront. A saw-toothed function is used to drive the galvanometer mirror back and forth with typical speeds of 0.1 to 0.5 deg per second or 0.4 to 2.0 mm per second of the spot across the diffuser. Faster speeds reduce the fringe contrast. No tilt fringes are produced when using the noise subtraction method.

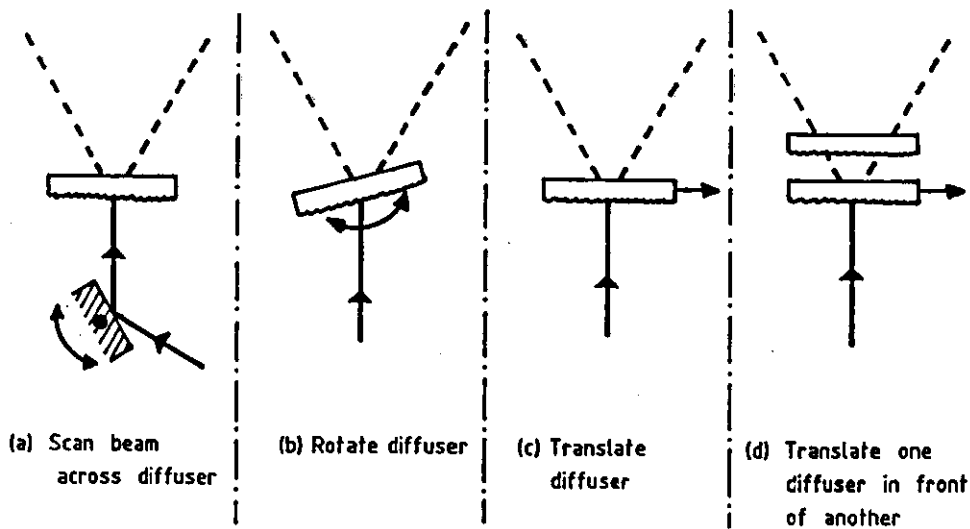


FIGURE 3.10 Four methods of using a diffuser plate to produce continuously changing random phase in an illuminating wavefront

If the diffuser plate is fastened to the galvanometer mirror (Figure 3.10(b)), the angle of illumination is kept ^{approximately} constant while varying the speckle pattern as the plate rotates in the laser beam. This works successfully in the time averaged mode but not when noise subtraction is used. In this mode, the system is sensitive to quasi-static phase changes in the light scattered from the object and up to 15 vertical tilt fringes have been observed with the rotation of the plate.

The origin of these fringes is thought to be due to a slight change in the angle of illumination (see Chapter 4) produced by the rotating plate. A small number of fringes are observed as the speckled wavefront moves over the object surface until they are obscured by speckle de-correlation at gross angular changes. Translating the diffuser plate across the beam (Figure 3.10(c)) maintains a constant angle of illumination and a similar set of vertical fringes is produced. In this case, because there is no beam rotation, it is thought that they are a form of in-plane fringes due to an overall shift in the illumination wavefront across the object surface.

A disadvantage with using a diffuser plate is that the use of a speckled illuminating wavefront produces poor quality time averaged fringes due to a high value of object noise. The optical noise subtraction method helps to a certain degree when using continuous de-correlation, but steps must be taken to reduce the value of the optical noise. Finer speckles can be formed in the illuminating wavefront using a second diffuser plate a short distance behind the first plate (Figure 3.10(d)). The phase of the wavefront is also randomised to such an extent as to remove the problem of tilt fringes.

Diffuser plates can tend to be inefficient and give a large angular spread to the beam. A plate prepared by grinding one surface for five minutes in a solution of water and grade 500 carborundum powder on a second plate was found to have a transmission efficiency of 82%.

Dyson (1960) describes a method for improving the efficiency and reducing the scattering angles by etching with hydrofluoric acid. A diffuser plate soaked for 20 minutes in a 5% solution of HF was found to have an efficiency of 87% and an improved intensity profile. The degree of etching controls the efficiency and the scattering angle.

After testing different translation speeds of the diffuser plate, a linear translation speed of 10 to 40 microns per second was found to be suitable for speckle averaging for a typical illumination angle of 25° to the viewing axis.

3.5 PHOTOGRAPHIC AVERAGING

Initial experiments were carried out with the photographic averaging technique reported by Lokberg and Slettemoen (1984), de-correlating by tilting a mirror in the path of the illumination beam.

The Loughborough demonstration rig was used to study the 4.0 kHz mode of the 50 mm loudspeaker. A smooth object beam is reflected from a mirror with a horizontal tilt facility onto the speaker at an angle of 40° with the viewing axis. A tilt of about 0.1° was sufficient to de-correlate, this being verified by storing an image of the object in the frame store and the mirror tilted until the screen showed maximum brightness, indicating full de-correlation. Full noise subtraction was used to give vibration fringes.

A technical camera with a repeat exposure facility was used to photograph the monitor screen, each exposure being 1/8 second. Different numbers of exposures were taken, tilting the mirror in between exposures. The total light exposure was kept constant, closing the aperture by one f stop for double the number of exposures e.g. starting at f/4 for 1 exposure, f/5.6 for 2, f/8 for 4 etc. Altering everything by hand, each exposure took about 20-30 seconds to perform.

Some typical results are shown in Figure 3.11 showing the striking improvement to the fringe contrast between 1 and 32 exposures. The decrease in speckle contrast also reveals more object detail. For the single exposure the circular portion in the centre is indistinguishable whereas at 32 exposures it is clearly defined, together with an outline of the wires to the coil. There is such an improvement in quality that it resembles a photograph of a hologram. A slight amount of blurring is apparent due to astigmatism from the use of a wedge beam combiner and simple lens.

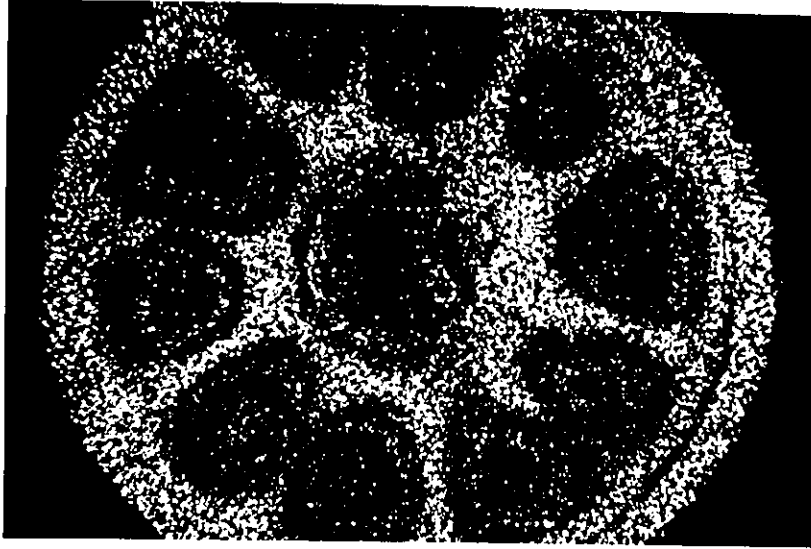
From a practical point of view this is a fairly simple, low cost method of enhancing results, particularly if instant processing cameras are used.

3.6 ELECTRONIC SPECKLE AVERAGING

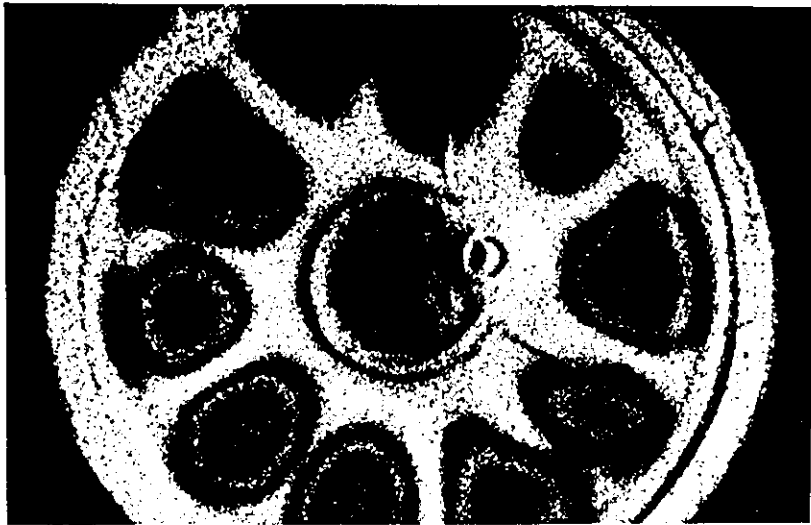
3.6.1 Introduction

While photographic averaging is suitable for presentation of results, it takes a few minutes to perform. It is desirable to display high contrast fringes on the monitor screen in seconds, or ideally at frame rate to allow full interactive analysis. As discussed earlier, because speckle averaging is limited to the reconstruction stage of the interferogram which takes 40 mS at 25 Hz frame rate, it is doubtful that it will be possible to work at frame rate. Until new ideas are discovered by which this may be achieved, which is entirely possible with ESPI, averaging is limited to multiple frame times at present.

Lokberg and Slettemoen (1984) suggest using a long lag monitor with a persistence of a second or so to give a running average of 25 frames. Full averaging can be achieved in video frame stores with an integration function. What follows is a description of the use of a Vidicon Storage Tube in an engineering application of ESPI, and a digital frame store for carrying out some quantitative analysis of speckle averaging.



(a) Single exposure - poor contrast



(b) 32 exposures revealing high contrast fringes and object detail

FIGURE 3.11: Fundamental noise reduction of time averaged fringes by photographic speckle averaging. 50 mm loudspeaker vibrating at 4.0 kHz

3.6.2 Engine Modal Analysis by ESPI Using Speckle Averaging in a Vidicon Storage Tube

Some of the first work with the Vidicon Storage Tube (VST) was carried out in conjunction with British Leyland Technology (BLT) to prove the use of ESPI in engine modal analysis. This is described in full by Davies et al (1985). It is briefly reported here to demonstrate the use of speckle averaging in combination with strobing, phase modulation and the more recent innovations of the zoom lens and noise subtraction techniques.

Experimental

The experimental work was carried out by the author at Loughborough using a four cylinder petrol engine loaned by BLT. A diagram of the apparatus is shown in Figure 3.12 and a photograph in Figure 3.13. The appearance of complexity is inevitable with the use of additional ESPI techniques for extracting phase information and higher resolution images, particularly with a breadboard system such as this. A "Coherent 52" Argon Ion Laser giving light of 514 nm wavelength is used, at a power of 200 to 400 mW depending on the size of the area viewed. The high laser power available relaxes the need for stringent system optimisation and enables high contrast results to be obtained from the undulating surface of the engine. Even though it is painted matt white, the surface details contribute significantly to the optical noise. Speckle de-correlation is performed with a single stationary diffuser plate scanned by the object beam deflected from a galvanometer mirror (as in Figure 3.10(a)). The VST was used in the integration mode with a 1 to 10 second period. Noise subtraction was carried out with the Pantak (EMI) digital frame store normally used in the subtraction mode.

The Pockel's cell in combination with an analyser is used as a shutter in the main beam opening at twice the frequency of vibration of the object. It is pulsed so that it illuminates the extremes of vibration to form addition fringes with a $\cos^2$ intensity variation

(Lokberg, 1979). A variable phase oscillator in combination with a double pulse generator produce the appropriate signals, an oscilloscope being used to set up the pulse timing. In this way, higher resolution maps of vibration are formed.

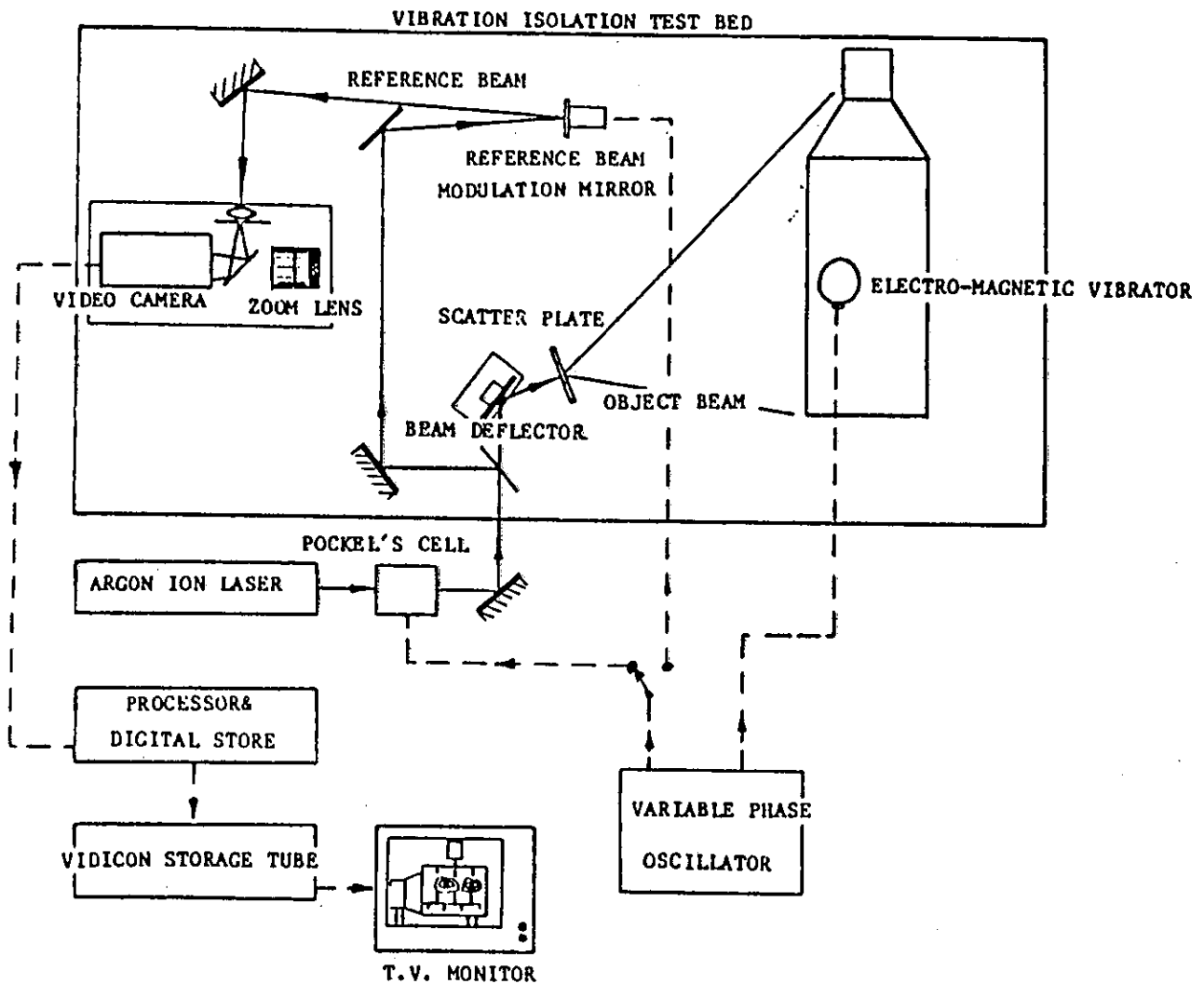


FIGURE 3.12 Schematic of ESPI system incorporating speckle averaging, strobing and phase modulation

Reference beam phase modulation is employed to determine the phase of complex vibration modes (Lokberg and Hogmoen⁽¹⁾, 1976). A home-built piezo mirror consisting of a 3 x 3 mm mirror glued onto the end of a 10 mm x 6 mm diameter piezo electric crystal is used to change the

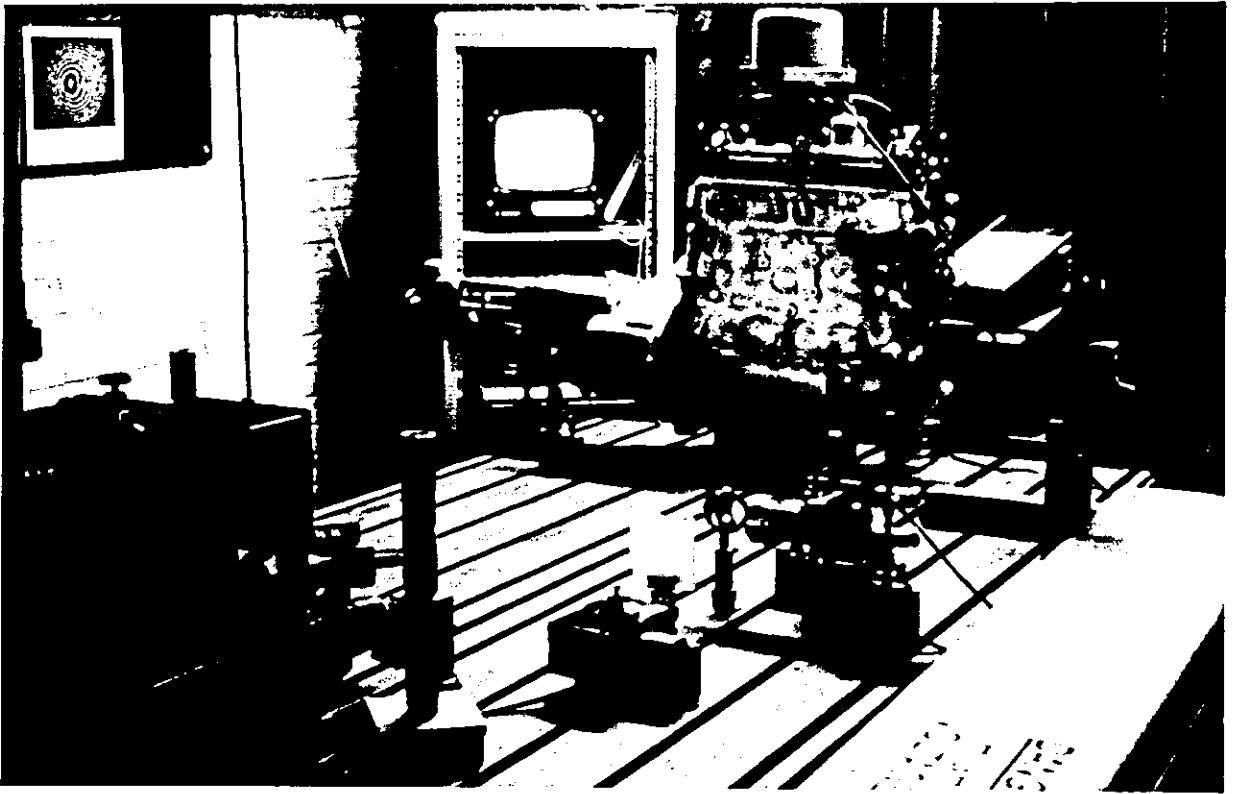


FIGURE 3.13: General view of optical table and ESPI system for modal analysis of B.L. series "E" engine under forced vibration

reference beam path length when driven with a high voltage from the Pockels cell amplifier. Oscillating at the same frequency as the transducer vibrating the engine, the amplitude and phase of vibration of the mirror are changed to determine the amplitude and phase of the vibration modes.

The engine is mounted on rubber bushes and force vibrated with a 5 kg electromagnetic vibrator. A series of experiments were carried out to explore the use of speckle averaging with strobing and phase modulation.

Two frequencies were of particular interest in this example of modal analysis. The first is at a typical engine running noise frequency of 3 kHz useful in the understanding of noise generation. The other is at a higher frequency of 6 kHz typical of that induced by knock detonation for the siting of knock detecting sensors used in electronic engine management control systems.

Results

Initial results with speckle averaging revealed a problem of noise not detected before. Using full noise subtraction, integration in the VST reduced the speckle content of the fringe pattern but left a pattern of white blotches similar in nature to the optical noise that could be seen on the reference beam. This is illustrated in Figure 3.20(b) in a different application with digital frame stores. Over a period of a few seconds the reference beam noise drifts slightly, which on subtraction produces white marks. This is probably due to *electronic variations* of this particular video system,

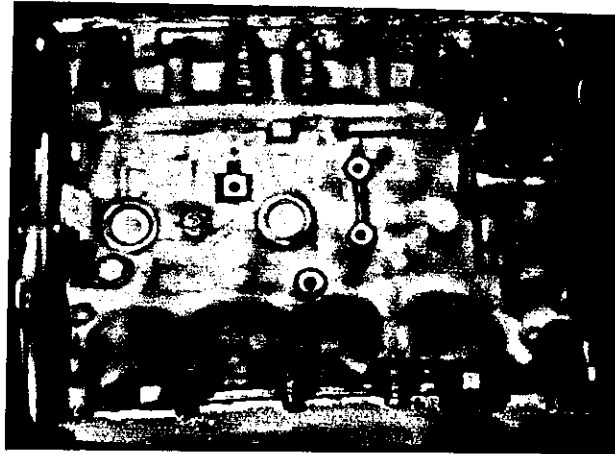
A temporary solution to this problem is to refresh the digital frame store every half second during integration on the VST. What did not help was the use of the noisy beam combiner shown in Figure 2.3(b), an unknown problem when this work was carried out.

A useful integrating time was found to be 5 seconds, or 125 successive frames. Shorter times revealed speckle noise and longer times gave no significant improvement in fringe contrast. Smoothing was aided by the filtering effect of the video store which had a *bandwidth* of approximately 2 MHz, the modulation transfer function rolling off to 50% at 8 MHz.

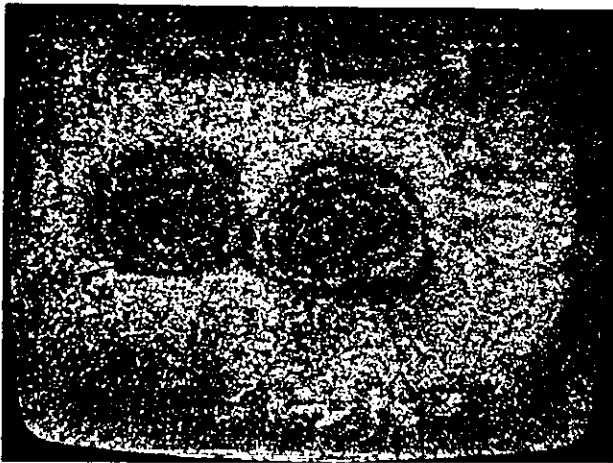
The effects of noise subtraction and speckle averaging are shown in Figure 3.14. Full detail of the engine is shown in (a) under white light illumination. With the standard ESPI system using noise reduction, the vibration mode can be seen in (b), but details of exactly where the peaks are on the engine are unclear. After averaging with the VST and strobing, the fringe detail becomes much clearer in (c). Because the engine detail is revealed, it is a lot easier to locate the precise centres of the antinodes. The blurred appearance is due in part to astigmatism from the wedge beam combiner and the reference beam noise.

The results of the other techniques are shown in Figure 3.15. Strobing at twice the frequency of vibration in (a) and (b) gives $\cos^2$ intensity fringes with the bright zero order fringe being the same brightness as the higher orders. In Figure 3.14 the whole side of the engine is encompassed with the lens at a focal length of 35 mm while a focal length of 50 mm gives a close up view in Figure 3.15. An 80-210 mm zoom gives even further detail if it is used.

Returning to the non-strobed time averaged mode in (c), what was the first order fringe has been changed into the zero order bright fringe by phase modulating the reference beam with the piezo mirror. This is useful to map phases over a fringe map when there is more than one antinode (e.g. by Davies et al op cit). It is also useful to detect large vibration amplitudes by moving the zero order fringe "up" the higher orders by increasing the amplitude of phase modulation of the mirror (Lokberg and Hogmoen⁽²⁾, 1976). Very small amplitudes of vibration can also be detected (Hogmoen and Lokberg, 1977) by modulating the phase change and using a photo-detector at the monitor



(a) View of engine in white light



(b) Time averaged pattern at 3.25 kHz vibration (with noise subtracted)



(c) Improved fringes at 3.25 kHz vibration by speckle averaging in a VST (strobing at 6.5 kHz)

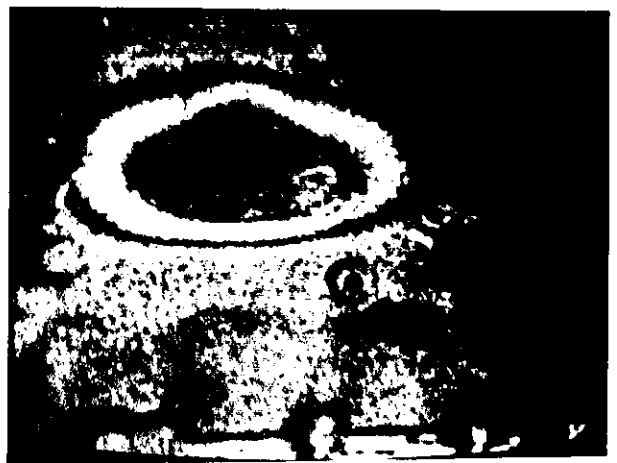
FIGURE 3.14: Effect of noise reduction by speckle averaging in engine modal analysis. Wide angle view at 35 mm FL.



(a) Close up detail for 3.25 kHz vibration (strobing at 6.5 kHz)



(b) Strobing at 5.78 kHz for 2.89 kHz vibration



(c) Phase modulation of reference beam at 2.89 kHz highlighting a higher order fringe for precise measurement of phase and amplitude

FIGURE 3.15: Speckle averaging combined with strobing and phase modulation. Close up at 50 mm FL.

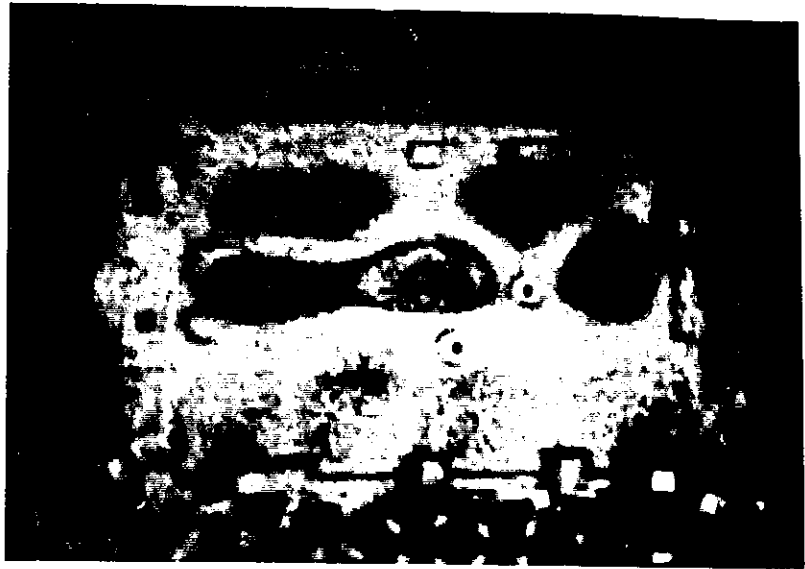
screen to measure slight changes in intensity.

Finally, a speckle averaged ESPI interferogram is compared with a holographic image in Figure 3.16. It took about one minute in the time averaged mode to find the particular resonance at 5.88 kHz in (a). About 30 seconds were spent taking a number of shots to optimise the contrast and gain controls on the VST, and then 5 seconds to actually record the interferogram in (a). By comparison, it can take a half to a day's work taking holograms at different frequencies to find a particular mode. Another hour can be spent exposing test plates to optimise the exposure time and a 10 second exposure and 15 minutes of developing, fixing and drying to obtain the result in (b). The difference in time is a couple of minutes for ESPI compared with a few hours for holography. The ESPI results were also obtained in a laboratory with semi-illumination conditions with other people working in the vicinity. This is almost impossible with holography where complete darkness or at the very least low level safe-light conditions and complete stillness are required.

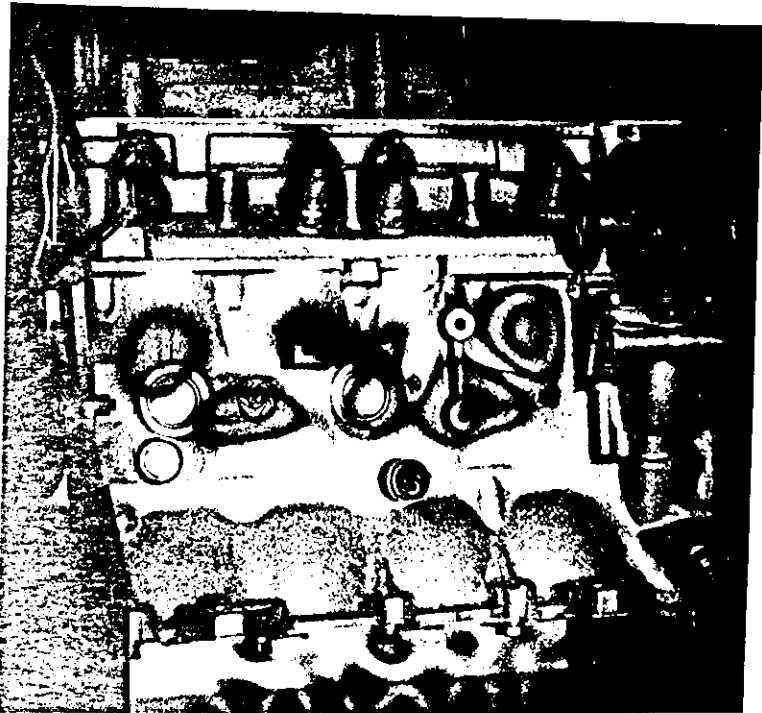
It is expected that with further improvements to the optical system, results with even greater resolution will be attainable.

3.6.3 Use of a Digital Frame Store in Speckle Averaging - Plate Resonance Studies

It is not uncommon for dedicated image processing systems to have noise reduction facilities for use in electron microscopy and thermal imaging. These are ideal for speckle averaging and more reliable than the VST. The following experiments were performed on an "Intellect 100" using a DEC LSI 11/23 16 bit computer. Two modes of noise reduction are available. The first is a running average on a 512 x 512 pixel by 8 bit image with an adjustable feedback control to give different levels of noise reduction. The second is an integration function adding successive video frames of 256 pixels by 512 lines resolution in a 16 bit memory. Display of the 8 most significant bits shows the results, the image being normalised below



(a) ESPI pattern at 5.88 kHz vibration formed in just over 1 minute by speckle averaging (*see text*)



(b) Hologram of 7.5 kHz vibration formed in over 4 hours by time averaged holography (Courtesy of J.R. Tyrer) (*see text*)

FIGURE 3.16: Comparison of results from speckle averaging with ESPI and holographic interferometry for modal analysis of B.L. series "E" engine

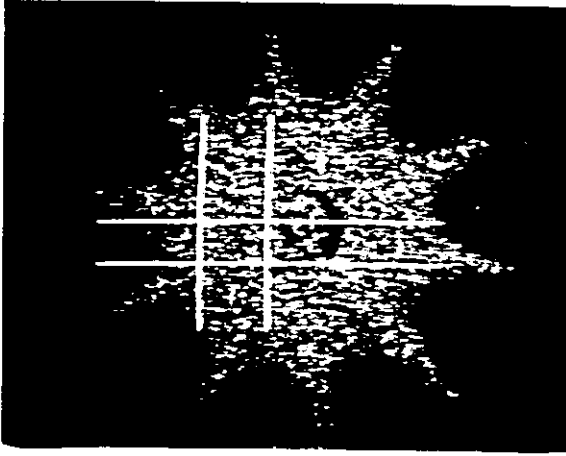
128 frames to compensate for low image brightness.

After carrying out some initial trials with digital speckle averaging, it was realised that further improvements can be made using other digital processing techniques before and after integration. In fact, there is a whole new field to be explored because of the large number of possibilities. The purpose of this section is therefore merely to show some preliminary results, quantifying the reduction in speckle contrast and demonstrating some patterns obtained with the classic vibration modes of a round plate.

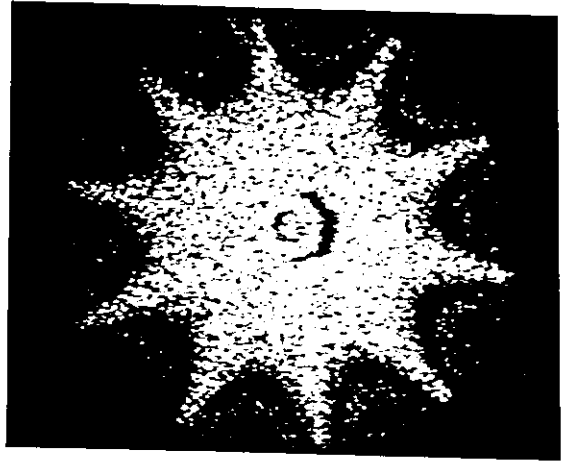
Measurement of Speckle Contrast Reduction

With discrete speckle de-correlation it is possible to fully de-correlate the pattern between each exposure, giving a $\sqrt{N}$ reduction in speckle contrast for N images. This is not the case for continuous speckle de-correlation where the speckle pattern is slowly changing in form in the image plane. When this is scanned by the video camera and processed by the ESPI system it is likely that the patterns in consecutive frames are partially related. What the reduction in speckle contrast will be with the integration of consecutive frames is unknown. An experiment was carried out to investigate the change in speckle contrast with the number of frames added.

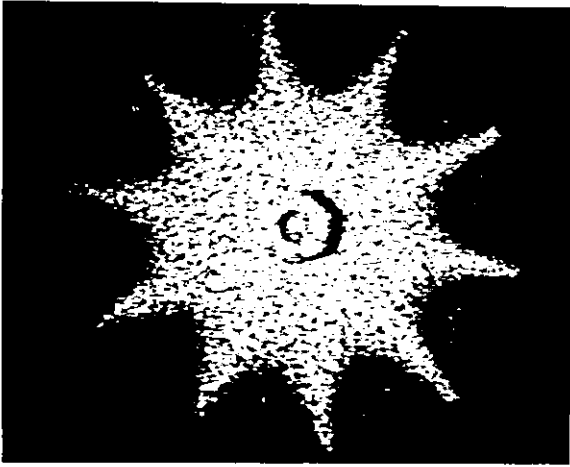
A bench ESPI system was set up in a similar format to the Vidispec, but using a 15 mW HeNe laser, a 35-80 mm zoom lens, and a clean uncoated wedge beam combiner. The 5D mode of a centrally mounted 75 mm diameter round metal plate was chosen because it yields a bright zero order fringe in the centre suitable for measuring the speckle contrast. Resonance at 6.4 kHz was obtained by exciting a piezoelectric crystal glued to the rear of the plate. To de-correlate, the advanced double diffuser plate system in Figure 3.10(d) was used with an illumination angle of 25° to the viewing axis. One diffuser plate was stationary and the other placed 15 mm behind it mounted on a linear translation stage. The diffuser plates had been etched in HF for 10 minutes. A speed of 10 microns per second gave good



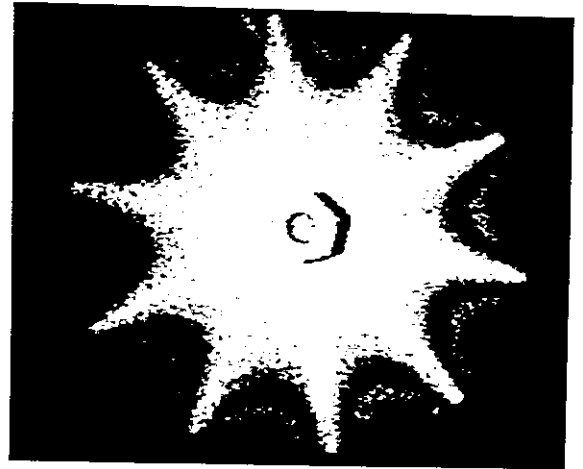
$$N_F = 1 \quad C_S = 0.83$$



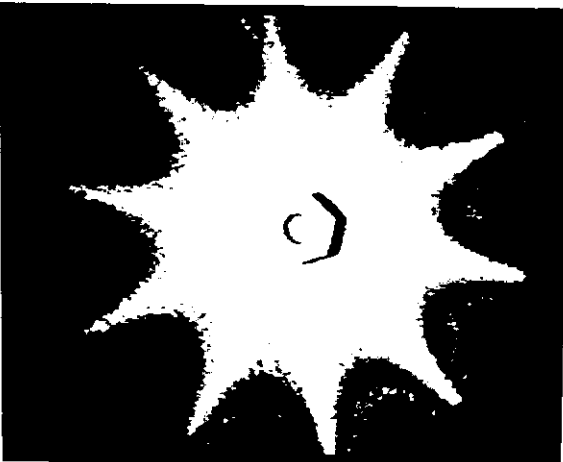
$$N_F = 16 \quad C_S = 0.47$$



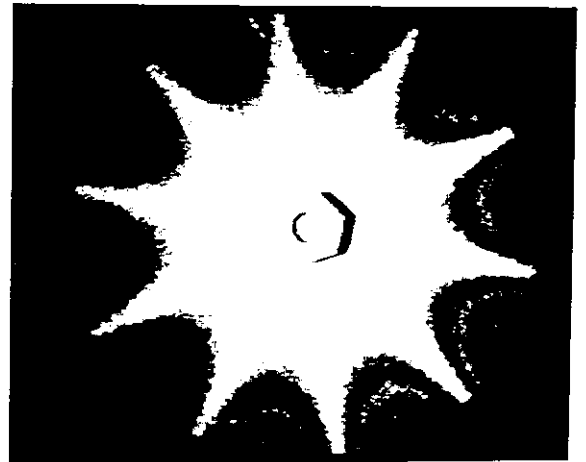
$$N_F = 64 \quad C_S = 0.30$$



$$N_F = 144 \quad C_S = 0.28$$



$$N_F = 400 \quad C_S = 0.12$$



$$N_F = 784 \quad C_S = 0.09$$

FIGURE 3.17: Digital speckle averaging of different numbers of frames, N_F , showing improvement in speckle contrast, C_S . 256 pixel by 512 line store used for a 75 mm diameter plate vibrating at 6.4 kHz

visibility fringes, though this may have been a slower rate of de-correlation than that used in the engine modal analysis experiments. It is a little complex to relate the speeds of the scanning and translation techniques.

The speckle contrast was measured in the area marked by the box in Figure 3.17 for $N_F = 1$ using the computer technique described in Appendix C. The number of frames added in each picture is given by N_F , while the speckle contrast is given by C_S . A graph is shown in Figure 3.18 displaying the variation of the speckle contrast with the number of frames added. If it is assumed that the contrast is reduced by $1/\sqrt{N}$, for large numbers of frames added, $N = N_F/K$ where K is the number of frames it takes to fully de-correlate. From the results between 64 and 784 frames the average value of K is 10.5, i.e. every 10.5 frames the speckle pattern can be said to be statistically unrelated, but in between, one frame bears some resemblance to the next. Further analysis requires experiments with different de-correlation speeds and types of diffuser plate to determine what exactly is happening from frame to frame.

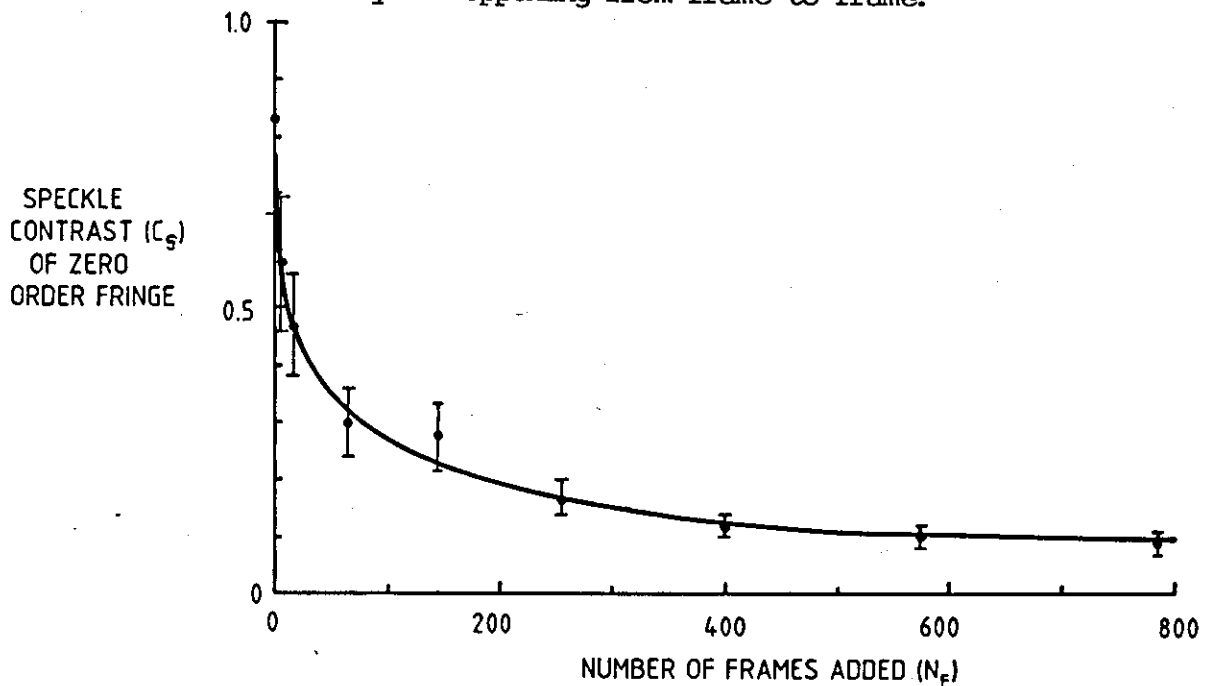


FIGURE 3.18: Variation of speckle contrast C_S with the number of frames added, N_F

Demonstration of Digital Speckle Averaging

To show some of the potential of digital speckle averaging, a number of images were formed on the "Intellect 100" and on a second image processing machine using a slightly better store.

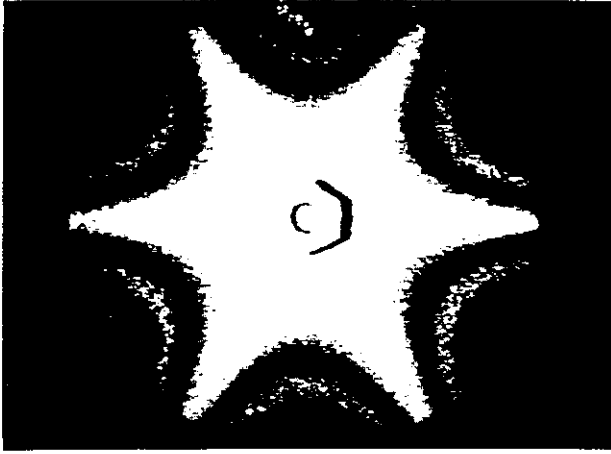
256 pixel x 512 line store - The same plate used in the previous experiment was analysed for other resonant modes and speckle averaged on the Intellect 100 to 800 frames. A number of classic modes are shown in Figure 3.19. These were obtained together with a number of other results in under an hour, showing the speed with which analysis can be performed.

512 x 512 pixel store - The second set of results were performed on a slightly better image processing system with a higher resolution image in the integration mode, run with a DEC LSI 11/73 computer and the system shown in Figure 3.12. When this was used, the noise subtraction method was not fully operational while integration was in progress due to a synchronisation fault. After storing the optical noise, the digital frame store in the ESPI system could not be refreshed every half second, allowing the reference noise to reveal itself. This is highlighted in Figure 3.20(b) where the speckles have been reduced, but the image is peppered with white marks.

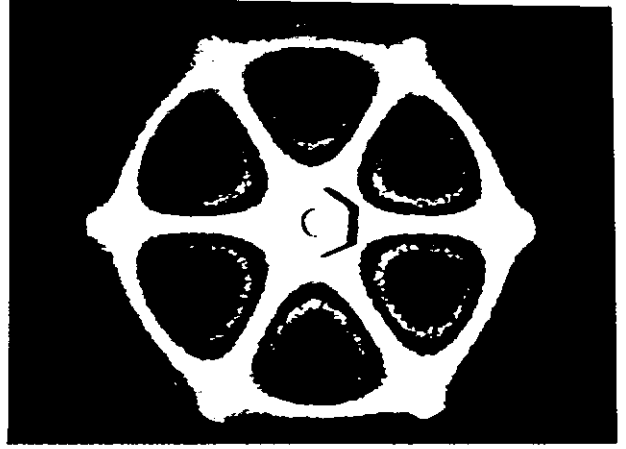
Finally the image in Figure 3.20(c) was formed by averaging over 256 frames, smoothing and contrast stretching using a look up table facility. The smallest fringes are 4 to 5 pixels wide, giving a fringe density of 100 to 130 fringes per picture width.

3.7 SUMMARY

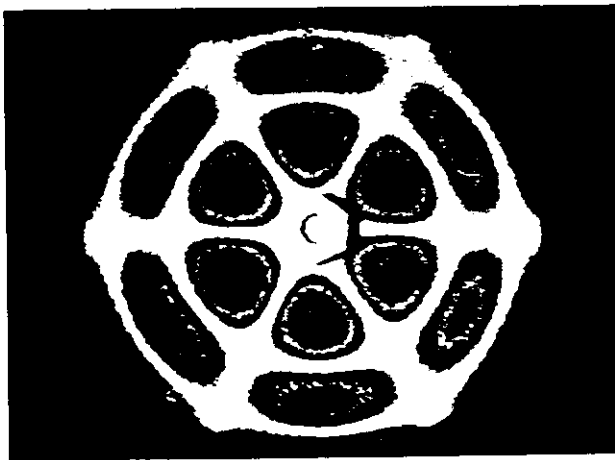
The three levels of noise reduction discussed apply particularly to correlation fringe formation, though noise subtraction and averaging are also applicable to phase stepping techniques.



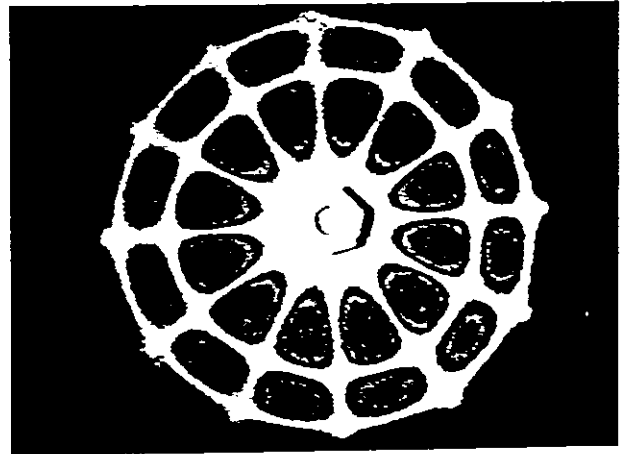
(a) 3D mode at 2.5 kHz



(b) 3D, 1C mode at 10.8 kHz

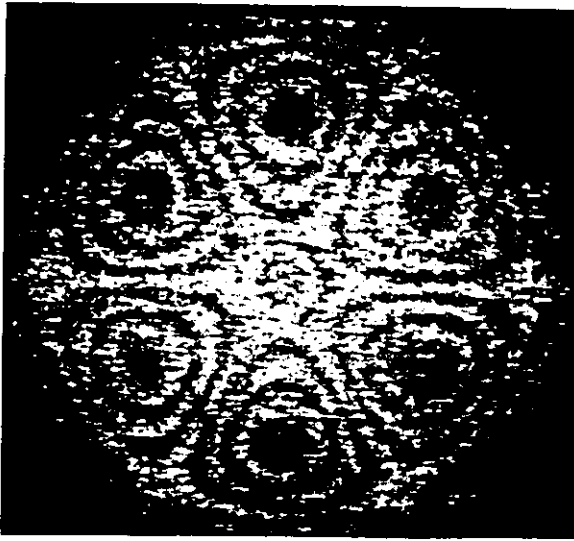


(c) 3D, 2C mode at 22.6 kHz

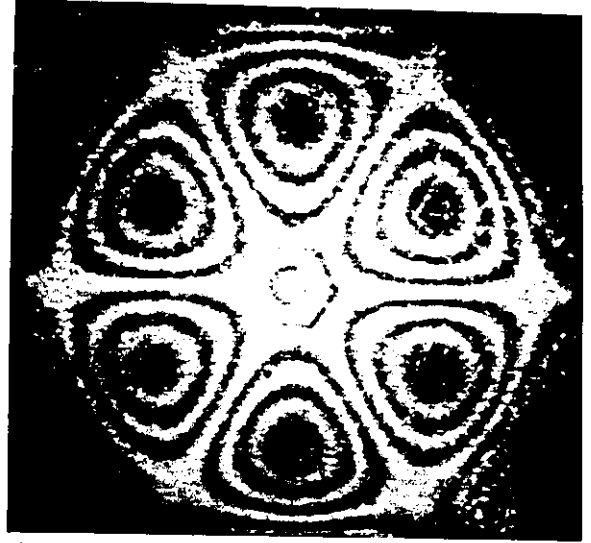


(d) 6D, 2C mode at 40.9 kHz

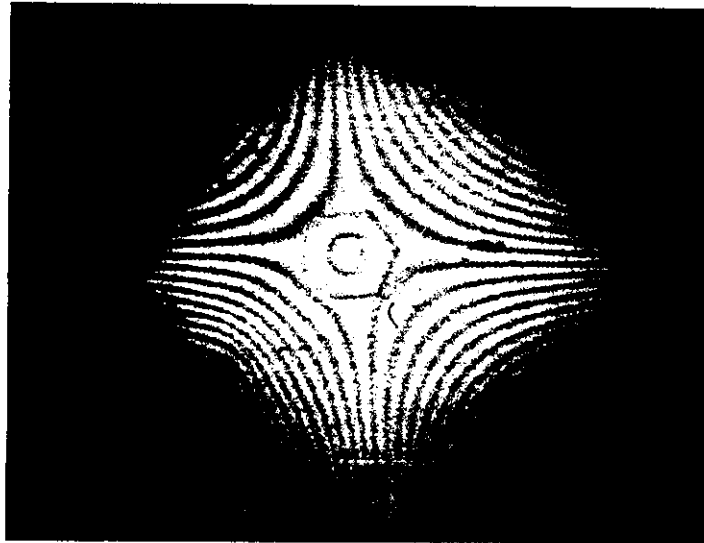
FIGURE 3.19: Classic resonant modes of a 75 mm diameter plate speckle averaged in a digital frame store (256 pixels x 512 lines) in 800 frames



(a) Strobed at 21.0 kHz for 10.5 kHz vibration. 3D, 1C mode. Single frame.



(b) As in (a) but speckle averaged. Reference noise visible as white blotches



(c) Strobed at 2.2. kHz for 1.1 kHz vibration, speckle averaged over 256 frames, smoothed and contrast stretched. 2D mode

FIGURE 3.20: Digital speckle averaging in a 512 x 512 pixel store

An ESPI design incorporating the noise reduction technique described in this chapter is shown in Figure 3.21. Analogue signal processing of the output involves 2D filtering and contrast stretching. 2D filters are now commercially available using active digital filtering, with adjustable levels for each dimension. A range of 0.4 MHz to 3.8 MHz in the horizontal direction gives a resolution of 20 to 200 fringes per picture width for a frame rate of 25 Hz. For a 625 line system, a range of 0.5 kHz to 5.0 kHz is required for vertical filtering. After smoothing, the signal is passed through a video signal processor to carry out thresholding and various forms of contrast stretching. A unit made by "Insight Vision" is now available at Loughborough to do this. These functions can be switched in and out and set for the required resolution and fringe contrast.

Optical noise subtraction can already be carried out with a conventional ESPI system, though the addition of a device for introducing a phase change into one of the paths would be an advantage. This can be achieved with the same device as used for phase stepping discussed in the next chapter.

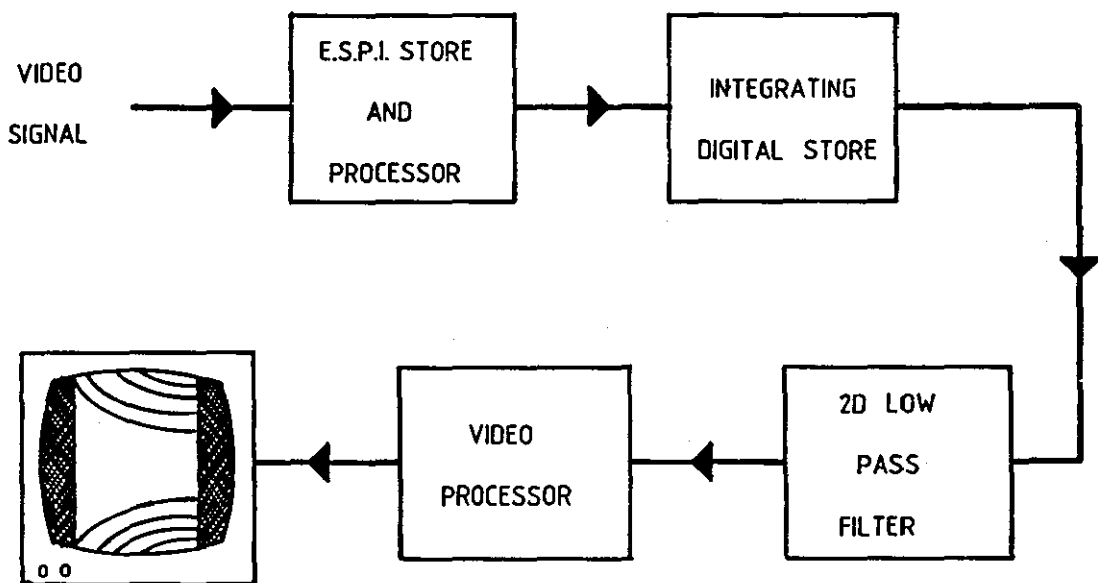


FIGURE 3.21: Schematic of advanced ESPI design using noise reduction techniques

Speckle averaging at low cost is best performed in a digital store dedicated to noise reduction by integration or a running average. These units are commercially available, and the price is decreasing as RAM memory falls in price. A simple design of speckle decorrelator is suggested, using two finely ground diffusers etched in HF acid for improved efficiency. One plate is fixed, 5 to 15 mm in front of the other which is mounted on a slowly rotating spindle. A clock motor giving a speed of one revolution per hour gives a plate translation speed of 40 microns per second for a plate diameter of 46 mm. A lens can be used to change the divergence of the object beam to cover the required target area. This unit would replace the conventional expanding lens L_0 in Figure 2.9 for use in speckle averaging.

CHAPTER 4

ELECTRONIC SPECKLE CONTOURING (ESC)

4.1 MEASUREMENT OF ABSOLUTE SHAPE WITH ESPI

Butters and Leendertz (1971) described the concept of a total inspection system that could measure absolute shape as well as displacement. In discussing the future development of ESPI they wrote:

"The next step in the development is to perform the equivalent process of holographic contouring with the equipment, thus enabling comparisons between different surfaces to be carried out with controlled sensitivity ... Given a satisfactory solution to the contouring process, the reality of an automatic inspection technique based on coherent optics will be confirmed."

What they were proposing was an optical system that could measure absolute shape at higher speeds than mechanical systems like the 3D coordinate measuring machine. This would enable form to be measured for checking against tolerance limits. It would also contribute to the determination of strain values when using the displacement measurement facility of the instrument. Since then, two approaches that have been taken to shape measurement are two wavelength ESPI contouring and the use of fringe projection techniques.

4.1.1 Two Wavelength ESPI Contouring

Two wavelength holographic contouring was first proposed by Haines and Hildebrand (1965). The idea was to make two holograms of the same object with two wavelengths of laser light. From the resulting interference pattern, contours superimposed on the surface of the object could be used to determine the shape of the object. The ESPI contouring technique discussed by Denby et al (1975) was similar in that it used two wavelengths of laser light but differed in that it

was a comparative technique. The shape of an object is compared with a master optical wavefront to give a measure of comparative shape instead of absolute shape.

An ESPI system with an in-line smooth reference beam is used to view the optically rough test surface. The surface is illuminated with the master wavefront which is similar in shape to the test surface. By generating the master wavefront at two wavelengths, λ_1 and λ_2 , addition fringes are produced. These contours give the difference in depth, Δd , along the viewing axis between the surface and the master wavefront given by:

$$\Delta d = \frac{\lambda_1 \lambda_2}{2(\lambda_1 - \lambda_2) \cos \theta}$$

where θ is the angle of incidence of the light with respect to the viewing axis. An alternative method is to illuminate the object sequentially at the two wavelengths and subtract the speckle images to form subtraction fringes.

The contour spacing of the interferogram is determined by the wavelength difference. A range of 2-30 μm can be obtained with suitable wavelength pairs from an Ar Ion laser. By using more closely spaced wavelength pairs with a dye laser this can be increased to the millimetre range.

The accuracy of measurement of the shape difference depends on the precision of the master wavefront. Diffraction limited optics can be used to minimise distortion in generating flat, spherical and cylindrical wavefronts. Careful alignment of the optical components and the jig holding the test object minimises further sources of error.

A holographic element can be made of a more complex master surface if an object with a specularly reflecting surface is available. Again the precision of the wavefront depends on the quality of the optical

elements. The reconstructing reference beam must be exactly conjugate with the original holographic reference beam. This can be achieved by using an aberration free plane wavefront. Processing the plate may introduce error fringes due to emulsion swelling. Using a pre-shrunk emulsion overcomes this problem. The two faces of the hologram plate must be optically flat but not necessarily parallel. Discontinuities in the surface or in the medium supporting the emulsion can cause diffraction effects in the light passing through the hologram, distorting the master wavefront. In the cases where more sharply curved objects are used where these errors are more noticeable, a specially coated optical flat can be used. For plates with non-parallel surfaces, the hologram can be tilted to re-align the reference beam. A kinematic mount is used to accurately locate the hologram.

Two wavelength ESPI contouring suffers the usual limitations of ESPI due to the speckled nature of the output. There are also restrictions on the type of object that can be contoured. The size of the object is limited by the size of the optical elements used to form the master wavefront. The surface roughness should fall within a range of values smooth enough to prevent de-correlation at the two wavelengths but sufficiently rough to form a speckle pattern. These problems are discussed more fully by Jones and Wykes (1983).

From this brief summary of two wavelength ESPI contouring, it is apparent that it is a specialised laboratory technique requiring expensive precision equipment and a high level of skill to perform successfully. It is susceptible to many sources of error, produces a poor quality interferogram and in its present form is impractical for industrial use.

4.1.2 Fringe Projection Techniques

Macovski et al (1971) suggested using projected Michelson-type fringes for contouring in a combined shape/displacement measurement system.

The use of projected interference fringes after Rowe and Welford (1967) and Brookes and Heflinger (1969) may prove a more suitable method than two wavelength ESPI contouring. The technique is easier to perform and gives higher quality fringes, although they are still speckled. It also has the advantage of not requiring interferometric stability although this may not be particularly important in a combined instrument where stability is still required for the displacement measurement mode with ESPI. A limitation of the method is the loss of up to 60% of the illuminating light where amplitude splitting interferometers are used. Efficiency can be improved by making use of both fringe fields from a Mach-Zehnder interferometer, by combining them to give moire contours or for contouring front and rear surfaces of an object for example.

An alternative to using interference fringe projection is the formation of equivalent fringes with ESPI by changing the illumination direction. This was introduced by Winther and Slettemoen (1984) and Bergquist and Montgomery (1985) who introduced the term "Electronic Speckle Contouring" (ESC). In this chapter the new family of ESPI contouring techniques is developed. In carrying out this work it has become apparent that single wavelength Electronic Speckle Contouring by changing the illumination direction is a large field in itself worth deeper exploration than is given here. This report is seen more as a selection of ideas than a thorough analysis of each technique. First, the basic principles of ESC are presented.

4.2 INTRODUCTION TO ESC

Tilt fringes due to a change in the illumination direction are a familiar occurrence to those working in ESPI. Jones and Wykes (1983, pp 266-268) report using the phenomenon to compensate for rigid body

tilt and rotation. The idea that these relate to the object surface shape as though the object cuts a projected grid was proposed theoretically by Bergquist (private communication, 1982) but not published until 1985 (Bergquist and Montgomery, 1985). Winther and Slettemoen (1984) described the formation of projected fringes equivalent to Young's fringes by translating the end of a single mode optical fibre carrying the object beam. There are various ways of changing the illumination direction and these are described after a brief look at the nature of ESC fringes.

4.2.1 Equivalence of Michelson and ESC Fringes

ESPI tilt fringes formed by subtracting two phase referenced speckle patterns produced by a small change in the illumination direction are equivalent to the interference fringes projected onto the same surface formed by two illumination beams tilted by the same amount. The following experiment demonstrates this.

An ESPI system is shown in Figure 4.1 with a Michelson Interferometer projecting two object beams onto the target. If mirrors M_1 and M_2 are tilted with respect to each other, localised interference fringes are formed and the target cuts this field to give results like those shown in Figure 4.2(a). To produce ESC fringes of the same nature, the reference beam is used and a phase referenced speckle pattern is stored with the object beam from M_1 illuminating the target. If the beam from M_2 illuminates the surface and the beam from M_1 is blanked off, fringes are formed on subtraction (Figure 4.2(b)). They have the same orientation and spacing as the interference fringes. The obvious difference in appearance is the noise due to the speckle content. While they have this similarity to the projected fringe technique in nature, they have a similarity to holographic contours in formation, in that the object surface forms part of the interferometer. This leads to the possibility of forming contours with a variable orientation of the reference plane as with holography (e.g. Yonemura, 1982). It displays advantages over interference fringe projection in

that 100% of the object beam is used. Because it relies on a video system, it is more suited to real time operation than holography.

4.2.2 Fringe Spacing on a Flat Target

The brightness of ESC tilt fringes on the monitor screen is described by the same expression used to describe normal ESPI fringes. For example, subtraction fringes (equation 1.4 in Chapter 1), follow a $\sin^2$ function:

$$B = 8K \langle I_S \rangle \langle I_R \rangle \sin^2 \frac{\Delta\phi}{2}$$

In the case of contouring, the phase change $\Delta\phi$ arises from the rotation of the illuminating wavefront. The derivation of $\Delta\phi$ for the general case of plane wavefront rotation is given in Appendix D and in the paper by Bergquist and Montgomery (1985). Figure 4.4 shows the optical geometry for the case of a flat target at an angle of γ to the viewing axis. The position of fringe m is:

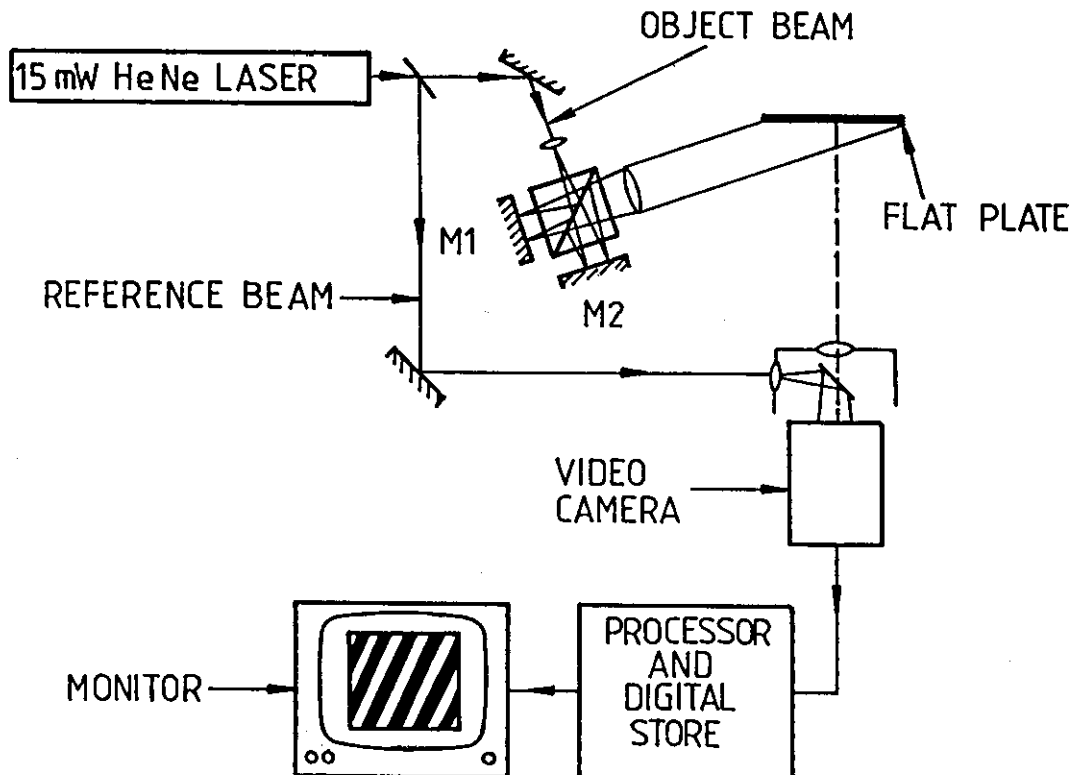
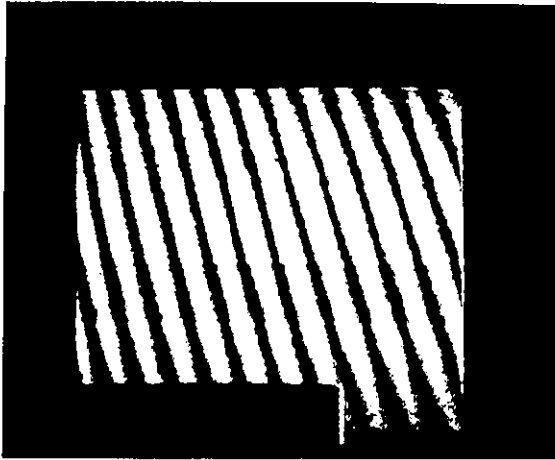
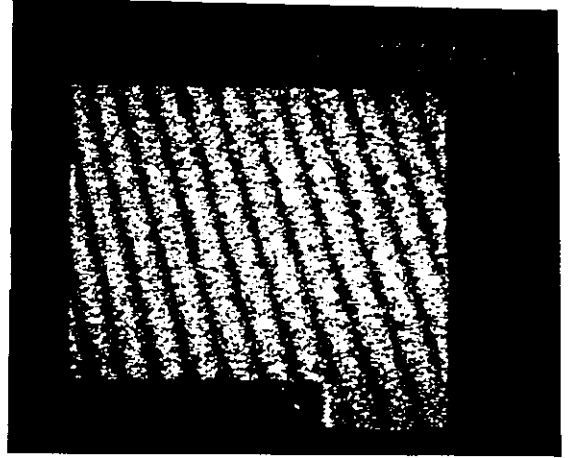


FIGURE 4.1: Apparatus used for demonstrating the equivalence of Michelson and ESC fringes



(a) Interference fringes from a Michelson Interferometer



(b) ESC correlation fringes

FIGURE 4.2: Equivalence of Michelson Interference fringes projected onto a flat plate and ESC fringes by subtraction of two speckle patterns

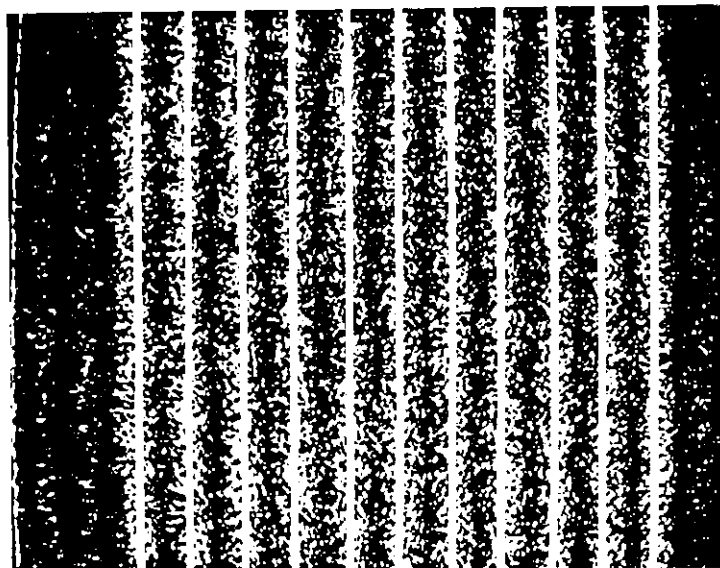


FIGURE 4.3: Comparison of ESC fringes with theoretical fringe spacing (white grid) for $\beta = 150^\circ$ and $\delta\beta = 0.15^\circ$. Target width is 31 mm.

$$\left(\frac{L \sin \theta_m}{\sin(\gamma - \theta_m)} \right) \left(\frac{\delta \beta}{\lambda} \right) \sin(\beta - \gamma) = \frac{2m-1}{2} \quad (4.1)$$

for a collimated illumination beam rotating about a point on the target in line with the viewing axis. For a target normal to the viewing direction, $\gamma = 90^\circ$ and the position x_m of fringe m is given by:

$$x_m = \frac{-\lambda(2m-1)}{4 \sin \frac{\delta \beta}{2} \cos(\beta + \delta \beta)} \quad (4.2)$$

To test this relationship between angle of rotation and fringe spacing, the apparatus in Figure 4.5 was used to form a set of vertical fringes by rotating the laser around the target on an optical bench. Two optical rails are used, one fixed to the table and the other hinged and free to move on steel roller bearings in the direction indicated. A micrometer fixed to the table translates this arm by a known amount. This enables a measurement of angular rotation to be made but causes the fringes to move across the target because of the change in the reference beam path length. It is also necessary to realign the reference beam due to the angular change, by tilting mirror M.

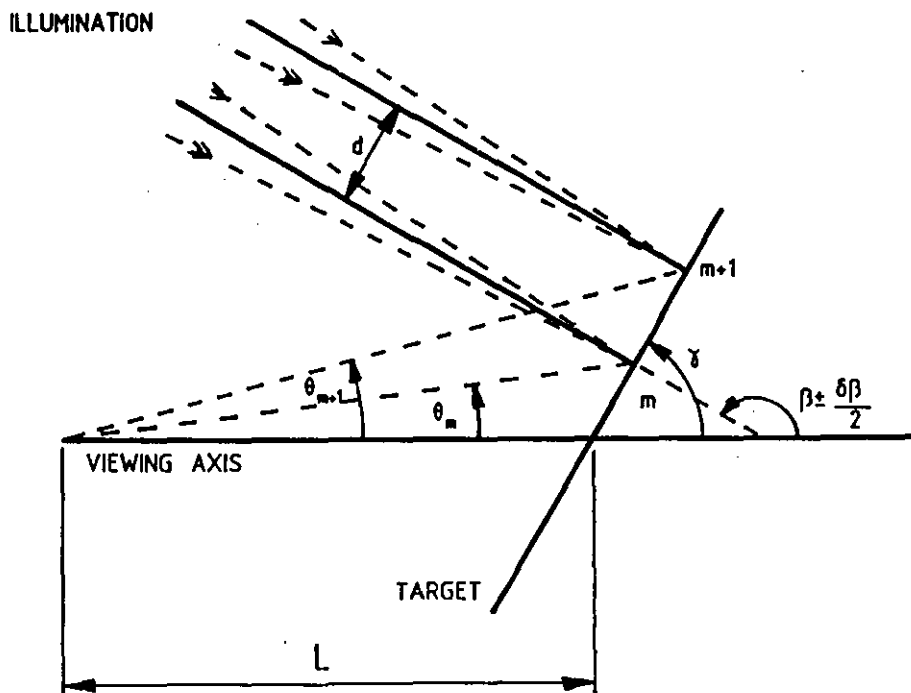


FIGURE 4.4: Geometry for determining fringe spacing on a flat target in basic mode ESC

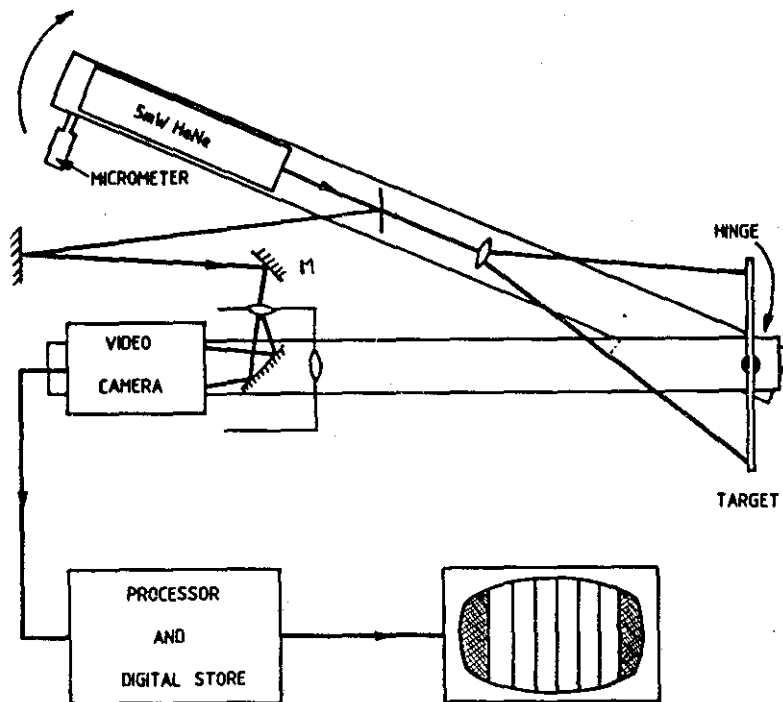


FIGURE 4.5: Apparatus used for checking fringe spacing by rotating object beam about object

A typical set of fringes is shown in Figure 4.3 for an illumination angle of 30° with the viewing axis and an increment of $\delta\beta = 0.15^\circ$. From equation (4.2), the fringe separation is 2.8 mm, giving eleven fringes across a 31 mm target, shown by the white grid, which is in good agreement with the results. Although a spherical wavefront was used in this experiment, the error in the fringe spacing across the target is undetectable because the origin of the object beam is a long distance from the target in relation to the target's size. After checking one angle of illumination, a number of values of β and γ were tested and the results of the fringe numbers across the target checked against the theoretical values. Some typical values for $\gamma = 90^\circ$ are shown in Figure 4.6. A repeatability of setting the micrometer to within 0.02 mm gives an accuracy in $\delta\beta$ of $\pm 0.5 \times 10^{-3}$ deg. The fringe number accuracy is ± 0.5 fringes. This is relatively low because fringe drift and the poor contrast of the target on the monitor make

it difficult to count the fringes by eye. The accuracy could be increased by using markers on the screen to define the target width. Covering the apparatus would reduce thermal drift.

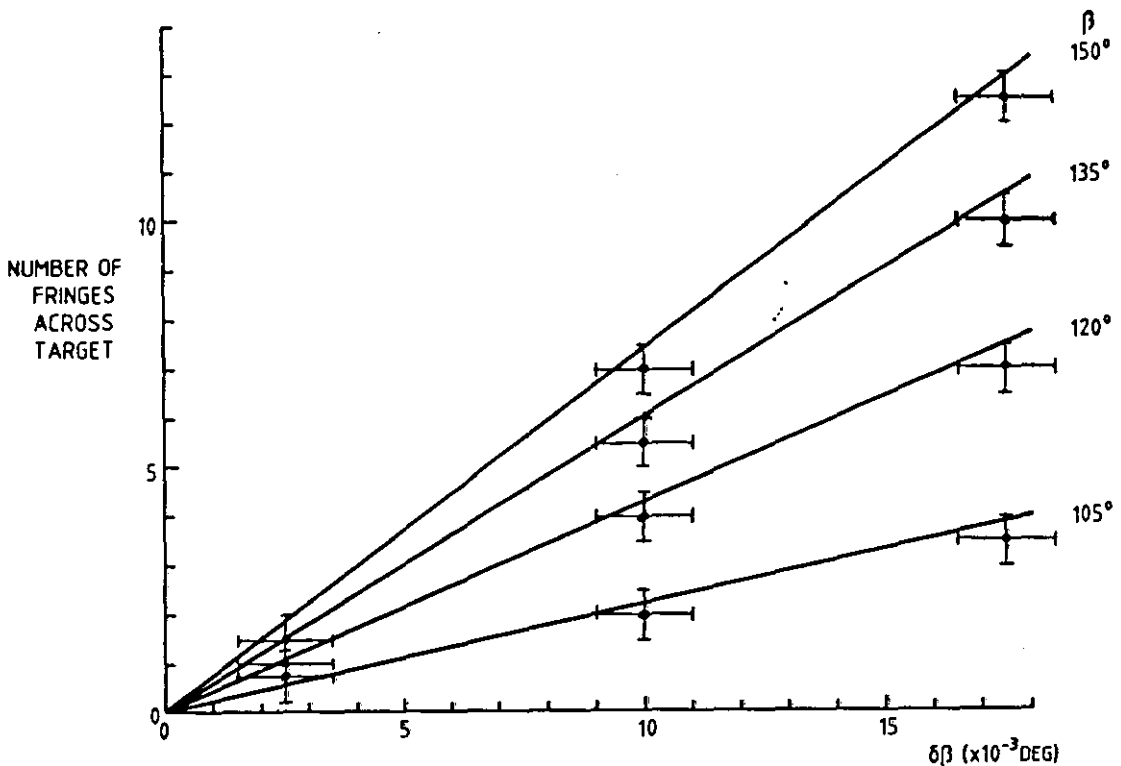


FIGURE 4.6: Comparison of experimental results (crosses) with theoretical values (solid lines) of fringe numbers against angular change of object beam for different illumination angles with the target normal to the viewing axis ($\gamma = 90^\circ$)

4.2.3 Methods of Changing the Illumination Direction

There are a number of methods for changing the illumination direction. Some of these are shown in Figure 4.7. Method (a) was used for checking the fringe spacing by rotating the beam with a hinged optical rail. This simplifies the measurement of angular rotation but in practice it is cumbersome to carry out. Yonemura (1982) uses linear translation of the object beam (Figure 4.7(b)) to give a projected grid in holographic contouring. At the beginning of this work an incoherent fibre bundle was used to rotate the beam about the target (Figure 4.7(c)) but this failed due to de-correlation as the bundle

moved. The method of using a single optical fibre by Winther and Slettemoen (1984) is a better approach. Another technique similar to (a) of rotating the beam about the target is to use two rotating mirrors (Figure 4.7(d)). Precise control of each is required to obtain pure rotation. Bergquist and Montgomery (1985) suggest the use of a single mirror in the object beam to alter the illumination direction. This has the distinct advantage in that it is simple and a stationary zero order fringe is formed. In the following experiments this has proved to be the most useful technique for producing ESC fringes.

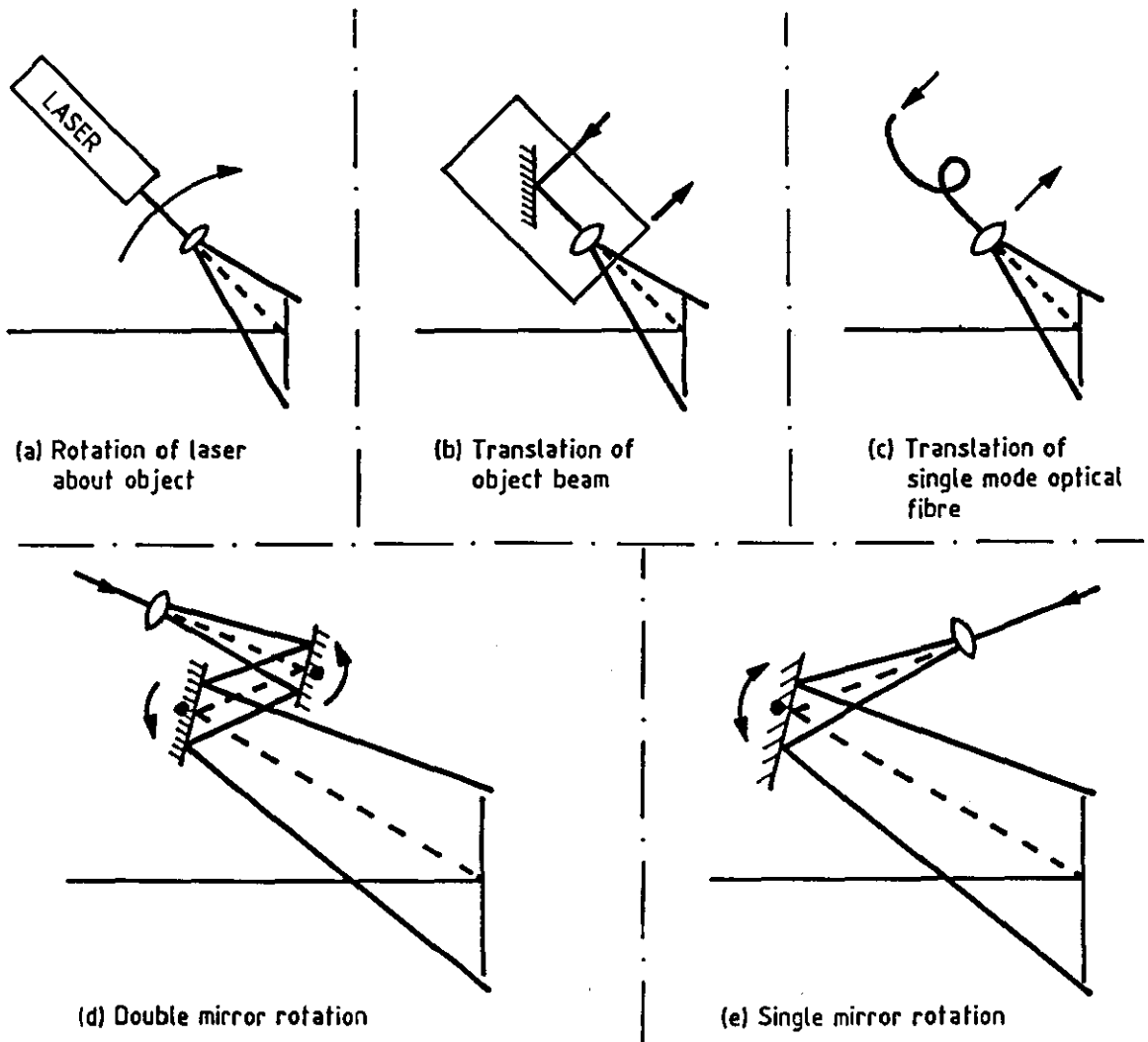


FIGURE 4.7: Methods of changing the illumination direction in ESC

4.3 SINGLE OBJECT BEAM

4.3.1 Projected Fringe Technique

Some of the properties of ESC projected fringes can be demonstrated with the apparatus shown in Figure 4.8. The target is a worm gear which is 53 mm in diameter and has teeth 2 mm deep and 3 mm apart, shown in Figure 4.9(a). When mirror M is tilted in the plane of the paper, fringes showing the shape of the teeth are illustrated in Figure 4.9(b), (c) and (d) with greater angular changes of the mirror giving higher fringe densities.

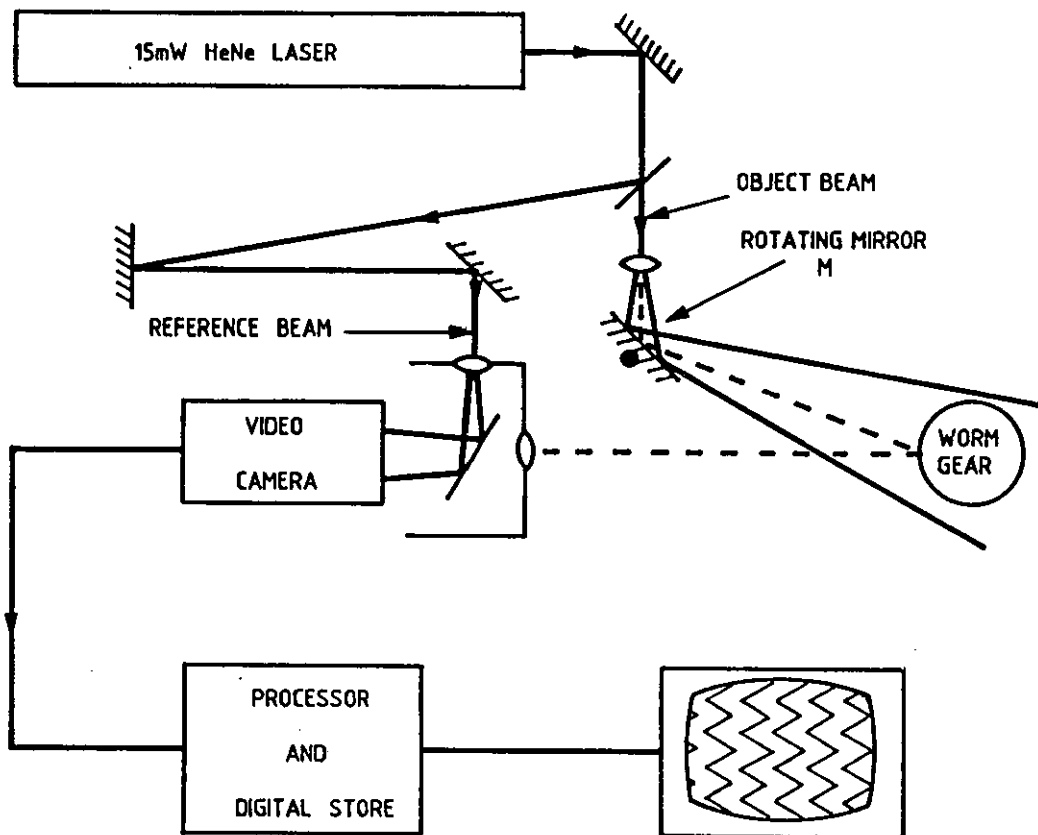
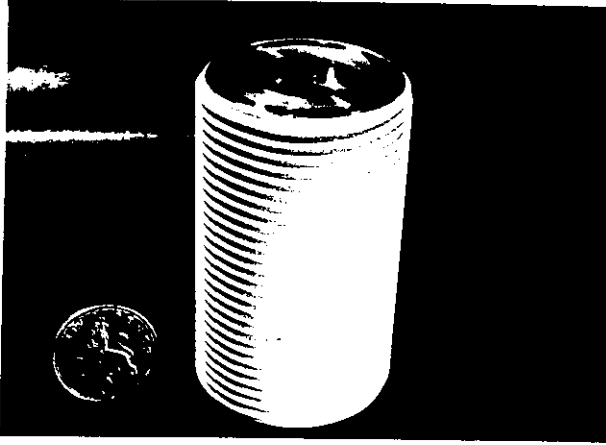
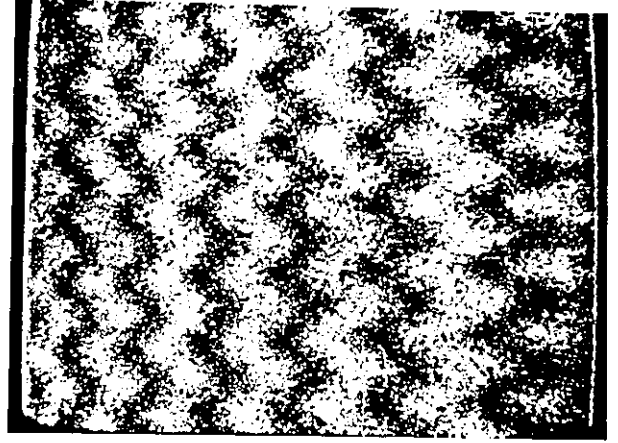


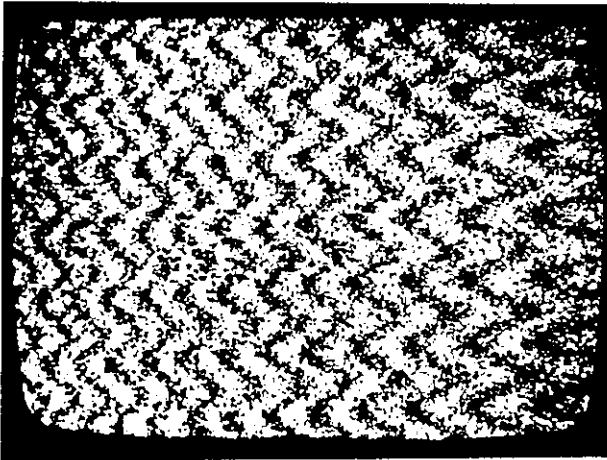
FIGURE 4.8: Formation of ESC fringes by tilting a mirror in the object beam



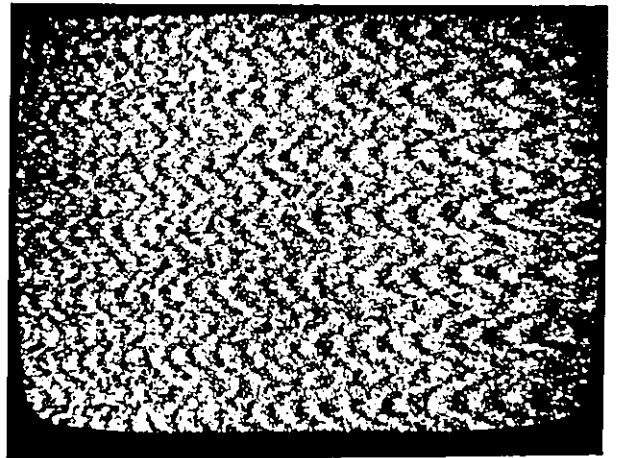
(a) 57 mm diameter worm gear



(b) 6 ESC fringes depicting teeth, 2 mm deep and 3 mm apart



(c) 13 fringes



(d) 20 fringes

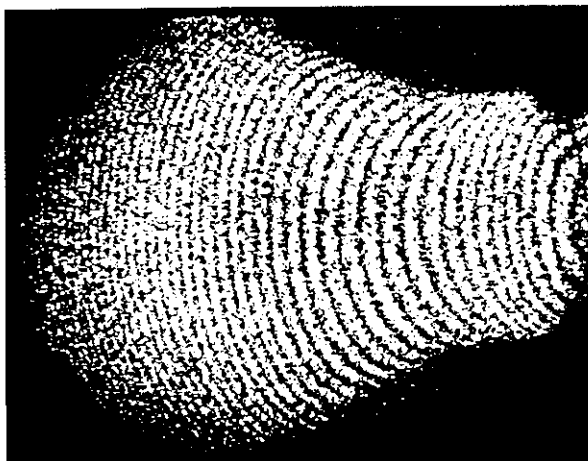
FIGURE 4.9: ESC grid fringes showing shape of worm gear teeth. Variable fringe spacing formed by rotating mirror in object beam

Up to 50 fringes have been resolved by eye with this system. A major problem with ESC is de-correlation due to the change in direction of illumination. A greater number of fringes cannot be resolved with this arrangement because of de-correlation of the speckle pattern. This depends on the illumination and viewing direction, the distance from the target, the viewing aperture, the lens focal length and the surface roughness of the target. A smoother surface minimises de-correlation effects to a certain degree (Jones and Wykes, 1977).

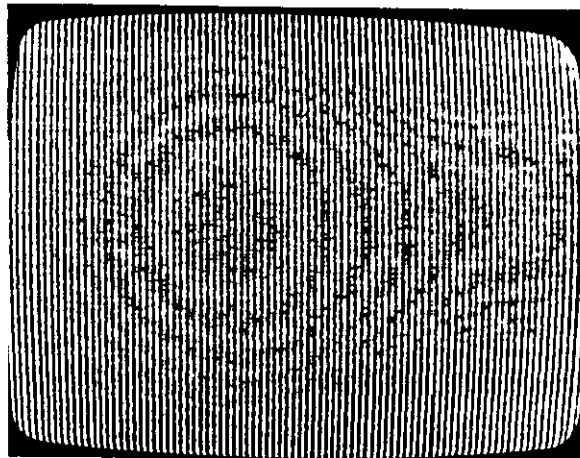
The important point to note is that the equivalence with projected fringes is exact, the spacing being wider on the right because of the curvature of the gear. It is possible to produce contours with the reference plane perpendicular to the viewing direction by using a reference grid to form moire contours. In Figure 4.10 this is demonstrated on a lightbulb with a more gentle curvature. In this example the reference grid is produced electronically and subtracted from the ESC grid and filtered, in a method similar to that used by Hormiere and Mathieu (1976).

4.3.2 180° Side Illumination

As has been observed (Figure 4.11), direct formation of contours with a reference plane normal to the viewing direction is achieved by side illumination. The author used the arrangement in Figure 4.12, producing two object beams illuminating the target from both sides of the viewing axis. Movement of the single mirror M_1 then produces contours with a variable spacing. In practice this requires careful alignment of the two beams at 180° to each other to ensure that the two sets of contours line up. The obvious limitation of the technique is the shadowing of convex and concave surfaces but it does enable closely packed ESC fringes to be formed with the reference plane normal to the viewing axis.



(a) 55 ESC fringes on a light bulb



(b) Moire contours by subtracting electronically produced reference grid from (a) and filtering

FIGURE 4.10: Moire contours on a light bulb using ESC and an electronically produced reference grid

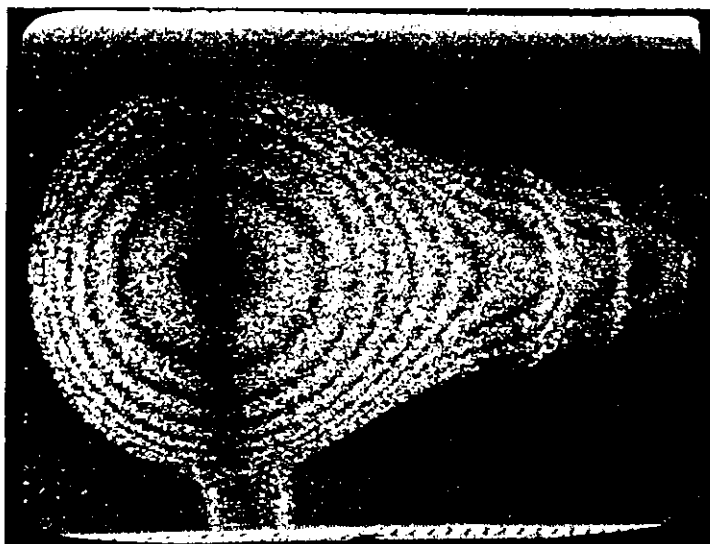


FIGURE 4.11: ESC contours with reference plane normal to viewing axis formed by 180° illumination from both sides

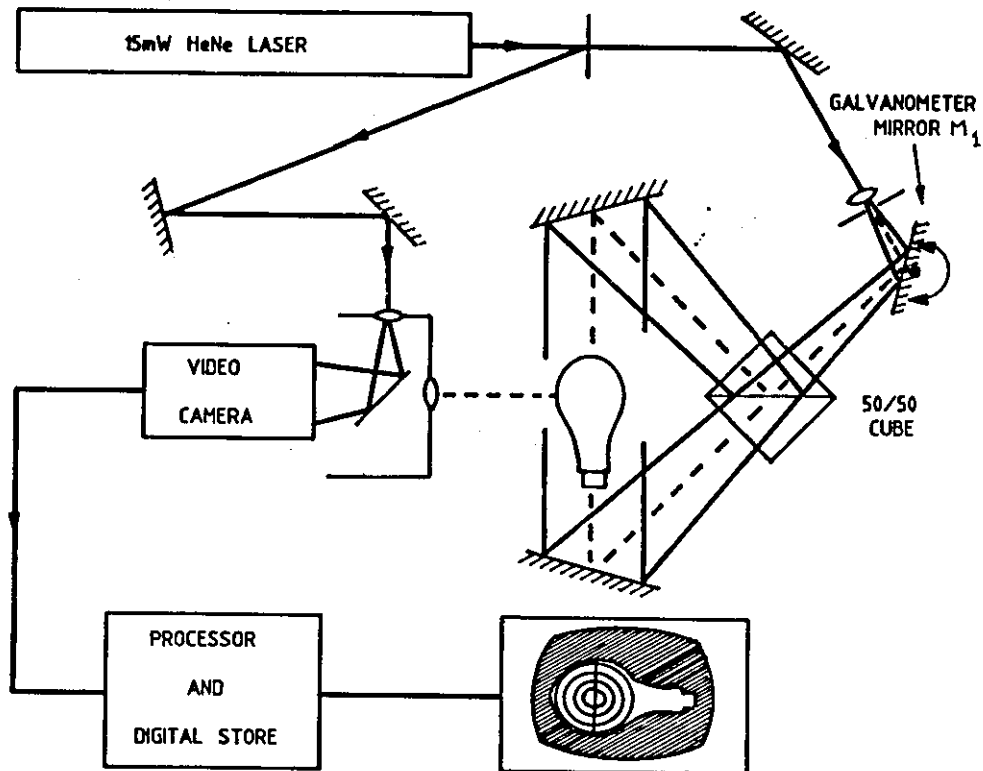


FIGURE 4.12: ESC contours with 180° side illumination

4.3.3 Object and Reference Wavefront Rotation Contours

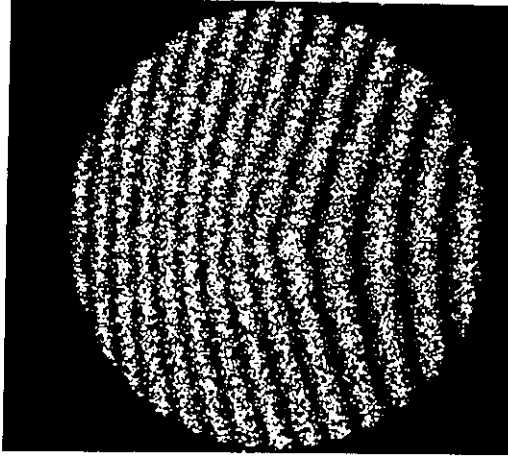
While using the single beam ESC projected fringe technique in Figure 4.8, the author found a new method of forming contours with an adjustable reference plane. The method is similar to the holographic contouring technique by Yonemura (1982). This consists of producing fringes on the image of the object with a change in direction of the illuminating beam, and changing the reference plane orientation by translating the hologram plate. Abramson (1976) arrives at a similar result of contouring with "sandwich holography", translating two plates that are held in close proximity to each other. With ESC the

reference plane orientation is altered by rotating the beam combiner in front of the camera. This is demonstrated with the contouring of a 25 mm diameter, 5 mm high cone in Figure 4.13. Tilting the object mirror produces correlation fringes similar to projected fringes on the surface in 4.13(a). A small rotation of a fraction of a degree of the beam combiner in the same plane produces a set of straight correlation fringes unrelated to the surface shape in 4.13(b). These fringes suffer a greater degree of de-correlation. As well as changing the apparent origin of the reference beam, there is also a change in refractive index introduced into the path of the viewing direction and a small amount of image shear as the glass wedge is tilted. If both the mirror and wedge are tilted, the contours in 4.13(c) are formed. Up to six circular contours have been obtained with this system, i.e. twelve fringes per picture width. Changing either the mirror or the wedge alters the orientation of the reference plane.

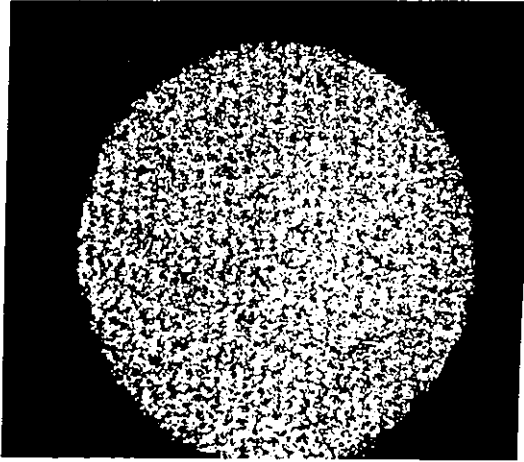
A similar effect is achieved if a glass plate is placed normal to the viewing direction between the imaging lens and object. Rotation of the plate by a few degrees alters the orientation of the reference plane but de-correlation limits the number of contours to one or two. This indicates that the change in refractive index may be contributing a small amount to the fringe pattern in 4.13(b) and that image shear is largely responsible for de-correlation. The main contribution is the change in the apparent origin of the reference beam. As with the holographic counterparts of ESC, manipulation of the orientation of the reference plane in both the vertical and horizontal directions is possible. In ESC this is achieved by a corresponding change in the tilt of the wedge. Further experimental work is required to quantify the effects of refractive index change and de-correlation and to gain more understanding of the technique as it is quite a complex process.

4.4 TWO OBJECT BEAMS

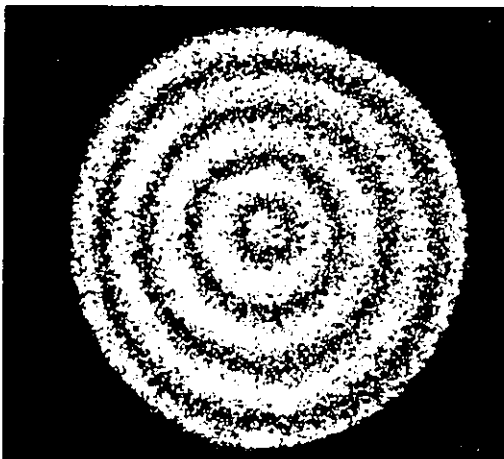
Tilt fringes are also produced with systems in which two object beams are used without a reference beam, one object beam acting as a reference to the other. The idea of contouring in this manner



(a) Projected grid by
object beam rotation



(b) Straight line grid
by rotation of wedge
beam combiner



(c) ESC contours by
combined rotation of
object and reference
beams

FIGURE 4.13: Formation of ESC contours on a 25 mm diameter, 5 mm high cone by object and reference beam rotation

occurred to the author in the process of designing an advanced version of the system shown in Figure 4.8 with a second object beam. What was being attempted was to form two ESC grids from the rotation of the two object beams by Pockel's cell switching of each beam to form moire contours between the two. Because the two beam arrangement looked remarkably like an in-plane system, it was thought that perhaps the same effect could be achieved by removing the reference beam and Pockel's cells and relying solely on the interference of the two speckle patterns. When this was carried out experimentally, it was found that tilting the two beams produced contours. These experiments are now reported.

4.4.1 Symmetrical Illumination Contours

This initial experiment involves a conventional in-plane system with the illumination axes at equal angles to the viewing axis (Figure 4.14). Each beam is reflected from a mirror to allow beam rotation. A photograph of this is shown in Figure 4.15(a). The target is the end of a light bulb, with an iris diaphragm marking the area to be contoured. Because there is no separate reference beam to be added an ordinary CCTV lens is used, in this case of 25 mm focal length. After storing a speckle pattern and subtracting the live image, horizontal tilt of the mirror on the right hand side of the viewing axis produces the ESC projected fringe pattern in Figure 4.15(b). Tilting the other mirror in the same sense and by the same amount rotates the reference plane so that it is normal to the viewing direction (Figure 4.15(c)). The poor contrast of the fringes indicates the problem with de-correlation again.

This system was tested on a Mini bonnet painted matt white, 1m in width to see if it worked on large areas. The bonnet was magnetically clamped at three points on a large optical table and a 1W Coherent "Innova" Ar Ion laser at a wavelength of 514 nm was used to provide the laser power required. Figure 4.16(a) shows the bonnet and 4.16(b) and (c) the tilt fringes and contour fringes respectively. Up to 6 contours were obtained. Further work is required to improve the

results, this experiment merely demonstrating that it is possible.

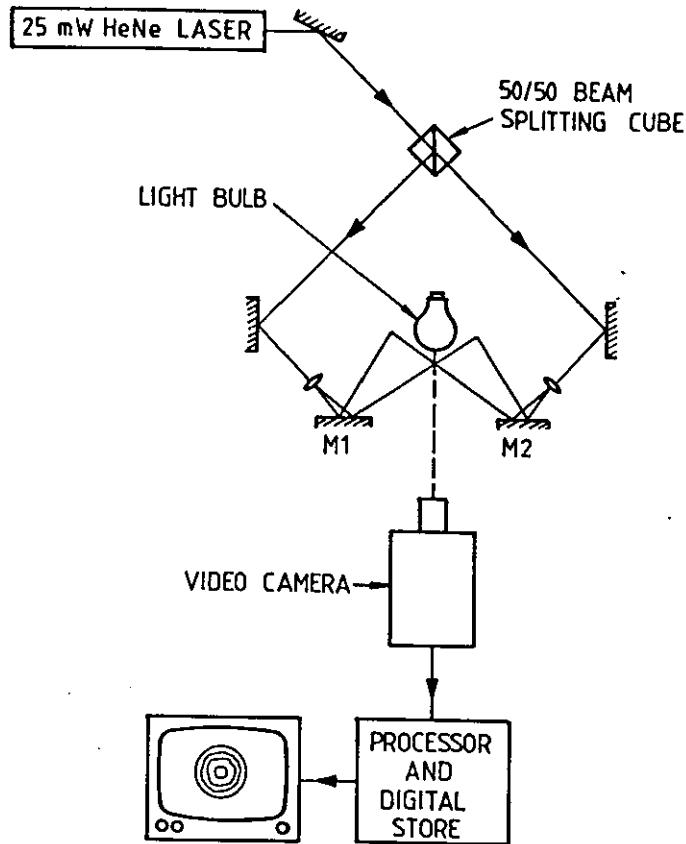
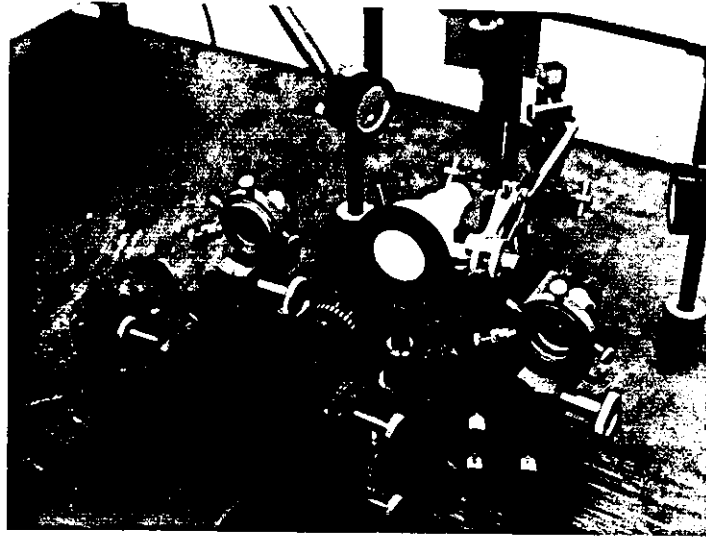


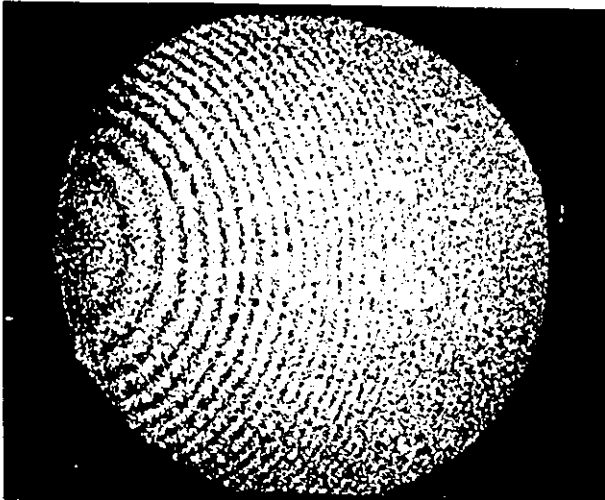
FIGURE 4.14: In-plane sensitive system for producing ESC contours

4.4.2 Programmable Contour Sensitivity

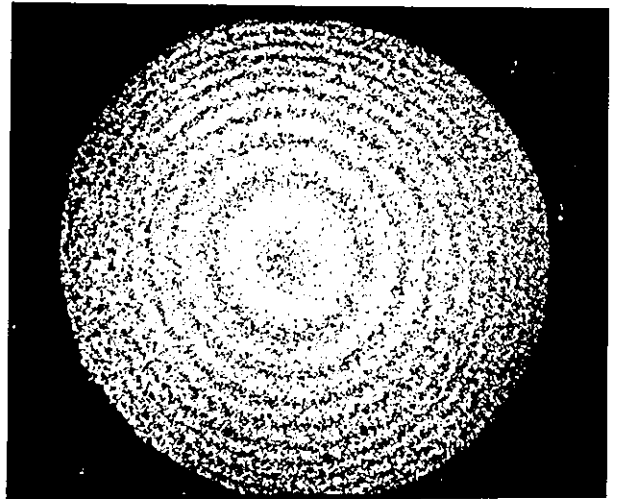
ESC contours with a programmable separation using the rotation of a single mirror can be formed with the beam splitting arrangement shown in Figure 4.17. An extra mirror is placed in the beam path reflected from the 50/50 beam splitting cube to make the beam rotation the same sense as the other beam illuminating the object. Rotation of the galvanometer mirror produces contours directly as shown in the results in Figure 4.18 but this arrangement appears to suffer from de-correlation, a maximum of 4 to 5 fringes being visible.



(a) Close up of apparatus showing camera, light bulb and optics for forming two object beams. Galvanometer mirror on left of camera

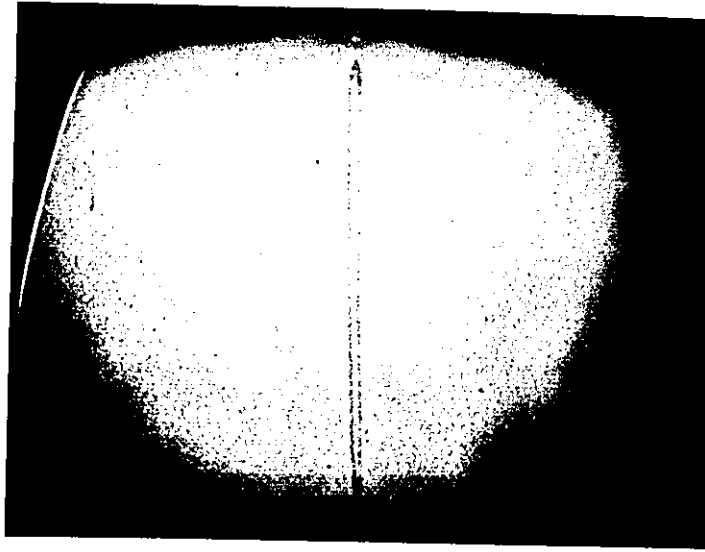


(b) ESC grid formed by tilting right hand mirror

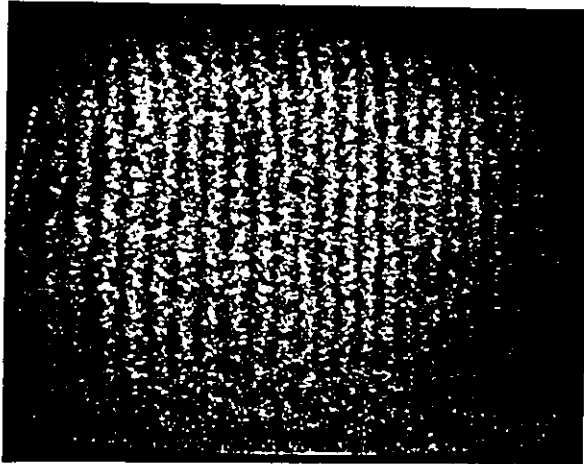


(c) ESC contours formed by tilting left and right hand mirrors

FIGURE 4.15: Formation of ESC contours on the end of a light bulb using two object beams



(a) View of Mini bonnet in laser light



(b) ESC grid formed by rotating left hand mirror



(c) ESC contours formed by rotating left and right hand mirrors

FIGURE 4.16: Formation of ESC contours on a Mini bonnet using two object beams

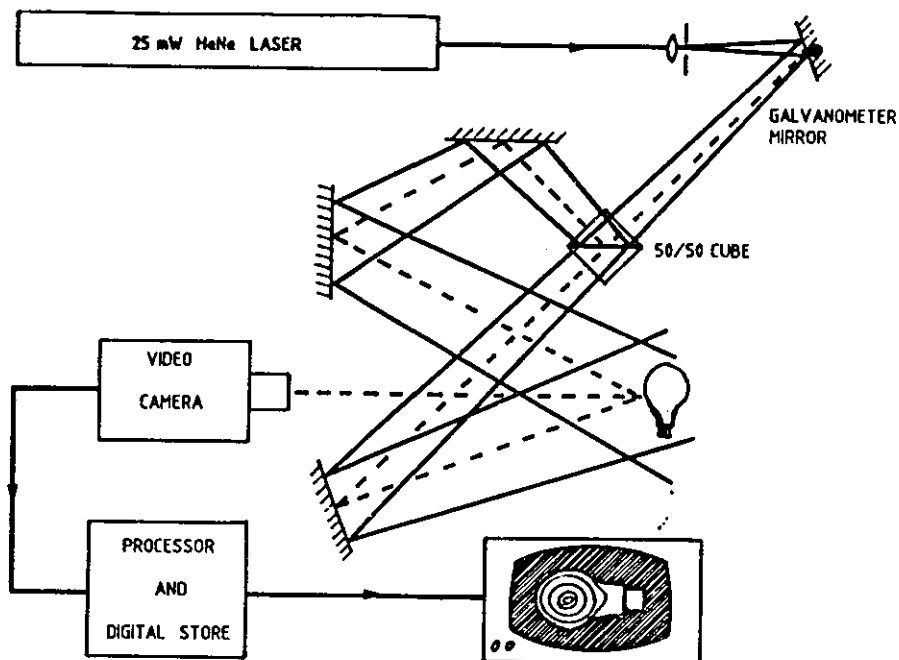


FIGURE 4.17: Programmable contour separation by single mirror rotation

4.4.3 Assymetrical Illumination Contours

After experimenting with different illumination angles it was found that contouring can be carried out with assymetrical illumination. An extreme case of this is to have both object beams on the same side of the viewing direction. Altering the layout in Figure 4.14 so that both beams come from the left hand side, contours are produced by tilting both mirrors in the same sense but by different amounts because of the lack of symmetry. Results in Figure 4.19 show the problem of shadowing on the opposite side to the illumination,. Because of the small angle between the two beams the mirrors have to be tilted a larger amount to produce the same number of contours. This makes it more prone to de-correlation effects.

4.5 TIME AVERAGED ESC

Because there is a stationary zero order fringe with a correctly aligned mirror rotated in the object beam path, this leads to the possibility of operating in the time averaged mode. This was first proposed theoretically by Bergquist (private communication) and

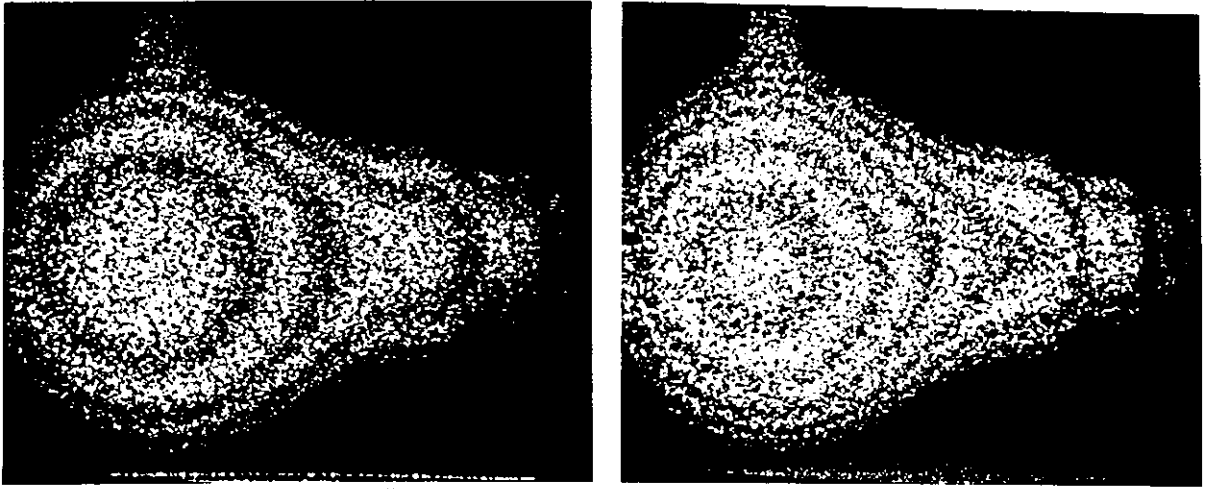


FIGURE 4.18: Adjustable contour spacing on light bulb using single mirror rotation

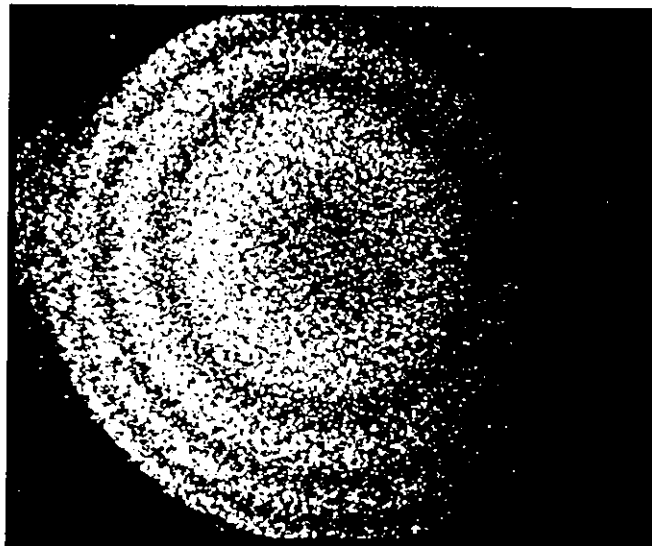


FIGURE 4.19: ESC contours on the end of a light bulb using two object beams on the left hand side of the viewing axis

published by Bergquist and Montgomery (1985).

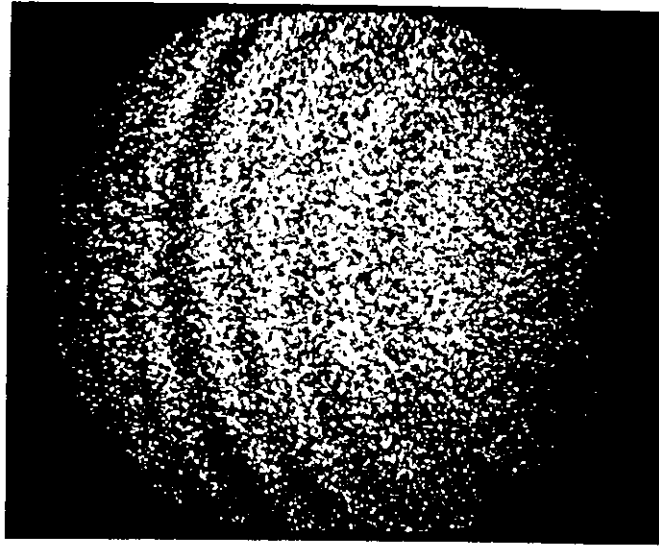
4.5.1 Formation of Time Averaged Fringes

To form time averaged contour fringes, the direction of illumination is altered using an oscillating galvanometer mirror in the object beam. One of these is seen in Figure 4.15(a) on the left hand side of the two beam system. Oscillating this mirror at 25 Hz produces fringes that are barely visible in the normal time averaged mode because of the high optical noise content from using two object beams. To overcome this problem, an image of the speckle pattern with the beams at rest is stored in the digital store and subtracted from the live image. This results in time averaged fringes with a dark zero order fringe (Figure 4.20(a)) as in CASE II for optical noise reduction described by Creath and Slettemoen (1985). In theory, this should not work at the low frequency of 25 Hz but with the longer persistence time of over 0.1 seconds of the Chalnicon tube it is possible. With suitable oscillating mirrors higher frequencies of oscillation can be used.

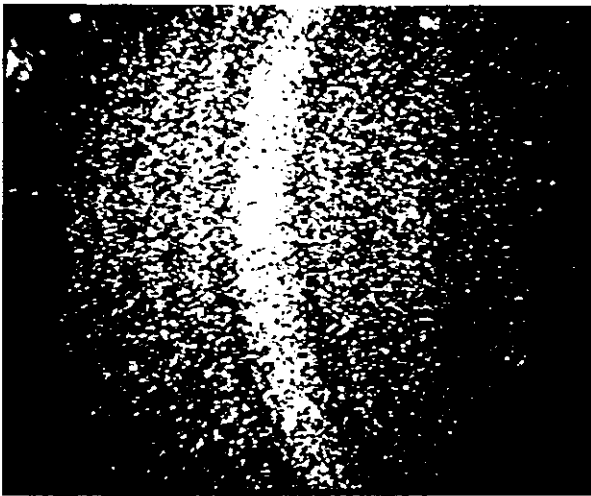
If the non-oscillating beam is removed and a smooth reference beam is added to return to the single object beam mode, conventional time averaged ESC fringes are formed (Figure 4.20(b)). The normal bright zero order fringe is observed. Strobing the main laser beam at 50 Hz, with a Pockel's cell highlights the higher order fringes (Figure 4.20(c)).

4.5.2 Speckle Averaged ESC

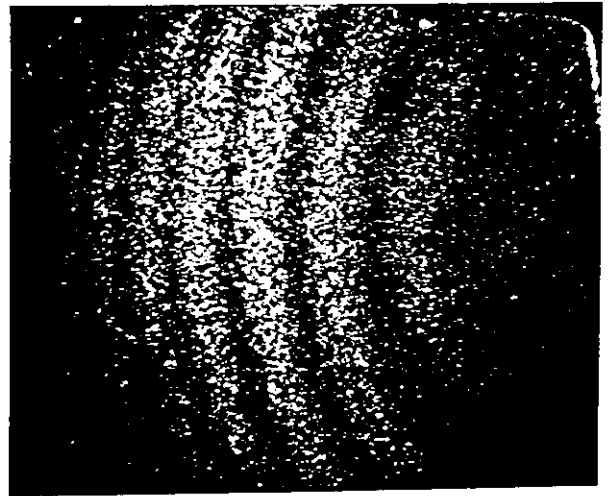
The quality of ESC fringes formed in the time averaged mode is improved by speckle averaging. In practice this is more difficult to carry out than with vibration patterns because many of the speckle decorrelation methods cannot be used. A large angular change of the mirror in the object beam (Figure 3.9(b)) tends to alter the form of the contour pattern, so that the signal does not add up, but cancels. If a diffuser plate is used (Figure 3.9(d)) very few contour fringes



(a) Time averaged ESC contours using two object beams, with the stationary speckle pattern subtracted to give a dark zero order fringe



(b) Normal time averaged fringes with smooth reference beam



(c) Strobed at 50 Hz with smooth reference beam

FIGURE 4.20: Time averaged ESC contours on the end of a light bulb. Galvanometer mirror oscillating at 25 Hz

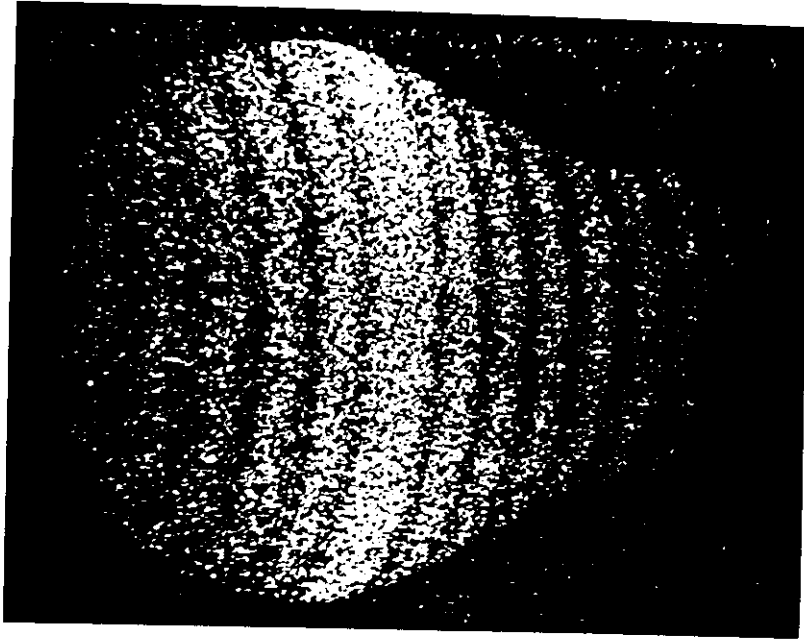
are formed because of de-correlation when the speckled object beam is rotated.

So far the only successful method has been to move the object by a small amount. An out-of-plane system as in Figure 4.8 was used with the galvanometer mirror oscillating at 25 Hz in the path of the object beam to form the time averaged pattern in Figure 4.21(a). These are better quality than the fringes in Figure 4.20(b) because the optical noise has been subtracted with the mirror oscillating and a phase change of π introduced between the reference and object beams. A high quality zoom lens was also used. Speckle de-correlation was performed by rotating the light bulb about its axis of symmetry. A rotation of 1° was more than sufficient to completely de-correlate. A number of interferograms with identical fringes but random speckle patterns were recorded on Ampex video tape. Twenty four interferograms were speckle averaged on a photographic camera to give the smoother contours in Figure 4.21(b).

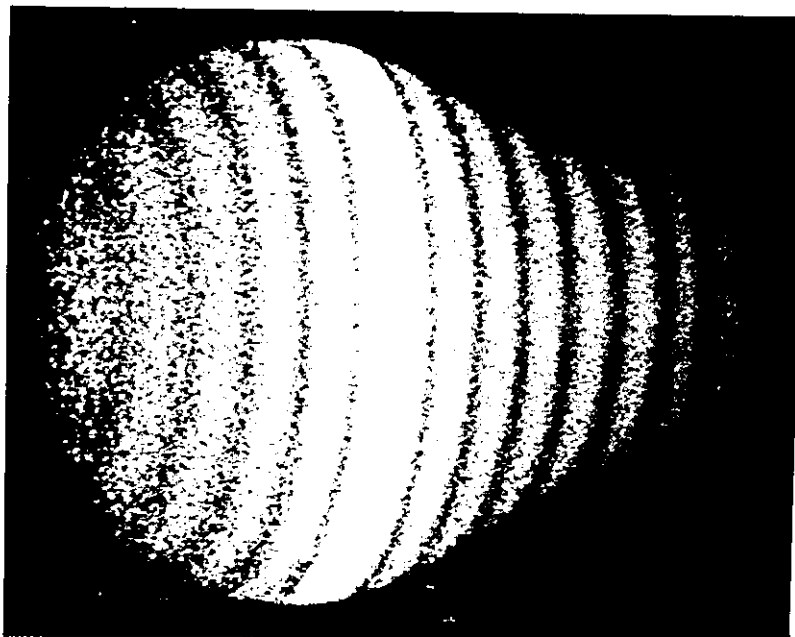
Because ESC projected fringes are formed by controlled positioning of the illumination direction, they are fairly repeatable. A consequence of this is that ordinary subtraction ESC fringes can be speckle averaged by repeating the mirror rotation, image storage and de-correlation. With a frame rate of 25 Hz this takes 80 mS, storing the speckle pattern with the mirror at one extreme of its rotation, moving the mirror to the opposite extreme and subtracting the new pattern. This is repeated after de-correlating, forming a new fringe pattern every second video frame.

4.6 PHASE-STEPPED ESC

Phase-stepping applied to deformation studies in ESPI by Nakadate et al (1985), Creath et al (1985) and Stetson et al (1985) is ideally suited to the Electronic Speckle Contouring mode. An outline of an application of phase-stepping to the ESC mode is now proposed.



(a) Single exposure time averaged ESC grid with object and reference noise subtracted and π phase change introduced



(b) Photographic speckle averaging (24 exposures) with light bulb rotated in between exposures

FIGURE 4.21: Enhancement of time averaged ESC fringes on a light bulb by noise subtraction and speckle averaging. Galvanometer mirror oscillating at 25 Hz.

Changing the phase of one of the beams in either the single or two beam systems gives a constant phase shift across the interferogram. For an ESC projected grid the whole pattern moves across the screen in the plane of rotation of the object beam. Contours with a reference plane normal to the viewing direction appear to converge at or diverge from a point depending on whether it represents a convex or concave surface.

From a minimum of 3 phase changes, for example -120° , 0° and $+120^\circ$, an arbitrary measurement of phase is made of the speckle pattern with the mirror in one position. After tilting the mirror, another 3 phase changes allows the second phase map to be measured which when subtracted from the first reveals a phase change map across the interferogram. This gives a higher resolution map of a projected grid. From the illumination and viewing geometry, together with the angular change in the illumination direction, the grid spacing is determined. The values of the height of each point above an arbitrary reference plane can be calculated after identifying a fringe order of one fringe and assigning numbers to the rest, or multiples of 2π phase change (e.g. see Section 5.3.2). The measurement accuracy depends on the accuracy of the imaging system and an appropriate correction for perspective errors.

Another source of error is points of zero measurement where no intensity modulation takes place due to poor illumination or optical noise. This can be overcome by making further sets of phase-change measurement with different speckle patterns i.e. after de-correlation. Zero measurement points are filled in and the phase change of other pixels averaged to give a more accurate value. Identification of a fringe number may be possible by making use of the zero order fringe.

4.7 DISCUSSION OF TECHNIQUES

A selection of new contouring techniques with single wavelength ESPI has been presented. Various methods of wavefront shearing using different modes of ESPI have been used to simulate projected grids and

depth contours with programmable sensitivity. These are now summarised together with comments on their particular features:

Grid pattern by translation of object beam: (After Winther and Slettemoen, 1984). Simulated projected grid formed, but no zero order fringe or time averaged mode; more complex to perform than mirror rotation.

Grid pattern by object mirror rotation: zero order fringe identifiable, up to 55 fringes counted, simple to perform.

Moire depth contours using electronic reference grid: adjustable orientation of reference plane but poor visibility contours.

180° side illuminated depth contours: reference plane perpendicular to viewing direction, contours directly available by single beam rotation, programmable spacing, but shadowing of concave and convex surfaces.

Depth contours by object and reference beam rotation: ordinary out-of-plane ESPI system used to give depth contours, 12 fringes counted, prone to de-correlation.

Depth contours by symmetrical two object beam illumination: no reference beam required, programmable contour separation by single mirror rotation, suffers badly from de-correlation.

Depth contours by asymmetrical two object beam illumination: possible advantage in producing depth contours using object beams from only one side of the viewing axis, but de-correlates more easily than with symmetrical illumination.

Time averaged ESC: oscillation of mirror in object beam gives time averaged fringes, on which optical noise subtraction, strobing and speckle averaging can be performed to enhance the fringes. Fringe identification possible.

Phase stepped ESC: proposed in theory, is very amenable to ESC because the patterns are repeatable, allowing noise reduction by speckle averaging.

In summary, a family of ESPI contouring techniques analogous to moire and holographic techniques have been presented. The positive and negative features of ESC as a whole may be summed up:

Positive features

- Operates with conventional ESPI system
- Programmable fringe spacing
- Programmable orientation of reference plane
- Full use of available laser power in object beam
- Amenable to speckle averaging and phase stepping for noise reduction and high resolution analysis of shape.

Negative features

- Noisy fringes in basic mode due to speckles
- Fringe numbers (and therefore resolution) limited by de-correlation effects
- Collimated beams required for uniformly plane contour surfaces, limits object size (though this is also true of holography and moire)
- Interferometric sensitivity, requiring a high degree of mechanical stability (though not as much as in holography).

Further work is required to optimise the system parameters and obtain larger numbers of fringes in order to give increased resolution in shape measurement. The use of a smoother surface would lower the problem of de-correlation. This property may be a method of quantifying surface roughness as well as shape (e.g. see Bergquist and Montgomery, 1985).

4.7.1 Addition of ESC to ESPI

Considering these techniques in the context of the overall aim of this work to develop ESPI as an industrial test instrument, a number of ideas have been suggested for adding an absolute shape measurement facility to ESPI. At present the most promising method seems to be the basic mode of ESC for simulating a projected grid by rotating a mirror in the object beam while using a smooth reference beam. This is preferred since it provides the largest number of high contrast fringes that will most likely result in the highest resolution. Depth contours lead to problems of de-correlation and do not indicate at present that they will yield any higher resolution of shape measurement.

The basic ESC mode is quite conveniently added to the improved ESPI design in Figure 2.9. The only alteration is to mount the mirror M_2 on a galvanometer or rotation stage and move this further from the viewing axis to give a higher resolution of shape measurement with the larger angle of illumination. The formation of a grid is then controlled by rotation of this mirror. To benefit from phase stepping techniques, the reference beam path length is altered using a piezo electric mirror or a Pockels cell arrangement using suitable $\lambda/2$ plates (e.g. Hariharan et al, 1982). An alternative method is to place a glass plate in the reference beam. Rotation of the plate provides a linear change in effective path length across the thickness of the beam. The effects of beam deflection are minimised by placing the plate near to the reference beam expanding lens. This may lead to a low cost phase stepping device suitable for an industrial system.

The addition of Electronic Speckle Contouring to ESPI enables out-of-plane displacement and absolute shape measurement to be performed on the same instrument. This should lead to a greater flexibility of shape measurement than has been possible with two wavelength ESPI contouring and an instrument that is easier to use and cheaper to manufacture.

CHAPTER 5

COMPARISON OF ESPI WITH OTHER OPTICAL TECHNIQUES

The purpose of this chapter is to provide a summary of photographic speckle techniques, holographic interferometry and moire methods and to compare them with ESPI. Details are also given of a large area white light grid projection technique for absolute shape measurement developed by the author that helps to illustrate some of the problems encountered with contouring and automatic fringe analysis.

5.1 PHOTOGRAPHIC SPECKLE PATTERN INTERFEROMETRY

Photographic speckle pattern interferometry can be divided into two main branches, commonly referred to as speckle pattern photography and speckle pattern correlation interferometry. The former uses only one illumination beam while the latter uses an illumination beam and a reference beam. Speckle photography arose from the general problem of speckle noise in holographic interferometry. Leendertz (1970) was the first to report the use of phase referenced speckle patterns in quantitative interferometric measurement. From work carried out in the late 1960's at NPL it was realised that surface displacements could be measured from displacements of the speckle pattern in the image plane without a reference beam. Jones and Wykes (1983, Chapter 3) give an in-depth theoretical analysis of each technique, which is summarised here.

5.1.1 Speckle Pattern Photography

In speckle pattern photography an object surface is illuminated with monochromatic light and photographed with a camera. No video system or electronic hardware is used. After deforming the object, a second exposure is taken so that two speckle patterns are recorded on the same plate. A number of methods are available for analysing the negative, based on the formation of the Fourier transform of the

pattern. Shining an unexpanded laser beam through the negative allows point by point analysis by measuring the spacing and orientation of the diffraction halo. This yields information on the movement of the speckle pattern that can be related to the movement of the surface. Alternatively, illuminating the negative with a converging wavefront allows sampling of the Fourier plane to reveal a fringe map superimposed on the image of the object. By either means, an intermediate step is required to analyse the results, unlike ESPI in which a fringe field is available almost instantaneously on the monitor screen.

If the speckle pattern is located in the image plane of the lens, the fringe field is sensitive to in-plane motion while de-focussed speckle patterns are mainly sensitive to out-of-plane motion. While this is a useful facility, errors are introduced in the interpretation of fringes by non-planar focussing caused by lens aberrations. Reducing the angular field of view by means of a long focal length lens minimises these errors. Using a reduced aperture also helps but this increases the speckle size. ESPI on the other hand is perhaps more tolerant of focussing errors since the fringe sensitivity depends more on the geometry of the illumination and viewing directions. The measurement range for speckle pattern photography is quite large, extending from 0.1 to 100 μm , compared with 0.1 to 15 μm for conventional ESPI, though with repetitive referencing in ESPI the range can be greatly increased. While it is easier to make a quantified measurement at a point with the photographic technique, it is particularly difficult to assign this to a point on the object. Careful scaling of the diffraction halo in relation to the object surface is required. Calibration is made more difficult by the image distortion introduced by the object lens and the diffuseness and lack of contrast of photographic speckle fringes.

Speckle pattern photography can be used in the time averaged mode by averaging many vibration cycles over one exposure. Analysis by the two methods described previously leads to the independent measurement of the in-plane and out-of-plane components of vibration. The form of

the vibration, whether it is harmonic or linear, can also be determined from the diffraction halo. More information is available than with the time averaged mode in ESPI which is restricted to out-of-plane vibration and harmonic oscillations in the conventional system. Time averaged fringes tend to be of higher contrast when formed with ESPI than with speckle pattern photography.

5.1.2 Speckle Pattern Correlation Interferometry

Speckle Pattern Correlation Interferometry was the direct predecessor of ESPI, so much of what has been discussed about ESPI is also true of the photographic technique. The main difference between the two is the equipment used, the photographic recording medium being of much lower cost than the video system. It is also of higher resolution. A reference beam is added to the speckle pattern to form a phase referenced speckle pattern in the image plane of the lens. Deformation of the target forms a new speckle pattern, similar in form but with a new set of speckle intensities. A second exposure forms an addition pattern on the photographic emulsion. After processing, fringes of equal phase change mark out the underlying correlation of speckle intensities. If a single exposure is taken and the negative is exactly relocated, subtraction fringes are formed as the object is loaded, due to the reversal in the film. Compared with ESPI, higher quality fringes over a larger measuring range are available. This technique is particularly useful for measuring in-plane motion at high sensitivity.

Out-of-plane, in-plane and displacement gradient sensitivities are available with speckle pattern correlation interferometry. The time averaged mode is restricted to qualitative analysis of resonant modes, the higher order fringes being difficult to identify.

In practice photographic speckle pattern correlation interferometry is difficult to carry out compared with ESPI in which the use of a fixed video camera simplifies matters. With a live *display* of the phase-referenced speckle pattern being readily available in ESPI, the

setting-up procedure is simplified compared with the photographic technique. There is also no delay introduced by chemical processing. In summary, ESPI can be used in all the photographic correlation techniques with greater ease but at lower resolution.

5.2 HOLOGRAPHIC INTERFEROMETRY

Holographic interferometry enables optically rough engineering surfaces to be measured. Two of the major disadvantages of HI, the delay in chemical processing and the difficulty experienced in interpreting the fringe pattern, are now considered. In situ chemical processing and the use of photo-sensitive erasable materials are discussed and compared with ESPI. Interpretation by phase stepping and diode array detectors is also presented.

5.2.1 General Background

The reconstruction of complex optical wavefronts came soon after the development of the first laser in 1960, based on initial investigations by Gabor in 1948. Holographic Interferometry was discovered soon after by a number of workers, (e.g. Powell and Stetson 1965). Just as two wavefronts of similar geometry from the same coherent source but of slightly varying phase interfere in classical interferometry, two complex holographic wavefronts also interfere. By means of double exposure holography, in-plane, out-of-plane and rigid body motion can be detected. In the single exposure time averaged mode, vibration of a surface can be studied. The fringes are of high contrast, superimposed on a clear image of the object, like that shown of the engine in Figure 3.16(b). The resolution of the emulsion is typically $3000 \frac{\text{line pairs per mm}}{\lambda}$ with an image resolution of $30-40 \frac{\text{line pairs per mm}}{\lambda}$. With ESPI, the use of a smaller aperture of $f/32$ to $f/8$ reduces the image resolution to below that of HI. More fringes can generally be resolved in one shot in HI than in one television frame with ESPI. For the special case of a telecentric system used in HI to ensure fringe localisation at the surface the reduced aperture gives similar problems of speckle noise to that of

ESPI. Up until now, the poor quality of the output has been a serious drawback in ESPI, but with the careful use of noise reduction described in this work, in the time averaged mode ESPI now gives results of comparable quality.

There are fundamental limitations to HI that have perhaps restricted its widespread use as an NDT tool in industry. The first restriction is the broadband sensitivity of the photographic emulsion limiting the use of large plates to a darkened laboratory environment. Camera based HI systems using a narrow band filter and enclosed holographic film overcome this problem (e.g. see Rowley, 1983). ESPI tolerates higher levels of background lighting because it detects changes in light intensities rather than absolute levels. The ability to operate under average indoor lighting conditions is an attractive feature of an industrial test instrument.

The second restriction is the relatively long exposure time which may be required and the necessity to keep the interference pattern at the emulsion stable to within a tenth of a fringe over a period of a few seconds. Without the use of a pulsed laser, this imposes a severe limitation on the number of applications and on the testing environment. In ESPI, the exposure time is reduced to 1/25 second for each video frame because of the high sensitivity of vidicon tubes. For one frame these require a light exposure of the order of $0.02 \mu\text{J cm}^{-2}$ compared with $50 \mu\text{J cm}^{-2}$ for holographic emulsions. The stability required is generally considered to be a tenth of the diameter of the Airy disc in the image plane, although this has not been quantified experimentally up to date.

To demonstrate some of these advantages over HI, the Loughborough demonstration rig was taken into an engine laboratory, which approximates a workshop environment. In Figure 5.1, the unit is seen supported on anti-vibration feet on a wooden table which is free standing on a concrete floor. One metre behind the unit there is a running IC engine fixed to a test bed, providing ground transmitted vibration and airborne noise, at a level making it necessary for the

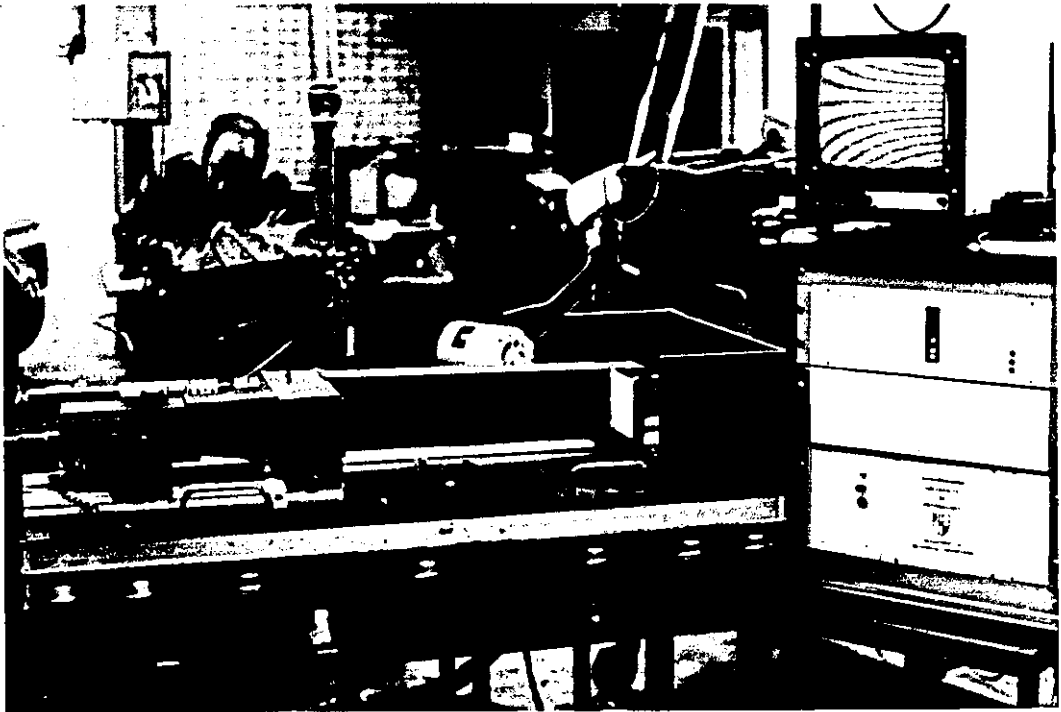


FIGURE 5.1: The Loughborough demonstration rig looking at torsion in a square plate while sitting on a wooden table 1 m from a running IC engine to demonstrate tolerance to background noise and lighting

engine operator in the background to be wearing ear protectors. On the television monitor is a live ESPI pattern showing torsion in a metal plate. The only problem experienced was fringe drift due to air movement from the fan cooling the engine directly behind the unit. A 5 mW laser was used under the illumination conditions shown, without the use of a narrow band filter. This shows some of the potential for using ESPI in an industrial environment.

The third and probably the most significant restriction of HI is the need for chemical processing. Whilst the use of a high resolution medium gives better results than conventional ESPI, for many applications in engineering it is of more importance to be able to perform interactive analysis. This is difficult when it takes up to 15 minutes to process a holographic plate after exposing it. Relocating in a kinematic mount using single exposure HI provides an interactive mode after the initial delay in processing but with the introduction of errors due to emulsion swelling and plate relocation.

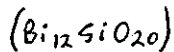
This time delay is a significant factor in considering the practical aspects of these techniques. What may take hours with HI takes minutes with ESPI, as is illustrated in Figure 3.16. Using the zoom facility and speckle averaging in ESPI, high resolution interferograms can now be achieved in a matter of seconds, making interactive analysis possible. Because it is a live technique, setting up a breadboard ESPI system tends to be quicker than a holographic system. Problems from external vibration and thermal drift become apparent in the nature of the fringes on the television monitor. With HI, the hologram may well be lost over an exposure of a few seconds when such noise is present. ESPI fringes drift across the screen with thermal drift, and move erratically with mechanically transmitted noise. These faults are more easily corrected with ESPI, reducing the setting up time. During experimental work interactive analysis can reveal more information than the analysis of a single frozen interferogram. The behaviour of creep and other non-uniform responses to loading can be studied.

In summary, conventional HI is restricted to skilled operation in a laboratory environment. ESPI, on the other hand, is in the form of a self contained electro optical instrument that can ultimately be used at a non-specialist skill level for quality control and defect detection in a workshop environment. To compete with ESPI automatic plate processing is required in HI.

5.2.2 Automatic Plate Processing

To overcome the problem of time delay in chemical processing, two solutions have been developed in HI; in-situ film processing and the use of erasable light sensitive materials. A number of holographic systems using a roll of holographic film and a monobath are now available commercially. The "Holomat 6000" from Ealing Electro-Optics gives a processing time of 15 seconds for holograms on a 35 mm format. A built in video camera provides a picture of the interferogram on a television monitor, giving a live facility for deformation analysis. In theory this sounds ideal with a high resolution output, but in practice it is a complex system to operate. This particular system has been tested in the laboratories in Loughborough, where it was found to be very difficult to get satisfactory results. It was also temperamental in operation, with so many factors affecting the quality of the end result. The design of a reliable system may overcome these problems.

Light sensitive polymers use a dry processing system. The thermoplastic plate is developed electronically and is erasable so that one plate can typically be used more than 300 times. In the "Instant" holographic camera from Newport Corporation the development time is less than 10 seconds. The format of the hologram is restricted to a 35 mm frame, reducing the resolution below that used in conventional holography. Nonetheless, this is seeing some commercial success, especially in the USA.



BSO crystals have been employed in the preparation of write-read-erase phase holograms using the photo refractive effect. These display lower photo sensitivities ^{than} λ holographic emulsions, requiring typically 20 mJ cm^{-2} (Huignard et al, 1976). They therefore require the use of more powerful lasers, but have a longer re-cycle life than photo-sensitive polymers.

Although each of these systems reduces the processing time significantly, the delay of 10 to 15 seconds is still much greater than the $1/25$ second in ESPI. It is still necessary to build up the holographic system round the detector, unlike ESPI where it can be conveniently packaged in a "point-and-shoot" instrument such as the "Vidispec".

The use of a video system in ESPI not only simplifies the design and operation of the instrument but it also provides a direct output that can be held in a digital store. With digital image processing the potential for the fast retrieval of metrological data is a significant feature in engineering measurement.

5.2.3 Fringe Analysis

In holographic interferometry it is more difficult to interpret the interferogram than it is to make it in the first place. Analysis of the fringe pattern is a complex procedure. The steps involved in fringe analysis in HI are:

1. Image detection
2. Fringe identification
3. Calculation of Z displacement
6. Identification of surface points
5. Strain calculation.

Image detection involves producing a 2D image from the hologram either in photographic form or as a digitised image in an image processing system. Both methods generally use a lens to image the

virtual image of the hologram onto a plane. A photographic camera can be used to produce a photograph for interpretation by hand. For automatic analysis, a single photodetector, a solid state camera or vidicon camera can be used to convert part or all of the image into a video signal. This is easily digitised for storage and processing in a microcomputer. As stated before, ESPI has an immediate advantage over HI in that the video camera is the primary detector and has a video signal readily available.

Once an array of intensities from the image has been produced, the second step is to identify the fringes. Identification involves locating the position of each fringe within the image, numbering them in relation to the zero order fringe and determining the direction of displacement. This needs to be carried out for each point in the array. The heterodyne and phase-stepping methods have been particularly useful in this second step. These are now briefly described.

Heterodyne HI: The classic technique of detecting the beat frequency formed between two signals of slightly different frequency has been successfully used in HI to determine accurate phase values. Heterodyne HI is described in a paper by Dandliker, Inleicher and Mottier (1973). A frequency shift is introduced between two illuminating beams such that they have frequencies of f_1 and f_2 where:

$$\Delta F = f_1 - f_2$$

The beams are used to form two wavefronts corresponding to the object in two positions. The wavefronts have amplitudes a_1 and a_2 and phases ϕ_1 and ϕ_2 where the phase difference is given by:

$$\Delta\phi = \phi_1 - \phi_2$$

The amplitude of each wavefront at time t is:

$$A_1(t) = a_1 \exp(2\pi f_1 t + \phi_1)$$

$$A_2(t) = a_2 \exp(2\pi f_2 t + \phi_2)$$

In HI, a_1 and a_2 are normally made equal. When the two wavefronts are added, the resultant intensity is:

$$I(t) = 2a_1^2 (1 + \cos [2\pi \Delta F t + \Delta\phi])$$

This signal is detected by a light detector that is able to resolve the beat frequency. The value of ΔF is typically 80 kHz. By comparing this signal with a reference signal also at ΔF , it is possible to measure the value of the phase difference, $\Delta\phi$. With a typical accuracy of 10^{-2} radians, displacement measurements in the region of 1 nm can be made.

The heterodyne method is particularly suited to holography where a detector with a fast time response can be used. In ESPI the use of a video camera with a frame rate of 25 Hz limits the value of ΔF to 0-10 Hz, to satisfy the sampling theorem. A limited form of heterodyning with ESPI by Hogmoen and Lokberg (1977) has been described in Section 1.3. The use of reference beam phase modulation and a photodiode at the monitor screen enables vibration measurements of 2 nm to be made.

Phase Stepping: The method of phase stepping can also be used to determine the phase of a fringe field. Hariharan et al (1982) describe a technique using a 100 x 100 array solid state camera. A hologram of the undeformed object is made on thermoplastic material

using a holocamera. The object is deformed and a section of the fringe pattern is imaged on the camera. A known phase shift is introduced between the reference and object beams using an electro-optic modulator. Three images are produced with the fringes in slightly different positions. For phase values of ϕ , $\phi + 120^\circ$ and $\phi - 120^\circ$ the corresponding irradiance at the same point in the image is:

$$I_1 = I_i + I_o + 2(I_i I_o)^{\frac{1}{2}} \cos \phi$$

$$I_2 = I_i + I_o - (I_i I_o)^{\frac{1}{2}} (\cos \phi + \sqrt{3} \sin \phi)$$

$$I_3 = I_i + I_o - (I_i I_o)^{\frac{1}{2}} (\cos \phi - \sqrt{3} \sin \phi)$$

where: I_i = irradiance of reconstructed image
 I_o = irradiance of object at the same point

The images are stored in an array processing system and the intensities at each point noted. From three images it is possible to calculate the value of ϕ at each point in the digitised image with the following equation:

$$\frac{1}{\sqrt{3}} \tan \phi = \frac{(I_3 - I_1)}{(2I_1 - I_2 - I_3)}$$

The result is a phase map of the fringe field measured to a typical accuracy of 3×10^{-2} radians.

Because ESPI uses a video camera, it is particularly suitable for the phase stepping technique, as discussed in Section 4.6. This combination simplifies fringe analysis, gives greater accuracy and

does not require extra time for the processing of a holographic plate.

With both the heterodyne and phase-stepping techniques, the fringe location is determined to a greater accuracy than is possible with a straightforward peak detection method or $\cos^2$ intensity fit. The problems of noise and spurious intensity fluctuations are reduced, as would be expected when larger amounts of information are sampled.

The third step in fringe analysis is to calculate the displacement values. In HI the fringe patterns generally include components of out-of-plane, in-plane and rigid body motion, that make it more difficult to isolate individual displacements. At least three holograms of the object made from different angles are required (e.g. see Jones, 1974) to enable the components to be separated. With ESPI, the geometry of the illuminating beams can be set such that it is only sensitive to out-of-plane movement or only to in-plane movement. This makes it easier to calculate the Z displacement.

Whilst HI and ESPI can give accurate measurements of point displacements in the region of μm and even nm, the accuracy of relating a point in the image to a point on the surface of the object is comparatively poor. The use of an imaging lens in both techniques introduces positional errors due to lens aberrations. With the reduced aperture, the minimum speckle size is also increased, creating further problems for defining exact positions of fringes in relation to surface features.

The developing field of hologrammetry provides information relevant to HI in the area of image accuracy. Using transmission holography, dimensional measurements are made on the reconstructed real image to yield data about remote components or assemblies located in a hostile environment. Tozer et al (1985) report a pulsed holographic system for monitoring fuel elements in nuclear reactors. A measurement resolution of 50 line pairs ^{per} mm has been achieved, with an accuracy of 0.1 mm for a 1m long fuel element. A lens-less video camera is used

to monitor the real image. Measurements made on a virtual image in HI are less accurate due to the limiting resolution of the viewing lens.

Apart from optical aberrations, the light detector and digitisation procedures introduce further sources of error. The solid state camera has a higher geometrical accuracy than the vidicon tube since the photodiodes are mechanically fixed in space. In cathode ray tubes the line scan can drift and is prone to positional aberrations. Digitisation itself introduces aliasing which adds random errors throughout the image.

These are just some of the factors that introduce an uncertainty in the location of a pixel in the digitised image in relation to the surface under investigation. It is an area that has not received a great deal of attention in the literature but deserves further work if the accuracies of the displacement measurements are to be validated. A displacement measurement having an accuracy of 2 nm is questionable, if not meaningless if the point in question can only be located to an accuracy of ± 2 mm.

Finally, the displacement measurement should be related to the size and shape of the object under investigation. As indicated in Chapter 4, it is necessary to know the shape of the object in order to be able to calculate the strain value. The problem is much the same for both the HI and ESPI techniques.

This summary gives an idea of the steps involved in fringe analysis in holographic interferometry.

5.3 MOIRE TECHNIQUES

Although the relevance of the moire effect to contouring has been known for some time, its application in measurement has only been widely explored since the late 1960s. Because moire techniques are of reduced sensitivity, they have a certain advantage over interferometric methods in engineering. While it can be used in

deformation analysis, it appears to have been more widely used in shape measurement. The general principles of moire are now discussed and compared with ESC in the context of shape measurement. Details are also given of the author's own work in white light grid projection contouring to demonstrate how ESC can be applied to shape measurement in practice.

5.3.1 General Background

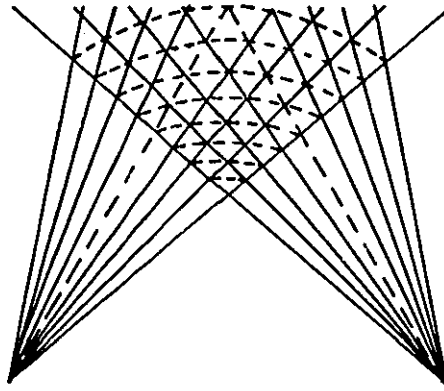
Rowe and Welford (1967) and Brookes and Heflinger (1969) were among the first to demonstrate that a projected grid light field can be used to characterize shape in a two dimensional image. In each case an interference grid from an interferometer was used. The addition of a reference grid (e.g. Hormiere and Mathieu, 1976) made it possible to rotate the reference plane normal to the viewing axis, making it easier to interpret the shape by eye. Since then, many methods have been developed for forming moire contours using laser and white light sources, diverging and collimated light fields, shadow moire and many different ways of adding a reference grid.

The nature of moire contours depends on whether the light field is diverging or collimated and on its direction of projection. The grids in Figure 5.2 demonstrate the different results. Two diverging fields form hyperbolic contours if the directions of the central axes are non-parallel in (a). When they are parallel the contours are planar, as in (b) and the contours increase in spacing further from the illumination source. Tokasaki (1979) uses the latter method successfully in the form of shadow moire to contour human subjects. A spotlight shines through a grating to project a shadow grid onto the subject. The grid itself then forms a reference grating when it is viewed through to form contours. Working close to the grid, the results are accurate enough to form the basis of a qualitative technique for detecting back deformities in children, indicated by an asymmetrical moire pattern on each side of the spine. This is now used in many Japanese hospitals.

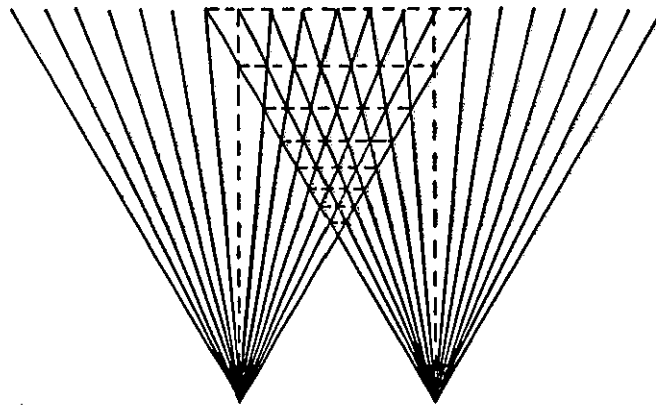
A novel form of reference grating is the electronically produced reference grating used in combination with a white light projected grid and video system proposed by Hormiere and Mathieu (1976). Although this gives a variable reference plane orientation, the contours are non-parallel, similar to the case in Figure 5.2(a). This leads to problems of interpretation which are absent in ESPI. Varman (1984) uses a video frame store to perform comparative moire in which an image of a collimated light field grid projected onto a reference object is subtracted from the image of a test object. A resolution of $10\text{ }\mu\text{m}$ in the line of sight measurement of shape difference over a 0.1m long turbine blade is achieved by this means. Planar equi-spaced moire contours are formed, similar in nature to those produced by two collimated fields (Figure 5.2(c)).

The main problem with moire shape measurement is to obtain the high resolution and accuracy required of an industrial test instrument. Comparative moire provides one solution but by far the most promising is the application of phase-stepping. A pioneering paper by Reid et al (1984) describes a method that combines this with some of the best moire methods to give a system yielding a resolution of $11\text{ }\mu\text{m}$ on an object size of 0.2m . A solid state camera is used for geometrical image accuracy, the test surface being illuminated with a fine grid from a white light projector. A reference grating in the image plane is too fine to be resolved by the camera, but this produces moire contours that can be resolved. Translating the reference grid alters the phase of the contours, and three fringe fields with different phases are converted into a phase map with the computer, to give a high resolution contour map. Phase stepping also overcomes to some extent the problem of holes and edges, normally a difficulty with conventional methods of fringe numbering. The technology is now in a form suitable for industrial use.

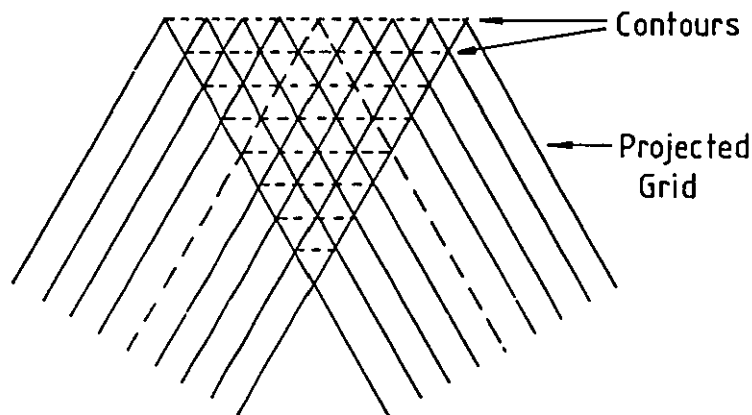
Because it is non-interferometric, moire methods have less stringent stability requirements than holography or ESPI. A large range of object size from fractions of a millimetre to many metres can be studied with sensitivities of microns to millimetres. At present the



a) Diverging fields directed towards the same point form hyperbolic contours of varying separation



(b) Diverging fields pointing in a direction parallel to each other form planar contours of increasing separation



(c) Equi-spaced planar grids form equi-spaced planar contours

FIGURE 5.2: Form of moire contours from diverging and collimated light fields

advantages of Electronic Speckle Contouring are that it does not suffer from the problems of fringe localisation and it can be performed with the same instrument as ESPI. Also ESC does not suffer from contour blurring due to diffraction effects. With projected image techniques the depth of field is limited by the aperture of the imaging system, whereas in ESC it is limited by the coherence length of the laser. At present ESC fringes are of much poorer quality than moire fringes, but the application of phase-stepping and other improvements may yield results with certain advantages compared with moire.

5.3.2 White Light Grid Projection Technique

The computer analysis of fringe fields developed for moire has obvious relevance to ESPI analysis. The author investigated the use of white light grid projection in shape measurement, the work giving an opportunity to examine the general problem of automatic fringe interpretation and the use of moire. As well as supplementing the author's knowledge of other techniques related to ESPI, the results of this work are applicable to the interpretation of projected ESC fringes discussed in Chapter 4.

The apparatus is relatively simple and this is shown in Figure 5.3 with the geometry of the system. A 35 mm slide projector with a 150W tungsten halide bulb projects an image of a square function grid onto the object, in this case a Mini bonnet. The grid was produced by photographically reducing a "Letraset" sheet of black and transparent lines having an equal mark/space ratio. With a restricted aperture in front of the projector lens a depth of focus of 0.6m is sufficient to illuminate the bonnet with a focussed grid at an illumination angle of 43° to the viewing axis. Figure 5.4(a) shows the image from the video camera photographed from the monitor screen. The bonnet is painted matt white to prevent glare and to give uniform fringe contrast.

The video image is digitised in a Matrox computer, accessible digital frame store 256 x 256 pixels by 8 bit grey scale. Image processing is performed on a Texas 990 16 bit computer. Initial image enhancement consists of thresholding to produce a binary image (Figure 5.4(b)) and a simple fringe tracking routine is used to mark the centres of the dark fringes as shown in Figure 5.4(c).

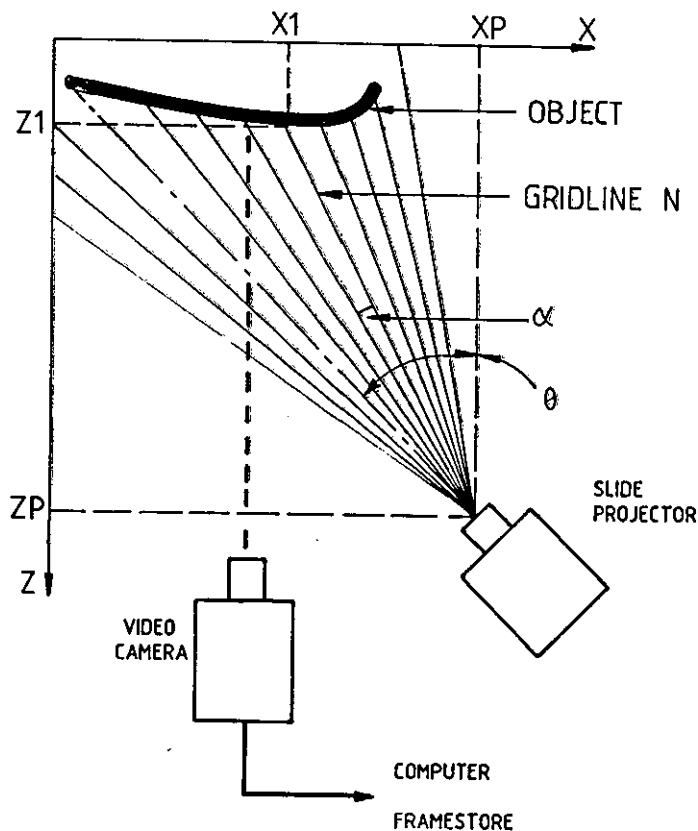


FIGURE 5.3: Layout and geometry for large area white light grid projection system

Analysis is simplified by the fact that the fringes are nearly vertical and can be numbered easily from left to right without any

holes or edges in the centre of the field to confuse numbering. Because processing consists of taking one line at a time, analysing an array of 256 points from left to right, the program can only cope with an edge if it is on the far right hand side where it defaults to zero. The value of Z_N , the height of the bonnet above the reference plane for fringe N is calculated for each fringe according to its position X along the X axis. This is given by:

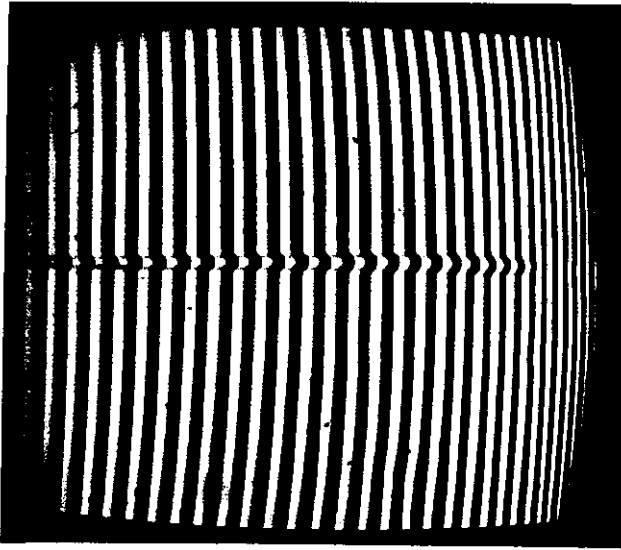
$$Z_N = Z_P - \frac{(X_P - X)}{\tan(\theta - N\alpha)} \quad (5.1)$$

where Z_P and X_P are the Z and X positions of the projector, θ is the angle of illumination with the viewing axis and α is the angular separation of the grid lines. After calculating the value of Z at fringes N and N+1, the program does a linear interpolation to calculate Z at intervening pixels. The results of the heights in millimetres are stored as a grey scale value from 0 to 255 in the frame store as in Figure 5.4(a), intensity corresponding to height.

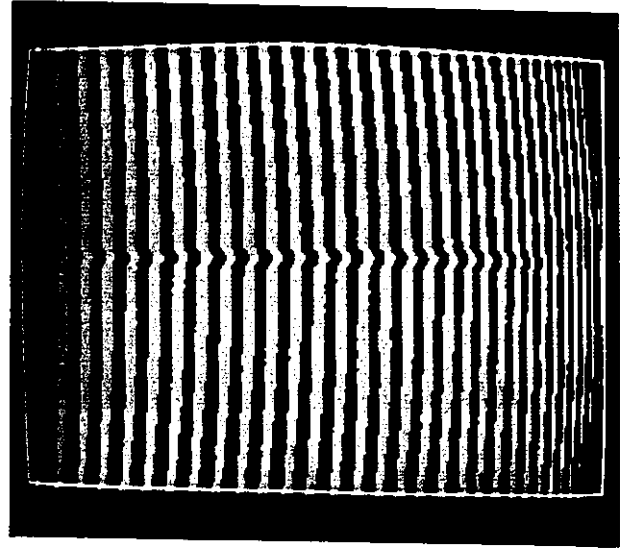
Two cross sections of this image are shown in Figure 5.5(a) and (b) together with error values determined from measurements made on a home built 3D coordinate measuring machine. This consists of a height gauge fastened to a saddle on an optical rail suspended over the bonnet supported horizontally on an optical table. A repeatability of ± 0.1 mm can be attained with the height gauge, ± 0.5 mm with the optical rail, and ± 1.5 mm with the positioning of the rail on the optical table.

For cross sections in the YZ plane, the standard deviation of measurements made by the optical method compared with the mechanical method is 1.6 mm, giving an accuracy of 2%. Cross sections measured optically in the XZ plane are not as accurate.

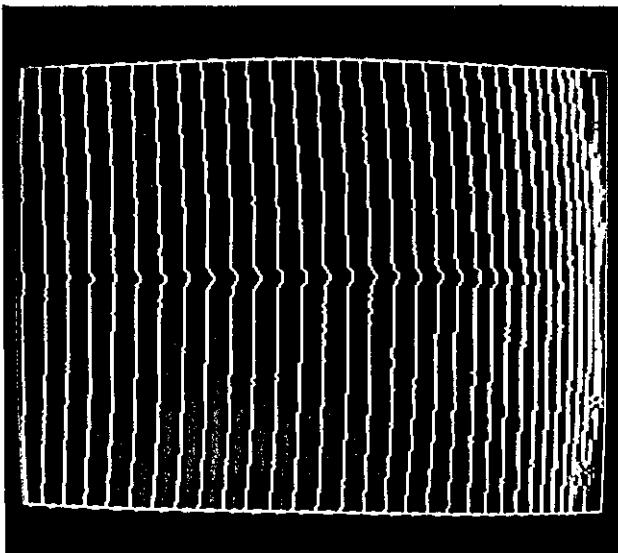
The value of Z is dependent on the value of X along the X axis which is measured from the screen width calibrated in the plane of XY for



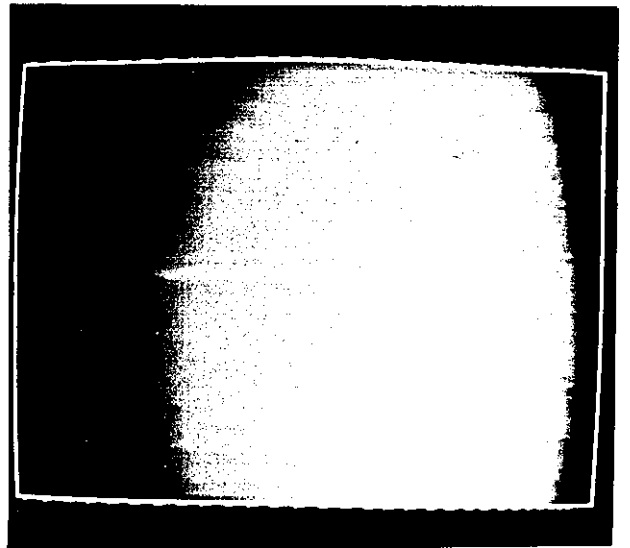
(a) Camera view of grid on bonnet



(b) Binary image of digitised grid in frame store

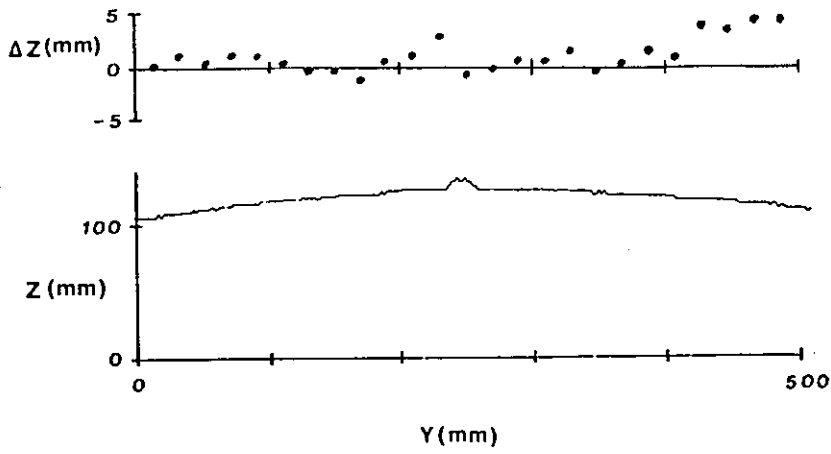


(c) Fringe tracking

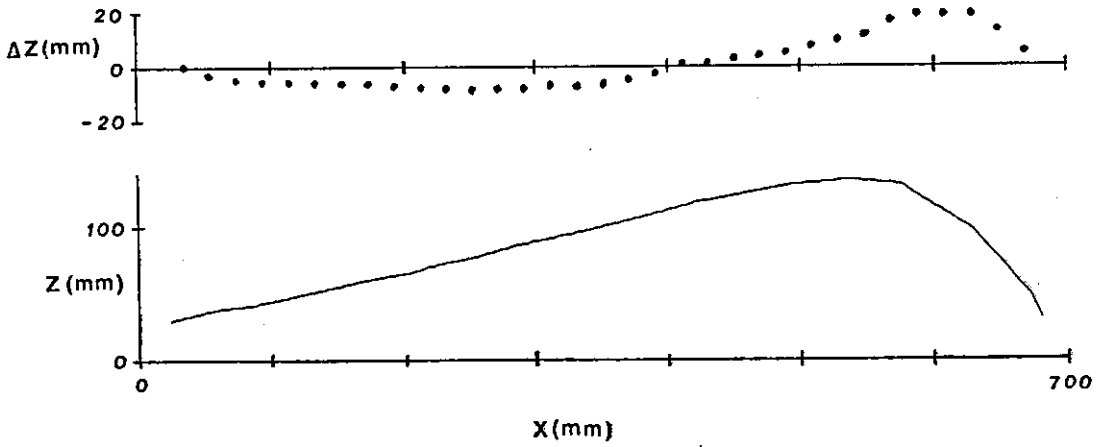


(d) Height values displayed as a grey scale

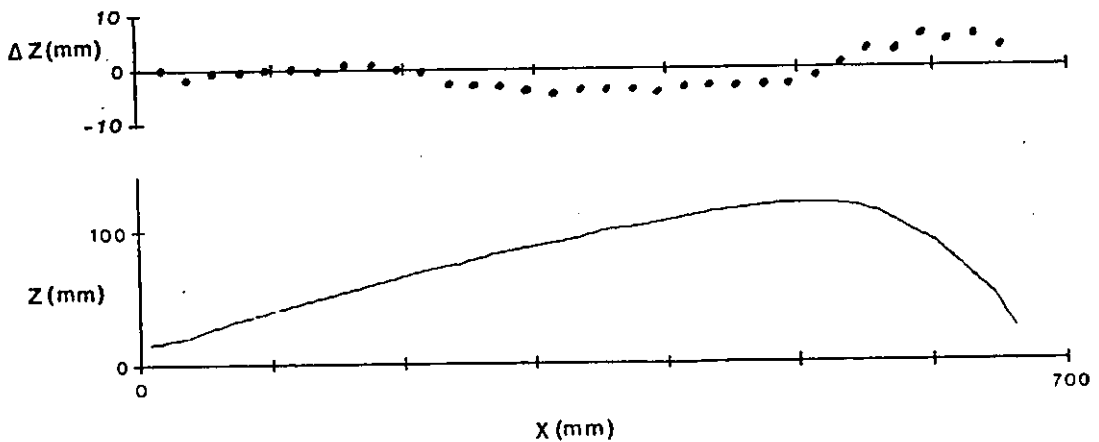
FIGURE 5.4: Absolute shape measurement of a Mini bonnet by white light grid projection. Image processing on Texas 990 computer and Matrox digital video store (256 x 256 pixels x 8 bits)



(a) Cross-sections for line $X = 190$ from Figure 5.4(d)



(b) Cross-sections for line $Y = 128$



(c) Cross-sections for line $Y = 128$ after perspective correction

FIGURE 5.5: Cross-sections of a Mini bonnet calculated by optical grid projection (solid line) and errors calculated from measurements made with a 3D coordinate measuring machine (dotted line)

$Z = 0$. For non-zero values of Z , the screen width is different because of the cone of view of the imaging system. This introduces a perspective error in Z for points not on the viewing axis. The error increases for measurements made at points further from the viewing axis in the X direction and for larger values of Z . In the example described, this accounts for errors of up to 10-30%, as can be seen in Figure 5.5(b) where the S.D. is 9.3 mm. To accommodate for this the author devised an iterative technique for reducing the perspective error. Using the initial approximation of Z , a better value of X is calculated. Using this new value of X , a more accurate value of Z can be calculated. Carrying out two iterations reduces this error due to perspective to below 0.5% (Figure 5.5(c)). The standard deviation of the Z values compared with the measurements made mechanically is reduced to 3.2 mm with a largest error of 10%.

The technique as it stands is suitable only for shape recognition but it illustrates some of what is involved in shape measurement. The whole process has been simplified by using a matt white surface with a gentle slope and no holes or edges and a simple method of fringe numbering. The accuracy and resolution could be significantly improved by using a higher resolution store and a sine function grid in combination with phase stepping. Taking three or more images with the grid moved through part of a cycle, a phase map can be calculated and Z values calculated at all points in the field. A study of the errors introduced by the optics, video camera and digitization is required to improve the accuracy still further. The details outlined here apply to shape measurement with ESC which operates on essentially the same principles of fringe projection.

5.4 CLOSURE

ESPI has been compared and contrasted with speckle photography, holographic interferometry and moire techniques, and shows some significant advantages:

1. The use of a video system giving immediate results allows interactive component testing.
2. The video signal from the primary sensor is available immediately via the digital store for near real time processing.
3. The high sensitivity of the video camera allows the use of low power lasers (e.g. 10 mW HeNe) and a short exposure time. This makes it easier to set up a breadboard system and gives a higher tolerance to environmental noise than holography.
4. It can be used under normal indoor lighting conditions.
5. In-plane measurements can be made directly.
6. Successive refreshing of the frame store allows displacement measurement from 0.1 μm to destruction of the component.
7. Phase stepping and speckle averaging techniques are readily applied in the subtraction and time averaged modes to improve the resolution and the quality of the results.
8. Contouring can be performed on the same instrument as displacement measurement using ESC, with a programmable grid spacing (see Chapter 4).
9. ESC does not suffer from diffractive blurring like projected image grids or shadow moire, moreover the grid can intersect the object at a choice of orientations (see Chapter 4).

Some of the disadvantages of ESPI are:

1. Conventional ESPI fringes have a low SNR value due to the speckle pattern, although phase stepping and speckle averaging largely overcomes this.
2. Interferometric stability of the apparatus is required, though not to the extent of that required for holography.

A "point-and-shoot" ESPI system is now commercially available with the basic subtraction and time averaged modes, requiring a non-specialist skill level of operation. It is expected that the further application of phase-stepping will produce some significant improvements to ESPI, particularly in the areas of noise reduction, resolution and fringe interpretation.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

Many advances have been made in ESPI since 1981. The purpose of this final chapter is to outline the author's contribution to the progress of ESPI during this period. The discussion includes summaries of the position of ESPI in 1981, contributions made by the author and other workers in the field, and the present state of ESPI. A number of recommendations are made as a result of the progress made. The work is completed with a list of conclusions.

6.1 DISCUSSION

6.1.1 State of ESPI at Beginning of Work

Design: After ten years of development, the ESPI interferometer remained largely a laboratory design in 1981. The layout was based on the well established focussed image holographic system with the reference and object beams having equal path lengths. Low grade optical components were commonly used in ESPI designs, introducing optical noise and aberrations in the image. There was a tendency to use large numbers of optical components. The Vinten's system, an early commercial design, is a typical example. The complex layout and use of the hole-in-the-mirror system made it difficult to maintain and prone to fringe drift. An ESPI instrument from Trondheim installed in a Norwegian turbine blade manufacturing company based on a simplified design experienced greater success. Simple fixed focus lenses were generally used in ESPI designs, giving a limited field of view. By 1981 digital framestores and digital image subtraction had replaced the older analogue systems. Digital storage and processing were found to give more accurate image subtraction and was more convenient to use in practice. High resolution Chalnicon camera tubes were being used in place of the older vidicon tubes.

It was generally thought in 1981 that the basic theory for ESPI was well understood. Optimisation of light intensity levels, image resolution, speckle correlation and wavefront conjugacy had been quantified. The consequence of this was that it was thought necessary to use small apertures of $f/16$ to $f/70$ in order to resolve the speckle pattern and to have well defined intensity ratios and conjugacy. A lot of the experimental work that led to this thinking had been performed on the lower resolution vidicon tubes, although the use of the Chalnicon tube was beginning to indicate otherwise.

Modes of Operation: By 1981, many of the modes of operation in HI had been successfully applied to ESPI. For example it was found that time averaged ESPI fringe analysis was helped by reference beam phase modulation to allow measurement of small amplitude vibration and phase. Beam chopping was being used to produce $\cos^2$ intensity vibration fringes. Although the pulsed laser mode had been applied to ESPI in 1976, it was not widely used in 1981. The ruby lasers used at that time tended to be expensive, unreliable and had a slow repetition rate. A pulsed ESPI system installed at Imperial College experienced some success in the study of in-plane displacement of large rotating machinery.

The out-of-plane ESPI mode was found to have a number of advantages compared with holography. The use of an in-line illumination and viewing system in ESPI simplified identification of the out-of-plane displacement component. In practice the live video format of the results was found to be particularly useful in out-of-plane analysis and non-destructive testing. Re-referencing of the framestore also allowed continuous monitoring of creep and relaxation. The ESPI in-plane and image shearing modes were not as widely used as the out-of-plane and time averaged modes.

The technique of two wavelength ESPI contouring had progressed by 1981 to encompass the measurement of complex surface shapes using holographic elements as well as simple surface shapes. The technique

saw little use, probably because it required complex apparatus, was difficult to perform and gave poor quality results.

Applications: Many of the traditional applications of HI could be performed with ESPI in 1981. Vibration analysis of turbine blades, loudspeakers, and metal diaphragms were popular applications, as was the loading of metal strips and plates. Although the results gave a noisier output than in HI, the use of a video system was found to be advantageous in certain areas of vibration analysis and NDT. The speed of acquisition of results made ESPI particularly suitable for the testing of resonance modes in turbine blades in the Norwegian system mentioned previously. This was the only proven industrial application at the time. ESPI was also found to be well suited for detecting faults in composites such as aircraft honeycomb section panels, skis, and brake shoe assemblies. Because NDT of this nature tends to be dynamic with the application of heat or pressure stressing, the re-referencing facility of ESPI is an advantage when looking for non-uniformities in the fringe pattern.

Fringe Analysis: Fringe analysis was limited in 1981, largely performed manually from a photograph of the image of the interferogram on the monitor screen. Digital image processing was just being introduced at the beginning of this decade. Elementary forms of noise reduction and automatic fringe tracking were being tested, but without the use of heterodyning or phase stepping the accuracy of measurement of fringe position was limited to about $1/4$ of a fringe due to the speckle noise.

At the beginning of this work in 1981 ESPI was a well developed laboratory technique that was capable of performing many of the functions that were possible with HI. Some of the fundamental principles of operation were quantified and were thought to be understood. The advantages of using a video system were being discovered, particularly with the early use of digital image processing for fringe analysis, but the problem of speckle noise was a severe limitation. The technique was restricted to laboratory use,

with only one industrial system having seen proven success in an industrial environment.

6.1.2 Advances in ESPI

Since 1981, work carried out by the author and other workers at Loughborough and elsewhere has resulted in some significant advances in the development of ESPI.

Design: The author has been one of the few workers in the field to analyse the basic optical design of the interferometer and to apply well known principles to bring about improvements. Simplification using multi laser cavity path length compensation reduces degradation of the output due to dust and dirt and instability of the components. The advantages of using carefully chosen optical components have been pointed out, to reduce light losses, optical noise and optical aberrations. Paying attention to design details of the interferometer in this way makes it cheaper to manufacture ESPI and results in an instrument that is more stable, gives higher contrast fringes and is therefore more attractive to use.

Due to development work by Tyrer and the laser group at Loughborough, two major optical firms are now marketing ESPI systems based on Loughborough designs. Ealing Electro Optics plc (UK) began marketing the "Vidispec" in September 1985 and Newport Corporation (USA) are in the process of building a prototype. The author's contribution to the design of the "Vidispec" includes the use of the zoom lens and coated optics. The shortened reference beam design has not been used yet since this work was carried out after the building of the prototype. A reference beam path length compensator adjustable for object distances of 0.3m to 1.2m is used to make the path lengths equivalent. While making the "Vidispec" easy to use, the use of prisms in the folded beam system introduces 20 extra optical surfaces into the reference beam. The result is a noisy reference beam even after spatial filtering. Future modifications will hopefully include more of the ideas suggested in this work.

Some significant contributions to the design have been made by Creath (1985). The first is the use of a single mode optical fibre to introduce the reference beam at the camera faceplate. By this means the noise and optical aberrations normally associated with the wedge or cube are removed. The absence of a wedge also permits the camera to be positioned closer to the lens, allowing the use of a standard OCTV zoom lens. No details have been given as to how practical it is to modify a lens to incorporate the optical fibre and to use it in a working system. The second contribution made by Creath is the application of a CCD array camera. A solid state array has a higher geometrical accuracy than the vidicon tube, is more compact, and with a frame transfer memory may allow subtraction to be performed at the camera faceplate. In practice, the 100 x 100 array used by Creath has too low a resolution to give satisfactory results with ESPI.

Work by Begquist and Mendoza-Santoyo (1986) in the area of conjugacy indicates that the fringe quality may not be as dependent on axial accuracy as was at first thought. While confirming the need for high lateral accuracy, they indicate that there may be a greater tolerance to a variation in the curvature of the reference beam wavefront. This confirms the results of the author who has obtained satisfactory results for a fixed reference beam position while changing the focal length of the zoom lens from one extreme to the other.

Modes of Operation: The range of operation modes possible with ESPI has continued to expand with the further application of ideas from HI. Varied success has also been achieved with the introduction of new laser sources to ESPI.

Rowland and Mendoza-Santoyo (1986) have successfully applied reference beam modulation to cancel the effects of fluid changes in a pressure test cell. By reflecting the reference beam from a mirror inside the test cell, dynamic movement of polymer samples have been studied directly with the effects of changing refractive index removed. Lokberg and Kwon (1984) have applied 10.6 μm wavelength

light from a CO₂ laser to ESPI. The associated difficulties of using infra red optics and a pyro-electric detector together with increased speckle size yields poor results but the work demonstrates how ESPI can be used at non-visible wavelengths. Using recent advances in frequency doubled ND YAG lasers, Tyrer (1985) has had more success at a wavelength of 530 nm. By double pulsing at video frame rates, the use of double pulsed ESPI has been demonstrated in vibration analysis. This is particularly applicable to industrial systems since the short exposure time reduces the need for interferometric stability. Nd YAG lasers are also more portable and reliable than the ruby laser used previously in double pulsed work.

ESC was first introduced by Winther and Slettemoen (1984) and Bergquist and Montgomery (1985). The former paper describes a method using an optical fibre to translate the object beam parallel to itself. Poor quality contour fringes are produced with no provision of a stationary reference fringe. Bergquist and Montgomery on the other hand use a rotating mirror in the object beam, giving a stationary zero order fringe and more scope for development of the mode. The essential theory for the 3D case of Electronic Speckle Contouring (ESC) is developed by Bergquist. The entire empirical development of ESC has been carried out by the author.

The work has confirmed that basic mode ESC fringes are equivalent to projected Michelson fringes and that the fringe spacings on a flat target agree well with the theoretical values. Moire contours can be produced between basic mode ESC fringes and an electronically produced reference grid. By using the basic mode with two illuminating beams at 180° on either side of the object, contours with the reference plane normal to the viewing direction are formed.

Progressing from the basic mode using a single rotating beam, some interesting ideas are produced with two rotating beams for altering the orientation of the reference plane of the contours. Rotation of

the reference beam in combination with the object beam reproduces a similar holographic contouring method reported by Yonemura (1982). If the reference beam is removed and two object beams are used instead, one acting as a reference beam to the other, rotation of both beams produces contours. The contour separation and orientation can be controlled automatically by rotation of the two beams. Results have been obtained on objects 30 mm and 1.0m in diameter. The method works with the two beams placed at equal angles on either side of the viewing axis or at different angles on the same side of the viewing axis. Assymmetrical illumination may be useful for certain cases of shape measurement where space for illuminating the surface is at a premium.

The formation of a reference fringe enables ESC to be used in a time averaged mode by oscillating the mirror in the object beam. Time averaged ESC was proposed in theory by Bergquist and first carried out experimentally by the author. Many of the techniques applicable to vibration analysis can be used in the time averaged ESC mode. For example beam chopping has been used to produce $\cos^2$ intensity fringes which are easier to analyse than J_0^2 fringes. The shortened illumination time also reduces the requirement for object stability. The application of noise reduction techniques described in Chapter 3 have also been applied successfully to time averaged ESC.

The significance of the advances made with the new ESC mode is that the foundation is laid for a single ESPI instrument that is capable of measuring shape as well as displacement. Unlike the two wavelength ESPI contouring method, ESC is conveniently added to the basic ESPI design. The author suggests the use of the basic mode for contouring, reflecting the object beam from a rotating mirror. Some of the principles involved in shape measurement using the grid projection technique have been illustrated with a white light shape measurement technique. The combination of ESC and phase stepping has been proposed by the author as a method of improving the resolution of ESC.

Applications: Since the beginning of this work the scope of applications of ESPI has been broadened. In terms of field size, the lower limit has been reduced to 200 μm , the limit being set by the large speckle size formed at the small numerical apertures used (Herbert, 1983). At the top end of the range, Bergquist (1982) has demonstrated the use of a 15 mW HeNe laser giving ESPI fringes on a target width of 1.25m. Extremes of temperature have also been tested. Lokberg et al (1984) have successfully obtained fringes on objects with a surface temperature of 1700°C.

The applications described in the present work have been chosen to demonstrate the benefits of the specific innovations introduced as well as the general use of ESPI as an industrial test instrument. The results of the improved optical design have already been highlighted. In practice the use of a zoom lens has been shown to be not only convenient for looking at different sized objects, but useful for analysing high density fringe patterns. Examples have been given of large amplitude loudspeaker vibrations and point loading of a 1 m² panel of plastic flooring. Using the zoom facility, the general view gives the operator an overview of what is happening, while close-up reveals detail of the form of the displacement in the region of interest.

The noise subtraction techniques for the time averaged mode are particularly useful for working systems where the accumulation of dirt and grease on the optics in the reference beam would normally impair the quality of the fringes. In vibration analysis, the ordinary time averaged mode with reference beam noise subtraction is suitable for ascertaining the vibration modes. To clarify the shape of the mode and to locate it on the surface of the object, the reference and object noise subtraction technique or the speckle averaging technique is used, depending on the degree of noise reduction required. These methods have been illustrated with vibration analysis carried out on a loudspeaker, metal plate and an IC engine.

To show some of the ruggedness of ESPI compared with HI, the author has successfully operated an ESPI system on a partially vibration isolated optical table supported on a wooden table in an engines laboratory. It has been shown to have a tolerance to a certain degree of environmental background noise, and to function under normal indoor lighting conditions. The use of a video system as the primary detector has been shown to give ESPI a fundamental advantage compared with photographic speckle and holographic techniques.

Fringe Analysis: A number of developments have been made in the area of fringe analysis since 1981. The author and others have taken different approaches to this topic. Early work in digital processing continued with Nakadate (1983) proposing smoothing and thresholding of the video signal before formation of the ESPI image and Varman and Wykes (1982) suggesting post image processing. While FFT's took many hours to perform on a mainframe computer in the early 1980's, it can now be performed in much the same time on a microcomputer (Montgomery, Bergquist and Henry, 1986). Hurden (1982) suggested a reduction in the amount of smoothing, relying on the eye of the operator to follow the noisy ESPI fringes using a light pen.

Because digital processing requires expensive apparatus and takes many times the frame rate for moderately priced systems the author has taken an alternative approach and suggested the use of analogue processing. Filtering in one or two dimensions and thresholding have been performed at or near frame rate using analogue units. These are a fraction of the cost of computerised systems and provide an alternative solution for image enhancement in industrial ESPI systems. A compromise between the low cost analogue units and fully computerised image processing systems may be the use of programmable filtering and image processing systems based on a microprocessor. These units have recently become available.

Filtering of the video signal reduces the resolution of the image. Noise subtraction gives a moderate improvement in resolution. Nakadate (1980) first reported a method involving the subtraction of

the speckle pattern of a vibrating object from the pattern of the object at rest to improve time averaged fringes. A number of related methods were developed by Creath and Slettemoen (1985). Although in theory these techniques should give improved results, neither the paper by Nakadate nor that by Creath and Slettemoen show fringes that are any better than standard time averaged patterns. In the present work, a method of reference beam noise subtraction is reported for the first time, although it is a well known technique at Loughborough. Further improvements are gained by subtracting both the reference and object beam noise while the object is vibrating. Again, this is the first time to the author's knowledge that such results have been published, although Creath and Slettemoen (1985) proposed the method in theory.

Speckle averaging gives a fundamental improvement in time averaged fringe patterns. Slettemoen (1980) and Lokberg and Slettemoen (1984) proposed a photographic technique for improving fringe patterns for presentation of results. The author has developed an electronic technique using either an analogue or a digital frame store to produce holographic quality interferograms. Results are illustrated with the help of beam chopping and phase modulation to show the versatility of the technique. Improvements of this nature increase the resolution of the time averaged mode and reduce the requirement for smoothing before fringe tracking. Similar theoretical ideas by Tyrer at Loughborough have led to a joint patent with the author in electronic speckle averaging.

A major step forward in the field of fringe processing has been the application of phase-stepping to ESPI, reported simultaneously by Nakadate et al (1985), Creath et al (1985) and Stetson (1985). This method reduces the problem of speckle noise in the out-of-plane mode, gives the sense of the displacement and simplifies fringe numbering. The significance of phase stepping for ESC in shape measurement has been discussed.

In summary, the author has contributed a number of forward looking innovations in the basic optical design, noise reduction techniques for improving the output and in a new contouring mode of ESPI. These innovations have improved present laboratory and industrial based systems.

6.1.3 Position of ESPI at End of Work

The state of ESPI at the end of the period of research in 1986 is much more positive in terms of becoming an accepted industrial technique than it was in 1981. This is evident in the fact that two major optical companies have bought a licence to manufacture ESPI, ten systems have been sold in the first year of production and five research groups in the UK, USA and Japan are seriously developing phase-stepping ESPI systems.

Design: As has already been mentioned, the "Vidispec" from Ealing Electro Optics plc and the prototype by Newport Corporation are based on Loughborough designs. The subsequent ideas resulting from research at Loughborough are added to these commercial designs after discussions between Loughborough, the British Technology Group and the manufacturers. BTG hold the patents for ESPI work carried out at Loughborough. On the recommendation of the author, high grade coated optical components are being incorporated in the "Vidispec". At some stage it is hoped to design a speckle averaging unit that can be added to the system to enhance the time averaged mode.

Bergquist and Mendoza-Santoyo (1986) also of Loughborough, are continuing with investigations into the influence of conjugacy and beam ratios on fringe visibility. They are studying the interaction of the image, video camera, A/D converter and digital framestore with respect to system resolution. The aim is to develop more satisfactory theoretical models of the ESPI process.

Modes of Operation: Winther and Slettemoen (1984) are proposing to use the ESC technique for a combined shape and displacement

measurement system. Bergquist (Bergquist and Montgomery, 1985) has noted that the visibility of ESC fringes is related to the roughness of the surface being contoured. For the same contour interval on a flat plate the fringe visibility decreases with increasing surface roughness. Following investigations into the reliability of this relationship, Bergquist is considering the possibility of a total system that is capable of measuring displacement, shape and surface roughness.

After successfully demonstrating the use of an Nd YAG laser in ESPI, Tyrer is embarking on a project to develop the double pulsed mode to establish the operation parameters and scope of applications. A longer term aim is to design a prototype commercial system. The attraction of the double pulsed mode is the ability to study structures and machinery under realistic operating conditions. A measurement and diagnostic tool that gives more information than the stroboscope and is more convenient to use than double pulsed holography is greatly sought after by engineers in a variety of fields.

Applications: An interesting point to note with the commercial "Vidispec" system is that most of those that have been sold are being used in vibration analysis. In the industrial sector ESPI is being used in fundamental loudspeaker design, noise and vibration testing of vehicle components and testing of pressure transducers amongst other things. At University level they are being used in combination with finite element techniques in turbine blade design and for educational purposes in vibration analysis. Tyrer and King at Loughborough are using a Vidispec system to study forced vibration in large 6.7 litre engines in a joint contract with a vehicle manufacturing company. In quite a different field, McCleod at Edinburgh and Buttons at Trent Polytechnic are using the only two Vinten's systems sold to study mass transfer of volatile liquids from absorbent surfaces in heat transfer modelling.

Fringe Analysis: In the area of image processing, Henry at Loughborough now has an extensive range of digital filtering, thresholding, peak detection and other routines for smoothing ESPI patterns and marking fringe positions. At present, these still take many minutes or hours to perform on a DEC PDP 11/03 computer.

The progress of phase stepping has reached different stages in the five centres in which it is being developed. Three centres have systems that are operational. Creath et al at the University of Arizona have shown limited success using a low resolution CCD array. Nakadate et al at Hirosawa (Japan) and Robinson et al at NPL (UK) show improved image resolution using high resolution vidicon cameras. Stetson et al at the United Technologies Research Centre have developed the theory for the analysis of results from a CCD based system. Tyrer and Kerr at Loughborough are presently developing the software for processing images from a Chalnicon camera. The development of a successful phase stepping system requires a number of steps to be overcome. The first step is to form a basic phase map. This is followed by a stage for reducing or removing the number of randomly scattered points where no phase measurement is made due to noise or low light level modulation. When a full phase map can be made, the final hurdle is to increase the speed of acquisition of the map. At present the most successful systems appear to be those using higher resolution imaging cameras in ESPI systems that are correctly optimised for maximum speckle contrast modulation.

6.1.4 Recommendations for Future Work

A number of recommendations for future work are now made resulting from the author's work:

- All future optical designs should take into account the lessons learnt and pay attention to the quality of the optical components. The use of high grade optically coated components, in a simplified design are recommended for efficient use of the laser light and reduced image noise and optical aberrations (Section 2.5).

- Analogue processing of the video signal after the formation of the ESPI pattern provides a low cost solution to simple speckle noise reduction (Section 3.7). One and two dimensional smoothing and thresholding can be performed at or near frame rate. Video processing units are available giving functions such as variable shading correction, variable corner contrast, automatic black level and variable white crush. Further work is required using this unit to ascertain the degree of normalisation, contrast stretching and thresholding that can be achieved. A similar project is recommended using variable active filters or even digital filters which have more accurate cut-off values and give less image distortion than the passive filters used in the present work. A more expensive solution is to use a programmable microprocessor based system such as the "Crystal" from Micro Consultants. This is programmed to process pictures from Scanning Electron Microscopes with many of the functions being suitable for processing ESPI images.
- The use of continuous de-correlation by introducing gross random phase changes across the illuminating wavefront combined with electronic image integration are recommended for producing high quality time averaged patterns. Further work is required to find the optimum de-correlation speed for different image geometries and different values of object surface roughness. Following the success of the rotating etched ground glass system, greater efficiency of light transmission may be achieved using a holographic element for reproducing a "fly's eye" lens.
- Speckle averaging should be carried out in a digital framestore. The integration function commonly found in image processing systems is ideally suited for this purpose. Further work is necessary to determine the balance between time taken to integrate and the degree of image processing before or after integration to give the required noise reduction.

- Shape measurement can be carried out using single wavelength Electronic Speckle Contouring (ESC). A variety of techniques have been demonstrated using single and double beam rotation and an oscillating beam to give time averaged fringes. Now that these methods have been established experimentally, further work is necessary to describe them mathematically using the general theory developed by Bergquist.
- The basic ESC mode is recommended for future ESPI systems incorporating shape measurement. The maximum number of fringes can be obtained in this mode with the simplest of optical arrangements. A diverging illumination wavefront allows large objects to be contoured. Where double beam rotation is used to give contours having a reference plane normal to the viewing axis, collimated beams must generally be used to give plane equispaced contours. In this case the object size is limited to the diameter of the collimating lens. De-correlation also limits the number of contours.
- It is now feasible to design and build an ESPI system that can measure shape as well as displacement. A rotating mirror in the object beam provides the beam rotation for contouring. To give the accuracy required of shape measurement, two methods are suggested. Either speckle averaging should be used to reduce the speckle noise or phase stepping. A combination of the two would give even better results.

This concludes the main list of recommendations. In the process of carrying out the research, a number of problems and ideas arose which fall outside the defined scope of the work, but nonetheless are important:

- The Loughborough digital ESPI processing system should be modified to standardise the form of the video signal and to operate from a central crystal controlled clock. Reducing the noise due to *electronic variations* (Section 3.6.2) and preservation of the full

information content of the video signal from the camera is particularly important where the use of speckle averaging and phase stepping techniques increase the resolution limit of the output.

- An investigation into the use of combined optics should be carried out. Any possibility of removing air/glass interfaces, particularly in front of the camera where the two beams are combined, should be investigated. One possibility is to glue the beam combining cube directly onto the face of the camera. Another idea is the use of a single mode optical fibre to introduce the reference beam, proposed by Creath (1985). A further advantage would be to seal this section completely to exclude airborne dust and dirt.
- A project should be initiated to study the problem of the errors involved in relating a point in the interferogram to a point on the object. With the recent progress in ESC, there is now an even greater need to understand the limits of accuracy of the imaging and video system. This topic is also relevant to the use of video cameras in holographic and moire techniques.
- As has already been suggested at Loughborough, high resolution CCD cameras should now be applied to ESPI. The 405 x 625 line frame transfer memory from Mullard is a good example. The advantages are high geometrical array accuracy, compactness, low voltage power requirement, and the possibility of performing the subtraction process at the camera. Frame rates higher than the standard 25 Hz are possible. A careful study is required of the effects of using individual pixel elements on the ESPI process, as against scanned lines in a vidicon tube. The effect of sampling by points may alter the degree of aliasing. Glass cover plates protecting the active area of the array may need coating to reduce the problem of Fabry-Perot fringes.

- The use of a sinusoidal grid and phase-stepping should now be applied to the white light grid projection technique. This may improve the resolution from ± 3.0 mm to as good as $100\text{ }\mu\text{m}$. The result would be a simple, versatile, medium accuracy shape measurement technique.

From the work presented in this thesis and the recommendations made above, it is obvious that there is more progress to be made in ESPI by applying new electro-optical devices. Solid state arrays and solid state lasers will make the optical head more compact and cheaper. Higher resolution video formats of 1024×1024 pixels at 50 Hz frame rate will give higher resolution images. The experience gained with developing electronic speckle averaging suggests that there may be other well known noise reduction techniques waiting to be applied to ESPI. As computing power increases, fringe processing will be faster and more intelligent. The progress of ESPI is linked closely with the progress made in electronics, optics and electro-optics. Considering the rapid advances being made in these areas, it is clear that there is great potential for the further development of ESPI as an automatic engineering measuring tool.

6.2 CONCLUSIONS

A number of innovations in the technique of Electronic Speckle Pattern Interferometry have been presented and discussed. The following conclusions are drawn from the work carried out by the author:

Optical Design: The optimum visibility of ESPI fringes is attained by paying far more attention to the quality of the optical components than has hitherto been the case. As much as 51% of the total light available is lost through not using coated optics. An increase of 45% in the intensity of the object beam can be achieved by using optical coatings to reduce unwanted absorption and reflection losses. The wedge beam combiner introduces optical aberrations into the

imaging system, astigmatism causing severe focussing problems at larger apertures. To overcome these problems, a cube beam combiner and well corrected objective lens have been found to give an improved image resolution.

Analysis of different optical designs has shown that a simplified optical arrangement generally reduces the problems of noise and drift and simplifies maintenance. One method of simplifying the optical design is to shorten the reference beam path by an integral number of laser cavity lengths compared with the object beam. Working at higher order coherence planes with a HeNe laser, no appreciable loss in fringe visibility has been detected. The practical use of ESPI systems is improved with the use of a zoom lens. The ability to change the viewing area is particularly useful for resolving areas of higher fringe densities.

Noise Reduction: Three levels of noise reduction for removing different components of noise in ESPI fringes have been demonstrated. At the simplest level, 1D filtering using passive low pass video filters has been found to reduce the speckle contrast from 0.70 to 0.31. A further reduction to 0.09 has been achieved using image blurring devices for 2D filtering. Associated with the smoothing is a reduction in the resolution of the system, a lower limit being set for the number of resolvable fringes. Image detail is also blurred. The advantages of analogue video processing are operation at or near the frame rate and low cost. Thresholding produces a binary image which is more suited for presentation of results than fringe analysis as there is an introduction of uncertainty in the fringe position. Digital processing on a microcomputer tends to take longer than the frame rate and is much more costly than analogue processing.

The second level of noise reduction involves the removal of time invariant noise components in the time averaged mode using the digital framestore normally used in the subtraction mode. Results of two methods are published for the first time. The first method involves the subtraction of the reference beam noise to give an

improvement in the image while allowing continuous frequency scanning of vibration modes. Although known at Loughborough, this technique has not been published before. Further improvement occurs if both the object and reference beam noise is subtracted while the object is vibrating followed by the introduction of a π phase change between the two beams. This method corresponds to CASE IV in the paper by Creath et al (1985) which was described without the provision of results. Little system optimisation is required compared with the standard time averaged mode, opening the mode to non-skilled use. The disadvantages of the technique are that it is sensitive to out-of-plane movement and a change in frequency requires re-subtraction of the noise. In practice reference noise subtraction is used during frequency scanning and then object and reference noise subtraction at the frequency of interest to give an enhanced pattern.

These two techniques represent a practical method for using ESPI in vibration analysis in an industrial environment where the accumulation of dust and grease on the optics may otherwise eliminate the use of the standard time averaged mode.

The third level of noise reduction involves ensemble averaging of time variant noise to reduce the speckle content of the final interferogram with an accompanying increase in resolution. Two modes have been identified. Discrete de-correlation by altering the speckle pattern in a stepwise manner, such as stepping the object beam through an angle, can be used for the slower photographic averaging technique proposed by Slettemoen and Lokberg. Continuous de-correlation by changing the speckle pattern slowly between consecutive video frames allows integration in an electronic framestore at a much greater speed. A double diffuser plate system, etched for improved efficiency, with one plate moving perpendicularly in the beam produces gross random phase changes in the illuminating wavefront. The second plate forms finer speckles in the illumination beam and removes the problem of spurious fringe formation when using the object and reference noise subtraction method.

Results using a Vidicon Storage Tube have been given with an example of engine vibration analysis. Speckle averaged results have also been given for the beam-chopping and reference beam phase modulation methods. Holographic quality interferograms are conveniently produced in seconds rather than many minutes with holography. Measurements made on speckle averaged images in a digital framestore showed reductions in speckle contrast from 0.85 with one video frame to 0.09 with 784 frames. In this particular example it was calculated that while consecutive frames had a degree of correlation with the next, the images became statistically unrelated every 10 or 11 frames. A fringe density of 100 to 130 measurable fringes per picture height has been achieved with digital speckle averaging. After developing the technique experimentally in this work, similar theoretical ideas by Tyrer at Loughborough have led to a joint patent with the author in electronic speckle averaging.

Electronic Speckle Contouring (ESC): Electronic Speckle Contouring is a single wavelength method of shape measurement which has significant advantages compared with two wavelength contouring. Having been proposed theoretically by Bergquist, the author has developed and broadened the technique, demonstrating the following:

- ESC fringes in the basic mode are equivalent to Michelson projected fringes
- Fringe spacings measured on a flat target for a number of illumination and viewing directions agree with the theoretical values predicted by Bergquist.
- A rotating mirror placed in the path of the object beam produces projected grid-like fringes with a programmable spacing and a stationary reference fringe. Moire contours have been produced by subtracting the ESC grid from an electronic reference grid

- ESC contours with the reference plane normal to the line of sight are produced using 180° side illumination of the object. The disadvantage of this method is that surface peaks and troughs are in shadow
- ESC contours with a variable orientation reference plane are produced by rotating both the reference and object wavefronts
- A novel method of producing ESC contours has been found by rotating two object beams, symmetrically or asymmetrically illuminating the surface. Results have been demonstrated on objects 30 mm and 1.0m in diameter
- A time averaged mode with ESC is possible by oscillating a mirror placed in the path of the object beam. Results with 25 Hz oscillation have been shown, together with improvements in fringe quality by beam chopping and speckle averaging.

The basic mode of ESC using simple mirror rotation in the object beam gives the greatest number of resolvable fringes out of all the methods described, fifty fringes having been counted. Double beam rotation suffers from de-correlation more than single beam rotation. A shape measurement facility is easily added to a standard ESPI system using this basic mode. Combined with phase stepping and speckle averaging, ESC should prove to be a viable contouring technique.

Comparison of ESPI with Other Optical Techniques: It has been shown that ESPI has distinct advantages compared with photographic speckle and Holographic Interferometry because of the use of a video camera as the primary detector. Immediate interactive analysis is available with ESPI, unlike photographic speckle and HI where a chemical processing step introduces a fundamental limit in the time before the results can be seen. In HI this step is reduced to 10 seconds using a thermoplastic holographic medium, and to video frame rate or faster with a photo-refractive crystal. The disadvantage of the crystal is

that it requires 20 mJ cm^{-2} for an exposure, involving the use of a 5 to 10W Ar Ion laser. Holographic emulsions are a little more sensitive at $50 \mu\text{J cm}^{-2}$. The high sensitivity of $0.02 \mu\text{J cm}^{-2}$ of video cameras means that a 10 mW HeNe laser is sufficient for an ESPI instrument on target widths up to 300 mm.

It has been demonstrated that the shorter exposure time makes ESPI more tolerant to environmental noise than HI and allows it to be used under normal lighting conditions. Re-referencing of the framestore permits continuous detection of displacement as experienced with continuous loading or plastic deformation conditions.

Another advantage of ESPI is that there is a video signal readily available for processing. In the present work, this has been useful in the noise reduction techniques described in Chapter 3. Other workers have found it useful for digital processing and subsequent analysis. ESPI is also particularly amenable to phase-stepping. In HI a second detector to the holographic plate is required to produce an electrical signal. ESPI fringes are generally easier to interpret than HI fringes since they can be made independently sensitive to out-of-plane or in-plane displacement according to the geometry of illumination.

One of the main disadvantages with ESPI in the past has been the speckle noise in the interferogram which detracts from the attractiveness of the results and impedes automatic fringe analysis. The speckle averaging technique described in the present work virtually eliminates this problem for time averaged fringes. The problem is also reduced by the other noise reduction techniques described, and by phase stepping proposed by other workers.

The use of ESC in contouring makes more efficient use of the available light power compared with equivalent Michelson projected fringes. ESC fringes do not suffer from diffractive blurring as do fringes formed by projected image or shadow moire. At present moire contouring generally suffers less noise problems and is not limited

by the need for interferometric stability. It is suggested that ESC could be a viable shape measurement technique if combined with speckle averaging and phase stepping to increase the resolution.

The objectives set out in Section 1.5.2 have been fully met:

1. A choice of simplified optical interferometer designs now exists that are simpler and more flexible to use than previous designs. The output gives higher quality fringes due to lower noise content with holographic quality fringes being available in the time averaged mode. Practically, ESPI is more attractive to use.
2. Having developed the new contouring mode of ESC, an ESPI system now exists that is capable of measuring shape as well as displacement with potential for high accuracy using noise reduction and phase-stepping.
3. The viability of ESPI in industrial measurement has been demonstrated through the applications given and comparison with other optical techniques, the advantages being largely due to the use of a video camera as the primary sensor.

The work has contributed a number of forward looking innovations that are benefitting laboratory and industrial ESPI systems now in use and that lay the foundation for new and better measurement systems in the future.

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APPENDIX A
GLOSSARY OF TERMS

ESPI has a growing vocabulary of terminology which contains well known terms from associated techniques and less familiar terms that can often lead to inconsistencies and confusion of meaning. The following summarises some of the meanings as interpreted by the author. An attempt has been made to use accurate terminology, for example not to call ESPI fringes "interference fringes" but "correlation fringes".

Absolute shape measurement - the measurement of the Cartesian coordinates of a number of points on a surface with respect to an arbitrary origin by mechanical or optical means to define the shape of the surface.

Addition fringes - correlation speckle fringes with a bright zero order fringe formed by multiple exposures on photographic film or a video camera or by adding video signals from a video camera.

Beam combiner - optical element between the imaging lens and the video camera to combine the reference and object waves in ESPI.

Breadboard system - an ESPI interferometer formed from discrete components magnetically clamped to a vibration isolated optical table.

Coherence plane - any plane in which an object is placed in front of the imaging lens which gives rise to the reference and object waves in the image plane having spatial coherence.

Conjugacy - condition in which the curvature of the reference wavefront is equal and opposite to the curvature of the object wavefront approaching an image point.

Correlation fringes - an interference-like fringe system formed by the combination of two simple speckle patterns, one of which corresponds to a reference state. In the case of ESPI, the speckle patterns are formed by interference with a smooth or speckled reference beam. In subtraction dark fringes correspond to maximum correlation. In the addition mode bright fringes correspond to maximum correlation.

De-correlation - occurs when changes in the illumination of object state alters the speckle pattern sufficiently for the visibility of correlation fringes to approach zero. De-correlation may be discrete in which two patterns are randomly different or continuous in which the pattern slowly changes and two patterns in successive video frames are partially related.

Ensemble averaging - the process of obtaining the function of a signal by averaging a number of signals with random background noise, in the case of speckle patterns, averaging a number of signal records.

ESC - Electronic Speckle Contouring, a mode of ESPI in which correlation fringes associated with rotation or translation of the object illumination wavefront are formed superimposed on an image of the object from which the shape of the object can be determined.

ESPI - Electronic Speckle Pattern Interferometry. Measurement technique based on speckle pattern correlation interferometry using a video camera and electronic signal processing.

Fringes - periodic variation of the average light intensity across the field representing a 2π phase change (different in the case of time averaged fringes - see Section 1.1.2).

Fringe visibility - C_F - a quantified value for the contrast of a fringe (see Appendix C).

HI - Holographic Interferometry - measurement technique using interference of wavefronts, at least one of which is reconstructed from a hologram.

Noise subtraction - The subtraction of a video frame containing either the static reference noise, object noise or both from a live image to enhance time averaged fringes.

Object beam - unexpanded or expanded laser beam used to illuminate the object.

Object wave - coherent light scattered from the object and collected in the image plane.

Path length compensator - optical system to adjust the path length of the reference beam.

Phase change map - two dimensional array of the phase changes across an image field obtainable by phase stepping.

Phase modulation - modulation of the relative phase of the reference beam with respect to the object beam at the same frequency as the vibration of the object to determine amplitude or phase in the time averaged mode.

Phase stepping - technique to produce three or more interference patterns from which a relative phase map can be computed across the image field.

Projected grid - a set of interference or white light fringes projected onto a surface or simulated by forming correlation fringes superimposed on an image of the surface with ESC.

Real time or live fringes - the formation of an interferogram that changes with the loading of the object, immediately with real time HI or every 40 mS with ESPI working with a 25 Hz video frame rate.

Reference beam - unexpanded or expanded laser beam used to form the reference wavefront.

Reference plane - an arbitrary plane normal to the viewing direction from which the height of a surface is taken in absolute shape measurement.

Reference wave - reference wavefront directed from the beam combiner onto the faceplate of the video camera.

Speckle averaging - technique for reducing the speckle content of ESPI fringes by averaging identical fringe patterns having different speckle patterns.

Speckle contrast, C_s - a quantified value for the contrast of a speckle pattern (see Appendix C).

Speckle pattern - granularity of coherent light scattered from a rough surface, said to be "objective" in free space and "subjective" when formed in the image plane of a lens. (See Section 1.1.1)

Speckle pattern photography - technique in which the movement of speckles in the image plane of a lens reveals information about a rough surface illuminated with monochromatic light, or having a speckle pattern painted onto it.

Speckle pattern correlation interferometry - technique using an object and reference beam as in ESPI but using a photographic emulsion in the image plane of the lens.

Strobing - pulsing of the laser beam at the extremes of vibration to form $\cos^2$ fringes in the time averaged mode.

Subtraction mode - used for the detection of quasi-static displacement by subtracting a reference speckle pattern from the live speckle pattern.

Time averaged mode - square law detection of correlation fringes formed from the speckle pattern averaged on the face plate of the camera due to the vibration of an object.

APPENDIX B

TECHNICAL SPECIFICATIONS

A large range of equipment was used in the carrying out of this work. The following details cover some of the specifications.

CAMERAS

Jackson 1" Chalnicon - Toshiba Chalnicon type E5001 (D) tube. The camera has a 20 MHz bandwidth and a limiting resolution of 800 TV lines. The specified maximum positional error is $\pm 1\%$.

Vidicon Storage Tube (VST) - Thompson (CSF) type TH7501 using a silicon wafer storage tube scanned with an electron beam. Analogue video store with electronic controls for write/read/erase, integrate and zoom functions.

LASERS

All the lasers used produced linearly polarised light, operated in the TEM₀₀ transverse mode:

Type	Hughes 3225 HeNe	Spectra Physics 106 HeNe	Spectra Physics 124 HeNe	NEC 5700 HeNe	Coherent 52 Ar Ion	Coherent Innova 90 Ar Ion
Wavelength (nm)	632.8	632.8	632.8	632.8	514.5	514.5
Power Output (mw)	5	10	15	25	20-400	10-800
Beam Diameter at 1/e ² Points (mm)	0.83	0.68	1.1	-	1.4	1.5
Beam Divergence at 1/e ² Points (mm)	1.0	1.2	1.0	-	0.8	0.5
Cavity Length (m)	≈0.38	≈0.456	≈0.69	≈0.94	≈1.20	≈1.15
Coherence Length (m)	>0.1	>0.1	>0.1	>0.1	>1.0	>1.0
Stability After 1 Hour Warm Up	-	±3%	±5%	-	-	±0.5%

ESPI DIGITAL FRAME STORES

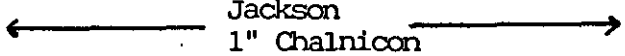
ESPI processing electronics, including the video frame store and electronic subtraction and processing units.

Vintens: 512 x 512 pixels x 4 bits using 16k DRAMs. On board crystal master clock driving the store and camera. Discrete component A/D, D/A converter. Modified version (LUT) - uses precision adder, improved high pass filter and A/D, D/A chip.

Pantak (EMI): 625 x 512 pixels x 5 bit. Timing for store derived from camera sync. 3.5 MHz low pass filter after subtraction. Uses discrete components in A/D, D/A converter.

FORA Type FM60: 512 x 512 pixels and 6 bit using 64k DRAMS. Timing for store derived from camera sync. Uses LSI chip in A/D, D/A converter.

ESPI SYSTEMS

TYPE	Vintens	Loughborough Demonstration Rig (Fig.5.1)	Breadboard System (Figs.2.7a, 3.13)	Vidispec (Fig.2.5)
Interferometer	Self- contained table	Self- contained table	Built on optical table	"Point and shoot". Separate table
Laser	5 mW HeNe	5mW HeNe	Any	10 mW HeNe
Camera	Standard vidicon			
Frame Store	Vintens	Modified Vintens	Pantak (EMI)	FORA
Comments	Discontinued	1981 Design	-	Available commercially (Sept 85)

VIDEO TAPE RECORDERS

Sony $\frac{1}{2}$ " Tape: Type AV 3670 and 3620.

Using $\frac{1}{2}$ " magnetic tape, reel-to-reel. Monochrome only.

Bandwidth $\approx$ 3.0 MHz.

Ampex 1" Tape: Type VR 7003.

Using 1" magnetic tape, reel-to-reel, colour and monochrome.

Bandwidth 3.5 MHz.

IMAGE PROCESSING

Texas 990 16 bit micro

Matrox digital frame store - 256 x 256 pixels x 8 bit

XY plotter - Hewlett Packard 7225A.

DEC PDP 11/03 16 bit micro

CVI digital frame store - 512 x 512 pixel x 6 bit.

"Intellect 100" - DEC LSI 11/23 16 bit micro

Digital frame store - 512 x 512 pixel x 8 bit

Integration - 256 x 256 x 16 bit

Complete image processing system.

DEC LSI 11/73 - 16 bit micro with 32 bit parallel processor.

Dedicated image processing system.

Digital frame store - 512 x 512 x 8 bit, 16 deep.

ELECTRONICS/ELECTRO-OPTICS

Low Pass Filters

Passive LC filters (7th order elliptic function), rapid roll off above cut-off frequency e.g. 0.5 MHz filter - reduces signal by 3 dB at 0.51 MHz and 45 dB at 0.63 MHz.

Pockels cell - Electro Optics Developments, type PC19

KD*P 45° Z cut crystal with transverse modulator, 6 mm aperture and a half wave voltage of 1.2 kV.

Linear amplifier - type LA10A.

Slide Projector - Zeiss Ikon "Compact Autofocus"

Tungsten halogen bulb, 150W.

Lens - f/2.8, 85 mm.

APPENDIX C

CALCULATION OF SPECKLE AND FRINGE CONTRAST

MEASUREMENT OF SPECKLE CONTRAST, C_S

The image is frozen in the CVI store and analysed with program FMOC (written by F. Mendoza-Santoyo and Paul Henry) on the DEC PDP 11/03 computer.

The intensity values, I_N of 1862 pixels from an area of approximately 50×40 pixels is sampled, and the mean value $\bar{I}$ calculated and the standard deviation, σ_I where:

$$\sigma_I = \sqrt{\frac{\sum_{1}^N (I_N - \bar{I})^2}{N}}$$

The speckle contrast is given by:

$$C_S = \frac{\sigma_I}{\bar{I}} = \frac{\text{Standard deviation of speckle intensities}}{\text{Mean value of speckle intensity}}$$

MEASUREMENT OF FRINGE CONTRAST, C_F

The image is frozen in the CVI store and analysed with program FM3C (written by F. Mendoza-Santoyo and Paul Henry) on the DEC PDP 11/03 computer.

A vertical array of 240 pixels from the centre of the image covering 7 to 9 fringes are sampled and smoothed over 20 smoothing cycles. This is sufficient to remove the speckle content of most fringe profiles. The levels of the maxima and minima are detected and the average values, $I_{\max}$ and $I_{\min}$ are calculated.

The fringe contrast is given by:

$$C_F = \frac{(I_{\max} - I_{\min})}{(I_{\max} + I_{\min})}$$

APPENDIX D THEORY FOR ESC

In this section the general theory for determining the contour spacing in the basic mode of ESC is considered as determined by Bergquist (Bergquist and Montgomery, 1985). The simple case of the contouring of a flat target is given.

General Case

Consider the arrangement in Figure D1. A stationary surface is illuminated with laser light with vector direction $\hat{K}_1$. The light scattered from the surface is imaged onto a camera faceplate with a lens having pole P. The line of sight direction $\hat{R}_{1m}$ is at an angle

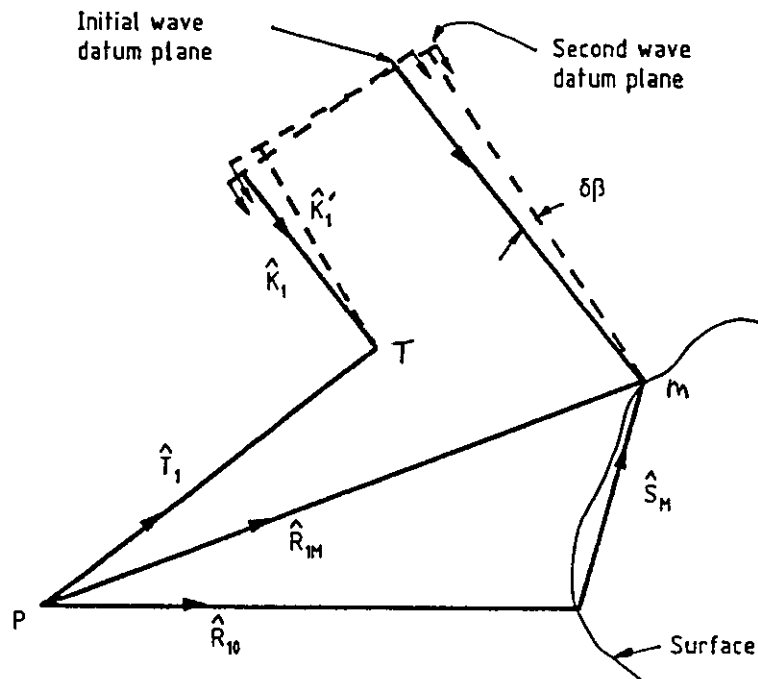


FIGURE D1: Vector Geometry for Basic Mode ESC

with the optical axis $\hat{R}_{10}$ within the paraxial and hence small angle limits. After storing a speckle pattern in the conventional manner, the illuminating wavefront is tilted through a small angle $\delta\beta$ to a new direction of $\hat{K}_1'$. The wavefront is rotated about point T defined by the position vector $t_1\hat{T}_1$ where t_1 is a scalar magnitude. $\hat{A}_1$ defines the direction of rotation. ESC fringes are formed on subtraction of the second speckle pattern from the first.

Consider the phase advance along the vector direction $\hat{R}_{1m}$ from the wave datum to the objective pole, P, via the m^{th} point on the object:

$$\phi_m = \frac{2\pi}{\lambda} [k_1 (\hat{K}_1 \cdot \hat{K}_1) + (r_m \hat{R}_{1m} - t_1 \hat{T}_1) \cdot \hat{K}_1 + r_m (\hat{R}_{1m} \cdot \hat{R}_{1m})] \quad (D1)$$

where k_1 is the scalar distance traversed by the wave to the general point T, r_m is the scalar distance of the line of sight direction $\hat{R}_{1m}$ and λ is the laser wavelength. Thus $(r_m \hat{R}_{1m} - t_1 \hat{T}_1) \cdot \hat{K}_1$ is the projection of the line joining T to the m^{th} point onto $\hat{K}_1$.

After rotation of the wavefront to $\hat{K}_1'$, the phase change, $\Delta\phi_m$ is

$$\Delta\phi_m = \frac{2\pi}{\lambda} [r_m \hat{R}_{1m} \cdot (\hat{K}_1 - \hat{K}_1') - t_1 \hat{T}_1 \cdot (\hat{K}_1' - \hat{K}_1)] \quad (D2)$$

Now,

$$|\hat{K}_1 - \hat{K}_1'| = |\hat{K}_1' - \hat{K}_1| = \delta\hat{K}_1$$

and for small $\delta\beta$:

$$\delta\hat{K}_1 = (\hat{A}_1 \times \hat{K}_1) \delta\beta \quad (D3)$$

Inserting these into equation D2:

$$\Delta\phi_m = \frac{2\pi}{\lambda} \delta\beta (r_m \hat{R}_1 - t_1 \hat{T}_1) \cdot \hat{A}_1 \times \hat{K}_1 \quad (D4)$$

As the line of sight vector $r_m \hat{R}_{1m}$ scans across the field of view, so the triple scalar product on the right hand side of equation D4 passes through integral multiples of $\lambda/\delta\beta$, giving dark correlation fringes on subtraction. If the incremental phase difference between the ℓ^{th} and m^{th} points is $\Delta\phi_{\ell m}$, then:

$$\Delta\phi_{\ell m} (\hat{R}_{1\ell}, \hat{R}_{1m}, \delta\beta) = \frac{2\pi}{\lambda} \delta\beta (r_m \hat{R}_{1m} - r_\ell \hat{R}_{1\ell}) \cdot \hat{A}_1 \times \hat{K}_1 \quad (D5)$$

This result is independent of the position of the axis of rotation. Moreover, the factor $(r_m \hat{R}_{1m} - r_\ell \hat{R}_{1\ell})$ is the relative position vector between the two points ℓ and m . Equation D5 indicates then, that $\phi_{\ell m}$ determines the distance between these points in terms of the contour interval $\lambda/\delta\beta$, as projected onto the common normal to $\hat{A}_1$ and $\hat{K}_1$. This is precisely the form of contouring described by Brookes and Heflinger (1969), with the rotation angle $\delta\beta$ replacing the angle between two simultaneously incident wavefronts.

If the axis of rotation is tangential to the surface at some point, then a dark reference fringe is formed on rotation. Choosing this point to be on the optical axis, at $r_0 \hat{R}_{10}$, say, then $t_1 \hat{T}_1 = r_0 \hat{R}_{10}$ and:

$$\Delta\phi_m = \frac{2\pi}{\lambda} \delta\beta (\hat{S}_m \cdot \hat{A}_1 \times \hat{K}_1) \quad (D6)$$

where $\hat{S}_m$ is the surface position vector relative to $r_0 \hat{R}_{10}$.

Contouring of a Flat Plate

The diagram in Figure D2 shows a simplified case for the contouring of a flat target positioned at an angle of γ to the optical axis.

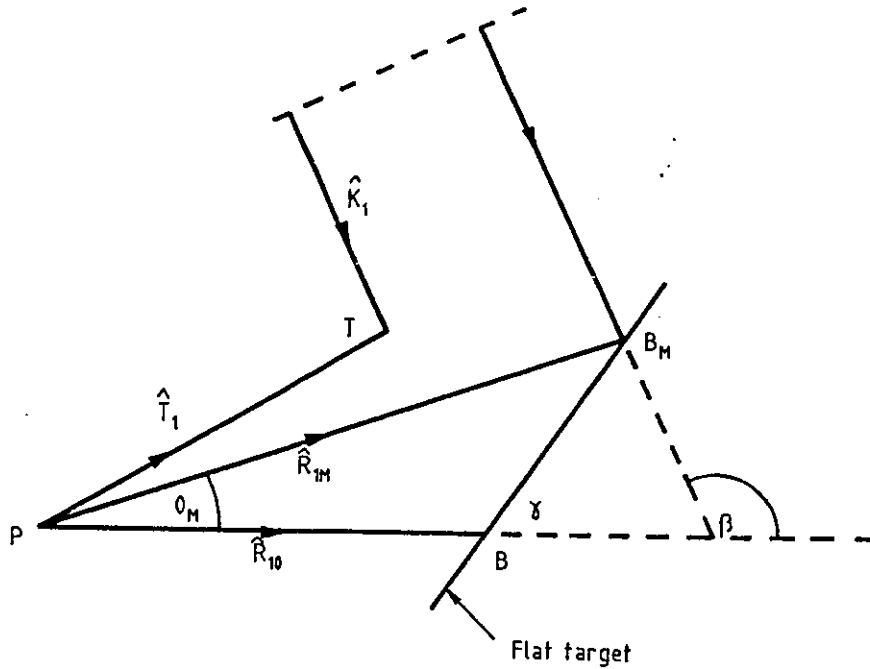


FIGURE D2: Contouring of a flat plate in basic mode ESC

With the illumination direction at angle β , and fringe m on the target subtending an angle of θ_m , the unit vectors are:

$$\hat{R}_{1m} = (\cos\theta_m, 0, \sin\theta_m) \quad \hat{R}_{10} = (1, 0, 0)$$

$$\hat{T}_1 = (\cos\theta_T, 0, \sin\theta_T) \quad \hat{A}_1 = (0, 1, 0)$$

$$\hat{K}_1 = (\cos\beta, 0, \sin\beta) \quad \hat{K}_1' = (\cos(\beta + \delta\beta), 0, \sin(\beta + \delta\beta))$$

Now,

$$\hat{A}_1 \times \hat{K}_1 = (\sin\beta, 0, -\cos\beta)$$

and

$$\hat{S}_m \cdot (\hat{A}_1 \times \hat{K}_1) = (r_m \cos \theta_m - r_0) \sin \beta - r_m \sin \theta_m \cos \beta$$

Inserting this into equation D6:

$$\Delta \phi_m = \frac{2\pi}{\lambda} \delta \beta [r_m \cos \theta_m \sin \beta - r_0 \sin \beta - r_m \sin \theta_m \cos \beta]$$

From the geometry of Figure D2:

$$r_m = \frac{r_0 \sin \gamma}{\sin (\gamma - \theta_m)}$$

which leads to:

$$\begin{aligned} \Delta \phi_m = \frac{2\pi \delta \beta r_0}{\lambda \sin (\gamma - \theta_m)} & [\sin \gamma \cos \theta_m \sin \beta - \sin (\gamma - \theta_m) \sin \beta \\ & - \sin \gamma \sin \theta_m \cos \beta] \end{aligned}$$

This simplifies to:

$$\Delta \phi_m = \frac{2\pi \delta \beta r_0}{\lambda \sin (\gamma - \theta_m)} \sin \theta_m \sin (\beta - \gamma) \quad (D7)$$

From equation 1.4 in Chapter 1, the fringe function $\sin^2 \frac{\Delta \phi}{2}$ is a maximum for $\frac{\Delta \phi}{2} = \frac{\pi}{2}, \frac{3\pi}{2}$ etc

i.e.

$$\frac{\Delta\phi}{2} = \frac{1}{2} (2m-1)\pi$$

Therefore the spacing of ESC fringes on a flat target is given by:

$$\frac{2\pi \delta\beta r_o}{\lambda \sin(\gamma - \theta_m)} \sin\theta_m \sin(\beta - \gamma) = \frac{2m-1}{2} \quad (D8)$$

with m the integral fringe number.

APPENDIX E

PUBLICATIONS

List of publications, solely or jointly by the author, arising from work presented in this thesis:

1. MONTGOMERY, P.C. and TYRER, J.
"The Use of Electronic Speckle Pattern Interferometry (ESPI) as an Inspection Tool". Proc. 2nd Int. Conf. on Lasers in Manufacturing, 26-28 March 1985, (Birmingham, UK), pp 141-150.
2. MONTGOMERY, P.C.
"Smoothing of Speckle Fringes by Real Time Video Signal Processing". Presented at "Holopro 85" (Belfort, France), 20-21 June 1985.
3. DAVIES, J.C., MONTGOMERY, P.C. and TYRER, J.R.
"The Application of Electronic Speckle Pattern Interferometry to Modal Analysis". Proc. Int. Symp. on Automotive Technology and Automation, 23-27 Sept. 1985 (Graz, Austria), pp 73-92.
4. MONTGOMERY, P.C. and BERGQUIST, B.D.
"Contrast Enhancement of ESPI Vibration Patterns by Speckle Averaging in a Video Frame Store". SPIE Proc. Vol. No. 599, pp 201-206, (Cannes, France), 2-6 Dec. 1985.
5. BERGQUIST, B.D. and MONTGOMERY, P.C.
"Contouring by Electronic Speckle Pattern Interferometry (ESPI)". SPIE Proc. Vol. No. 599, pp 189-195 (Cannes, France), 1985.
6. MONTGOMERY, P.C., BERGQUIST, B.D. and HENRY, P.
"Contouring by Electronic Speckle Pattern Interferometry (ESPI): the Problem of Fringe Enhancement". To be published in Proc. of Electro-Optics/Laser International '86 UK, 18-20 March 1986 (Brighton, UK).

7. BERGQUIST, B.D., MONTGOMERY, P.C. MENDOZA-SANTOYO, F., HENRY, P. and TYRER, J.R.

"The Present Status of Electronic Speckle Pattern Interferometry (ESPI) with Respect to Automatic Inspection and Measurement".

To be published in SPIE Proc. of Automatic Optical Inspection, 14-18 April 1986 (Innsbruck, Austria).

