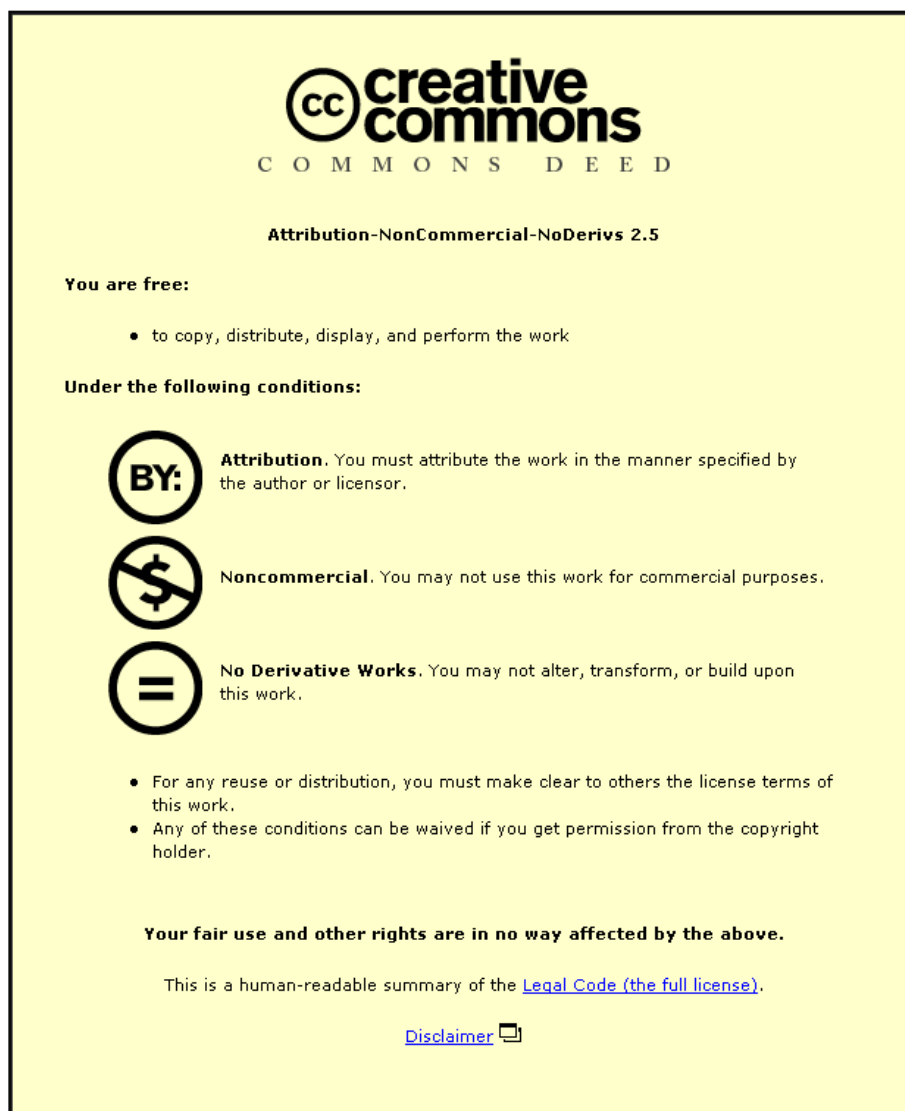


This item was submitted to Loughborough University as a PhD thesis by the author and is made available in the Institutional Repository (<https://dspace.lboro.ac.uk/>) under the following Creative Commons Licence conditions.



For the full text of this licence, please go to:
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

Dx 234 957



Pilkington Library

Author/Filing Title *HARLAND*

Vol. No. Class Mark *T*

**Please note that fines are charged on ALL
overdue items.**

FOR REFERENCE ONLY

0402696433



BRITISH THESIS SERVICE

Dxno 3576.

DX234957

Awarding Body : Loughborough

Thesis By : HARLAND Andrew R.

**Thesis Title : THE APPLICATION OF LASER DOPPLER
VELOCIMETRY TO THE MEASUREMENT OF
UNDERWATER ACOUSTIC PRESSURE FIELDS**

We have assigned this thesis the number given at the top of this sheet.

**THE BRITISH LIBRARY
DOCUMENT SUPPLY CENTRE**

The Application of Laser Doppler Velocimetry to the Measurement of Underwater Acoustic Pressure Fields

by

Andrew R. Harland

Submitted in partial fulfilment of the requirements
for the award of

Doctor of Philosophy

18 November 2002

[Loughborough]

© by Andrew R. Harland 2002

 Loughborough University Reading Library
Date <i>Dec 03</i>
Class
Acc No <i>060269643</i>

Acknowledgements

Firstly, I would like to record my grateful thanks to both of my supervisors, Dr. Jon Petzing and Dr. John Tyrer for providing me with the opportunity to undertake this research. Specifically, I would like to offer my sincere thanks to Dr. Petzing for his invaluable support and enthusiasm throughout the duration of this work. His ideas for experimentation and confidence in my work have inspired me in my studies. I would also like to record my thanks to Dr. Tyrer for providing me with direction and sharing his vision for the research.

Grateful thanks are given to the National Physical Laboratory for their funding of the studentship by which the work described here was completed. Particular acknowledgement is given to Mr. Stephen Robinson for sharing his considerable knowledge of underwater acoustics, which has enabled me to develop an understanding, which would otherwise have been difficult to gain. Additional thanks are given to Dr. Roy Preston for his direction and support and to Dr. Trevor Esward, Miss Catherine Bickley and Mr Justin Ablitt for their assistance.

Acknowledgment is given to Roger Traynor of Lambda Photometrics for the generous loan of the Polytec Scanning Vibrometer and continued support throughout the project.

I would also like to offer my thanks to Dr. Steve Rothberg for sharing his extensive knowledge of laser Doppler velocimetry and Prof. Roy Jones for allowing me the flexibility in my current employment to complete this thesis.

Finally I would like to thank my wife, Lynn, for her amazing support and patience over a length of time that no doubt feels longer than it actually was!

Abstract

Underwater acoustic pressure fields are widely employed by the medical and marine communities in a variety of applications. Ranging from communication through pulse echo and other diagnostic techniques to methods of inducing cavitation in the case of shock-wave lithotripsy, acoustic fields vary considerably in frequency, magnitude, duration and linearity. The conventional instrument for recording measurements from within an acoustic field is the hydrophone, which provides a measurement of the pressure variation at a point within the field. Hydrophones are restricted in that they only provide a measurement at a single point and whilst it is possible to establish arrays of multiple devices, these are expensive and additionally perturbing.

This work successfully demonstrates the ability of the beam from a Laser Doppler Velocimeter (LDV) to record quantifiable measurements from an acoustic field in a non-perturbing manner. The theoretical interaction of an LDV beam with an acoustic field is discussed and supporting experimental evidence is presented. The technique is developed by the application of a scanning LDV system, which takes repeated measurements from an array of predetermined positions in two dimensions. This facilitates the whole field mapping of a range of characteristics from an acoustic field, both theoretically and experimentally. Experimental results are also presented enabling the influence of impeding obstacles within the field to be observed.

It is concluded that the novel application of Laser Doppler Velocimetry for underwater acoustic measurement described in this thesis represents a significant development. It is anticipated that this work will be of interest to a wide-ranging audience including the acoustic calibration community, transducer manufacturers and clinical users. Recommendations are made for additional work, which would enable further refinement and development of the technique.

Contents

ACKNOWLEDGEMENTS	III
ABSTRACT.....	IV
CONTENTS	V
GLOSSARY OF TERMS.....	X
ACRONYMS AND CONVENTIONS	XIII
CHAPTER 1 INTRODUCTION TO UNDERWATER ACOUSTICS.....	1
1.1 INTRODUCTION	1
1.1.1 Philosophical Grounding.....	2
1.2 HISTORY	4
1.2.1 Marine Applications	5
1.2.2 Medical Ultrasound.....	7
1.2.2.1 Diagnostic Ultrasound Imaging.....	8
1.2.2.2 Doppler Ultrasound.....	9
1.2.2.3 Physiotherapy Equipment.....	10
1.2.2.4 Lithotripsy Equipment.....	10
1.3 PHYSICAL THEORY OF ACOUSTICS AND ACOUSTIC INTERACTION	11
1.3.1 Generation of Underwater Acoustic Pressure Waves	11
1.3.1.1 Quality Factor.....	12
1.3.2 Propagation of Underwater Acoustic Waves.....	13
1.3.2.1 Speed of Sound in water.....	15
1.3.2.2 Boundary Considerations	17
1.3.3 Detection of Underwater Acoustic Pressure Waves.....	19
1.3.3.1 Decibels	21
1.4 CLOSURE: IDENTIFICATION OF RESEARCH NEED	22

CHAPTER 2 LITERATURE REVIEW	24
2.1 INTRODUCTION	24
2.2 UNDERWATER ACOUSTIC MEASUREMENTS	26
2.2.1 <i>Measurements of Acoustic Scattering</i>	28
2.3 UNDERWATER ACOUSTIC CALIBRATION TECHNIQUES	29
2.3.1 <i>Three Transducer Spherical Wave Reciprocity</i>	29
2.3.2 <i>NPL Laser Interferometer</i>	30
2.4 APPLICATION OF OPTICAL METROLOGY TECHNIQUES TO UNDERWATER ACOUSTIC MEASUREMENT	34
2.4.1 <i>Diffraction and Schlieren Methods</i>	34
2.4.2 <i>Electronic Speckle Pattern Interferometry</i>	37
2.4.3 <i>Other Interferometry</i>	38
2.4.4 <i>Particle Image Velocimetry</i>	41
2.4.5 <i>Laser Doppler Anemometry</i>	42
2.4.6 <i>Laser Doppler Velocimetry</i>	46
2.5 CLOSURE	49
 CHAPTER 3 CHARACTERISATION OF EQUIPMENT	51
3.1 INTRODUCTION	51
3.2 ELECTRICAL SIGNAL GENERATION.....	52
3.3 UNDERWATER ACOUSTIC SOURCE TRANSDUCERS	53
3.3.1 <i>Characterisation of Underwater Acoustic Source Transducers</i>	53
3.3.1.1 <i>Piezo Electric Sounder</i>	53
3.3.1.2 <i>Met-Optic Plane Piston Transducer</i>	55
3.3.1.3 <i>Panametrics Immersion Transducers</i>	55
3.4 UNDERWATER ACOUSTIC MEASUREMENT TRANSDUCERS.....	57
3.4.1 <i>Characterisation of Underwater Acoustic Measurement Transducers</i>	57
3.4.1.1 <i>25.4 mm diameter ball hydrophone</i>	57
3.4.1.2 <i>ITC 6128 Probe Hydrophone</i>	59
3.5 DATA ACQUISITION	61
3.6 OPTICAL MEASUREMENT METHODS.....	62
3.6.1 <i>Laser Doppler Velocimetry</i>	62
3.6.1.1 <i>Characterisation of Polytec Standard Optic Vibrometer</i>	62

3.6.1.2 <i>Characterisation of Polytec Scanning Vibrometer</i>	65
3.6.1.3 <i>Calibration of Polytec Vibrometers</i>	65
3.6.2 <i>NPL Laser Interferometer</i>	68
3.6.2.1 <i>Comparison of LDV with NPL Laser Interferometer</i>	68
3.6.2.2 <i>PVDF Pellicle</i>	72
3.7 CLOSURE	77
CHAPTER 4 NON-PERTURBING LASER DOPPLER VELOCIMETRY	
MEASUREMENTS FROM UNDERWATER ACOUSTIC FIELDS IN ONE-	
DIMENSION	78
4.1 INTRODUCTION	78
4.2 THEORETICAL ANALYSIS	80
4.2.1 <i>Piezo-Optic Coefficient</i>	80
4.2.2 <i>Laser Doppler Velocimetry</i>	81
4.2.3 <i>Theoretical Analysis of LDV laser beam passage through an underwater acoustic field</i>	82
4.3 EXPERIMENTAL METHODOLOGY.....	87
4.3.1 <i>Acoustic Standing-wave</i>	93
4.3.2 <i>Acoustic Tone-Burst</i>	98
4.3.2.1 <i>Measurements from an 80 kHz Acoustic Tone-Burst</i>	102
4.3.2.2 <i>Calibration of a Line Section through an 80 kHz Acoustic Tone-Burst</i>	107
4.3.2.3 <i>Calibration of a line-section through a 500 kHz Acoustic Tone-Burst</i>	113
4.3.3 <i>Calculation of Minimum Sensitivity</i>	121
4.3.3.1 <i>Noise Floor</i>	121
4.3.3.2 <i>Minimum Resolvable Signal</i>	122
4.3.3.3 <i>Comparison of Minimum Resolvable signal from Ball Hydrophone and OFV-302 / OFV-3000 LDV</i>	123
4.3.3.4 <i>Comparison of Minimum Resolvable signal from the ITC 6128 Hydrophone and OFV-056 / OFV-3001-S LDV</i>	128
4.4 CLOSURE	133

CHAPTER 5 LDV MEASUREMENTS OF SPATIALLY DISTRIBUTED UNDERWATER ACOUSTIC FIELDS IN TWO-DIMENSIONS	135
5.1 INTRODUCTION	135
5.2 THEORETICAL METHODOLOGY	136
5.2.1 <i>Application of a Polytec Scanning LDV</i>	136
5.2.2 <i>Theoretical Analysis of Scanning LDV laser beam passage through an underwater acoustic field.....</i>	139
5.3 EXPERIMENTATION METHODOLOGY	145
5.3.1 <i>Experimental Arrangement.....</i>	145
5.3.2 <i>PSV 200 Software</i>	145
5.3.2.1 <i>Cosine Compensation for Laser Scanning Angle</i>	148
5.3.2.2 <i>Windowing.....</i>	148
5.3.2.3 <i>Universal File Format</i>	149
5.3.3 <i>Generation of Colour Scaled Images.....</i>	153
5.3.3.1 <i>Image Interpolation</i>	155
5.3.4 <i>Formation of Images from Rate of Change of Optical Path Length Data</i>	155
5.3.4.1 <i>Magnitude and Power Images</i>	157
5.3.4.2 <i>Phase Distribution Images.....</i>	161
5.3.4.3 <i>Combined Magnitude and Phase Images</i>	164
5.3.4.4 <i>Time Resolved Images</i>	166
5.4 CLOSURE	172
CHAPTER 6 EXPERIMENTAL RESULTS	174
6.1 INTRODUCTION	174
6.2 MATHEMATICAL SIMULATION OF LDV INTERROGATION OF AN ACOUSTIC FIELD	175
6.2.1 <i>Field from a Focused Acoustic Source</i>	176
6.2.2 <i>Field from a Plane Piston Source.....</i>	181
6.3 LDV MEASUREMENT SCAN.....	186
6.3.1 <i>Field from a Focused Source.....</i>	186
6.3.2 <i>Field from a Plane Piston Source.....</i>	190
6.4 CLOSURE	194

CHAPTER 7 SCATTERED FIELDS	195
7.1 INTRODUCTION	195
7.2 INTERROGATION OF REFLECTIONS FROM INTERFACES	196
7.3 ANALYSIS OF FIELDS IMPEDED BY OBSTACLES	198
7.3.1 LDV Measurements from fields including a hydrophone	198
7.3.2 LDV Measurements from fields including a pellicle	204
7.3.3 LDV Measurements from fields including rigid body obstacles.....	208
7.3.3.1 Ball Bearing.....	208
7.3.3.2 Steel Bar of 3 mm diameter.....	215
7.3.3.3 Steel Bar of 9 mm diameter.....	220
7.3.3.4 Steel Bar of 15 mm diameter.....	224
7.3.3.5 Hollow Aluminium Tube of 12 mm diameter.....	228
7.4 CLOSURE	233
CHAPTER 8 CONCLUSIONS.....	235
CHAPTER 9 FURTHER WORK.....	240
9.1 RECOMMENDATIONS FOR FUTURE DEVELOPMENT OF UNDERWATER ACOUSTIC LDV MEASUREMENT METHODS	241
9.2 TOMOGRAPHIC DERIVATION OF SINGLE POINT PRESSURE DATA FROM LDV MEASUREMENTS.....	242
CHAPTER 10 REFERENCES	247
APPENDIX A.....	261

Glossary of Terms

ψ	number of standard deviations from mean
ξ	acoustic displacement
α	image reconstruction phase angle
β	phase of rate of change of optical path length
ϕ	angle in x - y plane
θ	angle in y - z plane
ρ	density of media
η	number of divisions along laser line within interactive region
λ	optical wavelength
Φ	phase of acoustic excitation
μ	population mean
σ	standard deviation of a population
Φ_0	initial phase of acoustic wave
φ_T	phase of light
ω_v	angular frequency of change in optical path length
δx	scan spacing in x
δy	scan spacing in y
A	amplitude of pressure variation
A_0	maximum amplitude of pressure variation
A_{LDV}	amplitude of LDV signal
a_v	amplitude of change in optical path length
c	speed of sound in media
d_a	distance of laser source from acoustic source
d_f	distance to far field
e	output voltage from transducer
E_T	amplitude of light
F	focal length of acoustic source
f	frequency of acoustic excitation
I	acoustic intensity

I_T	optical target beam intensity
I_R	optical reference beam intensity
i	input current to transducer
$\mathbf{i}$	unit vector in x-axis
$I.L.$	acoustic intensity level
I_R	optical reference beam intensity
I_T	optical target beam intensity
$\mathbf{j}$	unit vector in y-axis
j	$\sqrt{-1}$
$\mathbf{k}$	unit vector in z-axis
K	sensitivity scalar of LDV electronics
l	optical path length
l_0	ambient optical path length
N	number of cycles
M	magnitude of the amplitude of rate of change of optical path length
N	number of terms within a population
n	refractive index
n_0	ambient refractive index
P	acoustic power
p	pressure
$\mathbf{p}$	probability
Q	quality factor
Q	instantaneous value of reconstructed rate of change of optical path length
r	radius of acoustic field
r_0	radius of acoustic source
r_{cas}	outer radius of acoustic source
s	distance along laser beam
$\mathbf{s}$	vector representing interactive region of laser beam within the acoustic field
$S.L.$	source level
$S.P.L.$	sound pressure level
t	time
T	water temperature
V	voltage output from LDV

w	width of tank
X	range of scan in x
x_0	distance of laser source from acoustic source in x -axis
x_n	value of the n th term within a population
Y	range of scan in y
Z	acoustic impedance

Acronyms and Conventions

DFT	Discrete Fourier Transform
DTI	Department of Trade and Industry
ESPI	Electronic Speckle Pattern Interferometry
FFT	Fast Fourier Transform
ITC	International Transducer Corporation
LDV	Laser Doppler Velocimetry
LDA	Laser Doppler Anemometry
LI	Laser Interferometer
NPL	National Physical Laboratory
PVDF	polyvinylidene fluoride
PZT	Lead Zirconate Titanate
SONAR	SOund NAVigation and Ranging
UNESCO	United Nations Educational Scientific and Cultural Organization
USRL	Underwater Sound Reference Laboratories

Throughout this work, the term 'log' is used to represent logarithm to the base 10 ($\log_{10}$). Additionally, when referring to images generated from measured data, the terms power and phase refer to the component of the power spectrum and the phase derived at the fundamental frequency of the measurement.

As a general rule, the trace colours on the graphs are coloured such that laser based measurements are shown in red and other measurements are shown in blue.

Chapter 1

Introduction to Underwater Acoustics

This thesis is concerned with the development of the theory and application of a novel, non-perturbing Laser Doppler Velocimetry based technique for the measurement and visualisation of underwater acoustic pressure fields. The technique is demonstrated to be effective in recording measurements from a single line section through a field in Chapter 4 and from a spatially distributed field in Chapter 5 and Chapter 6. Accompanying mathematical theory is developed alongside the experimental results. The technique is shown to benefit from excellent spatial resolution and an ability to independently identify reflected or scattered acoustic components. This is exploited in the measurements made of acoustic scattering in Chapter 7. The preliminary chapters provide the historical and theoretical background and context for the work.

1.1 INTRODUCTION

This chapter provides a brief overview of the historical developments in the general understanding of underwater acoustics. The discussion begins with the early recordings of da Vinci and includes the studies of Newton and Rayleigh, who developed mathematical models and theories to describe underwater acoustic wave propagation. The evolution of acoustic measurement is also discussed, beginning with the initial studies of Colladon and Sturm.

A brief résumé of the discovery of piezo-electric materials is given, which enabled underwater acoustic transduction and the development of early projectors and hydrophones. The development of underwater acoustic technologies for the benefit of the marine community is described, including the advent of the first calibration procedures during the early years of World War II.

Most attention within this chapter is focused on the advances of acoustics within medicine. The development of four major medical procedures is detailed: Ultrasonic imaging, Doppler ultrasound, ultrasound physiotherapy and lithotripsy. Many researchers have made significant contributions in establishing these procedures as regulation practices in contemporary medicine.

An overview of the development of the mathematics required to define and describe underwater acoustic propagation is presented. This will form the basis for the development of further mathematical models later in this thesis.

1.1.1 Philosophical Grounding

This thesis engages in the theoretical and experimental investigation of underwater acoustic pressure measurement. The results of experimental studies are presented as variables within the context of the conventional mathematical models, originating from the early studies of Newton, Rayleigh and others. However, the absoluteness of such mathematical descriptions has been the subject of much debate.

Realism and instrumentalism are two opposing extreme philosophical positions used to justify scientific theory. On the one hand, the traditional view of the realist suggests that the conventional mathematical or scientific description of an event, process or phenomenon evolved over many years, represents a true and exact description of that occurrence. Such theories have their origins in the reasoning of Pythagoras, who upheld that numbers were reality itself. In contrast, the more contemporary view held by the instrumentalist suggests that a mathematical or scientific explanation or model proposed to support a theory can only be considered valid when used to predict events or explain experimental data. Their truth does not lie in their absolute description of the event or phenomena.

In philosophical terms, acoustic phenomena cannot be accurately observed, that is to say it cannot be perceived directly by any of the human senses in any detail. The aim of this work is to develop a measurement method enabling observations to be made representative of acoustic pressure. However, the continuous, 4-dimensional nature of acoustic pressure waves determines that measurements can only be made on the

macroscopic and not microscopic. Therefore, whilst the mathematical models developed to represent underwater acoustic propagation may approach reality, deductions made from measurements of acoustic parameters through an unobservable molecular structure remain an instrumentalist science.

My personal belief is that neither of these arguments alone fully describes the precise nature of underwater acoustics. Instead, a position part way between the two extremes of realism and instrumentalism is held. Whilst the discussions and measurements presented in this work may not represent the absolute truth, they assist understanding and enable predictions to be made. They are therefore considered worthwhile.

1.2 HISTORY

The earliest recorded reference to underwater acoustics was made towards the end of the fifteenth century by Leonardo da Vinci, who wrote:

"If you cause your ship to stop, and place the head of a long tube in the water and place the outer extremity to your ear, you will hear ships at a great distance from you" [1]

Whilst it is unlikely that da Vinci fully understood the precise mechanisms by which this phenomenon occurred, he was able to describe the propagation of sound through water, remarking how sound could be transmitted over great distances. This observation identified the fundamental principle of underwater acoustic propagation, which forms the basis of a wide range of contemporary medical, marine and communication applications. Significantly, da Vinci also highlighted a desire to eliminate noise and consequently described a method of achieving this by stopping his own ship. Indeed the corruption of an acoustic signal through undesirable interference with a source of noise remains a major concern in all underwater acoustic applications to this day.

In 1687, Newton published the first mathematical theory of sound propagation [2], but the first underwater acoustic measurements were not made until 1827 when Colladon and Sturm measured the speed of sound in water [3]. Their experiments, undertaken at Lake Geneva, involved detecting the arrival of the sound from a submerged bell using a long tube, similar to that suggested by da Vinci. By initiating their timing using a flash light at the moment the bell was struck, they were able to measure the speed of sound in water at 1.8 °C to be 1435 m/s. This result is within 3 m/s of the value accepted today, which can be calculated using a formula such as that derived by Coppens [4], which will be discussed in more detail in Section 1.3.2.1.

The origins of contemporary acoustics are often traced to the seminal works published by Lord Rayleigh in 1877 and 1888 [5,6]. Rayleigh was the first to describe a sound wave as a mathematical equation and to consider the wavelength dependent reflection and scattering of acoustic waves. Importantly this principle

applies also to the behaviour of sound waves in water. Although his works were largely concerned with sound in air, reference was made to propagation in water and the studies of Colladon and Sturm.

Around this time, attention was given to the conversion of electrical energy into sound or vice-versa; a phenomenon known as transduction. Jacques and Pierre Curie are credited with the discovery of the first piezo-electric transducer when they reported the ability of certain crystals to develop an electric charge between opposite faces when stressed [7]. This followed the discovery of a similar principle, magnetostriction, by James Joule in 1847 [8,9], where a change in physical dimension can be observed in magnetised substances such as iron, nickel, cobalt, manganese and their alloys. Similar to the piezo-electric effect, this change was found to be reversible by Villari in 1864 [10]. Piezo-electric and magnetostrictive materials were to form the basis for the invention of the telephone. However, at the time the carbon button microphone, for which a patent was issued to Edison in 1878, was the most prevalent underwater acoustic transducer. The principle of operation of the carbon button microphone is one where the contact resistance between a conductive membrane and a packet of carbon granules is caused to change by the presence of a sound wave [11]. This remains one of the most sensitive acoustic measurement devices to this day.

1.2.1 Marine Applications

One of the first applications of underwater acoustics was the submarine bell, introduced around the turn of the 20th century to assist offshore navigation. This system utilised the simultaneous sounding of a submerged and an airborne sound source from which a ship could determine its distance from the coastline.

This was followed by echo-sounding, a technique suggested soon after the Titanic disaster in 1912 by Richardson [12]. His theory of measuring the reflected component of a transmitted underwater acoustic signal was successfully implemented by Fessenden in 1914, who was able to detect the presence of an iceberg. During World War I, Langevin and Chilowsky [13] developed the technique of echo-sounding such that military craft were able to detect the presence of

submarines and other submerged objects. The transducer used by Langevin was a composite of thin quartz crystals glued between two steel plates, encased in a submersible housing. It had a resonant frequency of about 150 kHz. A joint patent was subsequently issued in 1920 for this device called a 'hydrophone'.

In the years that followed World War I, the rate of progress within underwater acoustics slowed considerably, although the depth sounding techniques developed for military purposes found service in a commercial device known as a fathometer. Interest and activity in the area of underwater acoustic measurement remained sparse, and although a few scientists, notably Smith [14] and Klein [15], each suggested underwater acoustic measurement methods, the potential for application of their techniques outside of a laboratory environment was limited.

As with many branches of science, significant advances in underwater acoustic measurement techniques were not made until a suitable application was found to sustain the basis for funding and development. The catalyst for development proved to be the outbreak of World War II and the subsequent need to develop underwater communication systems between naval craft. In 1941, prior to the United States participation in the war, despite a large number of US war ships being equipped for both underwater listening and echo-ranging, capability for the calibration of underwater acoustic transducers was negligible. Intense activity then followed to address this issue, with the Office of Scientific Research and Development entering into partnership with first the Bell Telephone Laboratory in July 1941, and later, the Columbia University Division of War Research in March 1942 to establish the Underwater Sound Reference Laboratories (USRL).

The principle of reciprocity as a means of calibrating electroacoustic transducers was independently devised by MacLean [16] and Cook [17] in 1940 and 1941 respectively. The concept was studied by USRL and found to be an accurate and reliable technique for evaluating and developing sonar transducers. This principle of reciprocity remains prevalent within acoustic calibration to this day [18,19]. Incidentally, it was during World War II that the name given to this branch of underwater acoustics, Sonar (SOund NAvigation and Ranging), became widely used.

In the immediate post-war era, research resumed at many of the naval laboratories established during the war aimed at improving underwater acoustic transducers and measurement methods. The discovery of the piezo-electric properties of some ceramics at this time led to the development of electroacoustic transducers with significantly improved performance. Other advances in the design of piezo-electric and magnetostrictive transducers followed, which resulted in the devices becoming cheaper and more commonplace. Improvements were also made both in their working frequency range and the accuracy of their output measurements.

1.2.2 Medical Ultrasound

The advances in electrical technology of the early 1950s engendered transducers capable of working at elevated frequencies with shorter pulse durations. This facilitated measurements of improved resolution to be made, which opened up a more varied and diverse range of applications. One of the most significant developments within acoustics upon which early medical experimentation was based was that originally suggested by Sokolov in 1928 [20]. Using a pulsed-echo ultrasonic system, the author reported a metal flaw detector capable of checking the integrity of metal hulls of large ships.

Whilst flaw detection and similar naval applications remained a significant avenue with considerable investment and development, the early experiments of Dussik represented a radical departure from convention [21]. Translations suggest that by utilising ultrasonic frequencies generated by a transducer at one side of the head, his aim was to detect tumours and intracranial lesions, using a second transducer on the opposite side. Although Dussik was able to visualize the brain, the procedure was unsuccessful since it produced artefacts that interfered with the image. This did, however, represent the birth of medical ultrasound as an imaging technique.

The treatment of medical ultrasound as a branch of underwater acoustics originates from the similarities between the properties of human tissue and water, presented in Table 1.2.1. These, together with the low cost and convenient availability of water make it an ideal substitute for laboratory based experimentation.

Material	Density ρ (kg m ⁻³)	Sound Speed c (m s ⁻¹)	Acoustic Impedance Z (kg m ⁻² s ⁻¹)
Water	1000	1500	1.5×10^6
Kidney, Liver, Muscle, Blood	1050	1580	1.65×10^6
Fat	920	1430	1.3×10^6
Whole Bone	1500	3300	5.0×10^6

Table 1.2.1: Physical properties of water and human tissue

1.2.2.1 Diagnostic Ultrasound Imaging

In the years that followed, many other researchers were influential in the development of ultrasonic imaging as a safe and viable medical procedure. These include Wild, Neal, French and Reid, who between them published work describing a method for the detection of changes in the texture of biological tissue [23,24], and a study on cerebral tumour detection in cadaveric human brains [25]. Additionally documented work included a study on the use of pulsed ultrasonic acoustic signals to obtain a two-dimensional record of tissue structure of the human stomach, breast and brain [26,27], and an overview of the application of ultrasonic imaging techniques including a comparison of echo-patterns from malignant and non-malignant tumours [28].

Further advances were made by Donald who together with Brown and MacVicar investigated the relative merits of ultrasound as a means of differentiating between cysts, fibroids and other intra-abdominal tumours. Using an almost identical procedure to that used in the metal flaw detection suggested by Sokolov [20], they were able to monitor and identify the scattering from impedance boundaries within the human body in a non-invasive manner. Their persistence with the technique in the face of significant cynicism led directly to what is arguably the most significant publication on diagnostic medical ultrasound in 1958 [29]. In it, the case of a patient

who had been misdiagnosed with an inoperable cancer was described. The ultrasound revealed the growth to be an easily removable ovarian cyst and the patient's life was duly saved.

Another significant area of medicine to which Donald applied his diagnostic ultrasound technique was that of foetal imaging after it became evident that clear echoes could be obtained from the foetal head. Nowadays, foetal imaging represents one of the most prevalent applications within medical ultrasound.

1.2.2.2 Doppler Ultrasound

During the 1950s, extensive, but at the time relatively unknown, research was undertaken in Japan, simultaneous to and in some instances predating that reported in Europe and the United States. Arguably the most significant development to emanate from Japan during this period was that of Doppler ultrasound. First published by Satomura in 1955, the technique involved utilising the Doppler frequency shift induced in an ultrasonic wave by reflection from a moving target. His work described a method of recording the Doppler signal induced by heart movements [30].

This initial work was developed by McLeod [31], who overcame the directional ambiguity present in Satomura's original system and Wells [32] and Baker [33] who used pulsed ultrasonic signals to enable measurement of tissue depth. Computer technology was then harnessed, which enabled Maslak to develop software controlled image formation techniques. He was issued with a patent for this "acoustic imaging apparatus" in 1979 [34]. This combination has led to the development of modern Doppler ultrasound equipment.

Today, Doppler ultrasound is utilised in a range of cardiovascular and peripheral vascular applications as well as foetal monitoring [35]. The ultrasound is generated either in pulses, typically between 300 ns and 10 μ s in duration, or continuous wave. Frequencies of the order of 2 to 10 MHz are used with acoustic pressures in the range 1 to 5 MPa [35].

1.2.2.3 Physiotherapy Equipment

Another significant application of medical ultrasound is that of rehabilitating physical therapy. The destructive properties of ultrasound were first recognised in the 1920s by Langevin when he noted the pain induced in his hand when submerged within a high intensity underwater acoustic field, but it was not until the 1940s that ultrasound was used as a physical therapy. The first application of ultrasound in the therapeutic treatment of patients suffering from rheumatic arthritis was reported by Gersten in 1953 and although complete understanding of the principle of operation remains unclear, it is based at least in part on tissue heating [35]. Another significant mechanism involved in therapeutic ultrasound is that of cavitation induced by non-linear acoustic propagation, a phenomenon that is difficult to measure and control [36]. Modern physiotherapy equipment can be expected to emit continuous or long tone-burst waves ranging from 0.75 to 3 MHz in frequency and 100 to 700 kPa in pressure [35].

1.2.2.4 Lithotripsy Equipment

An extension of therapeutic ultrasound is the process of extra-corporeal shock wave lithotripsy. Whilst lithotriptors are not normally considered as ultrasonic devices, the fields generated are similar to those of diagnostic medical ultrasound hence they are included within this discussion. The process of lithotripsy involves the generation of high pressure acoustic shock waves which are focussed onto renal, ureteral or other calculi. The repeated shock waves induce mechanical stresses in the calculi, which eventually exceed the comprehensive strength of the material and cause its destruction. The resultant debris is then passed naturally.

Pioneering work in this area was completed by Chaussey, following the development of a lithotripter device by the German aircraft manufacturer Dornier. The first patient was treated on 7 February 1980 from which point the technique has grown to assume a dominant position in clinical therapy. The typical acoustic emission from a lithotripsy device is a pulse of frequency of 200 to 900 kHz, with a duration between 200 ns and 10 μ s and a pressure amplitude between 10 and 100 MPa [35]. A full discussion on ultrasonic technology is presented in the text by Graff [37].

1.3 PHYSICAL THEORY OF ACOUSTICS AND ACOUSTIC INTERACTION

The science of acoustics is defined as the generation, transmission and reception of energy as vibrational waves in matter [38]. Acoustic waves are generally grouped in three families, determined by their frequency of oscillation. Audible sound is that with frequency within the limits of human hearing, while infrasound and ultrasound describe those waves with a frequency lower and greater than the limits of human hearing, nominally 20 Hz and 20 kHz respectively.

The natural phenomenon of lightening and thunder represents perhaps the oldest known electroacoustic transducer. Here, the electrical discharge responsible for the lightening converts or 'transduces' some of its energy into sound. The word transducer derives from the Latin *transducere*, meaning to lead across [39] and within acoustics is used to describe a reversible device which converts energy from electrical to acoustical or vice versa. The transducers used to transmit and receive sound in air such as loudspeakers and microphones are of little use underwater since the acoustic impedances of air and water are radically different. The acoustic impedance, Z (or ' ρc '), describes the efficiency with which energy is transferred across the interface of the transducer and is given as the product of the density, ρ , and the speed of sound in the media, c [3]. Therefore, in contrast to the requirements of a transducer in air, the most effective generators or detectors of sound in water are those which develop a large force over a small area.

1.3.1 Generation of Underwater Acoustic Pressure Waves

As discussed in Section 1.2, the development of underwater acoustic transducers was greatly influenced by the discovery of piezo-electric and magnetostrictive materials. Piezo-electric type devices represent the most efficient transducers available, with energy conversion factors as high as 80%, in contrast to the 50% typical in magnetostrictive devices. However, the reduced cost of manufacture of magnetostrictive transducers ensures they remain in the market.

Nowadays, piezo-electric transducers dominate the market, with ceramic polycrystalline materials having superseded quartz, which only remains in significant usage in frequency control applications. The performance of the ceramic is determined by its shape and mechanical properties, which are known to vary widely with ceramic type, and deteriorate with time [40]. Typically shaped piezo-electric elements include rings, plates and bars. A number of piezo-electric elements may be used together within a transducer to increase the acoustic output. The construction of a typical piezo-electric source transducer will have the active element or elements bonded to a thin metallic membrane or encapsulated in rubber. Rubber membranes are used since their acoustic impedance closely matches that of water.

An alternating current electrical signal is required to obtain an acoustic output from a transducer. In many cases, particularly those where the generated sound is required to travel long distances, a high power electrical supply is needed. For this reason, high quality power amplifiers and conditioning circuitry are regularly employed to provide a signal of sufficient amplitude.

Each acoustic transducer will have a characteristic directional response profile, dependent on its physical shape, materials and construction. This is also frequency dependent. Whilst the simplest design of acoustic projector is a spherical oscillator able to generate harmonic spherical waves, the majority of source transducers are designed to emit a principal beam in a specific direction [40]. The width of this principal beam in angle is usually described by the half power points at either of its sides. Thus, the pressure amplitude generated by an acoustic transducer is a function not only of the electrical input, but also the properties of the transducer and frequency of excitation.

1.3.1.1 Quality Factor

The quality factor (Q-factor or Q) of a transducer describes the ratio of the mass reactance to the resistance [38]. In effect it relates the amount of energy required by the system to establish an equilibrium where subsequent energy can flow through or be dissipated within the system. The Q-factor of a transducer describes the bandwidth around the resonant frequency and can be used to quantify the number of

cycles required to reach a fraction of full signal amplitude (since the rise is exponential, full amplitude is reached asymptotically). 95.5% of full amplitude is reached after Q cycles and 99% after $1.5Q$ cycles [41].

In order to maintain a reasonable working bandwidth a transducer with a low Q is desirable, although the greatest efficiency of operation can be found at the resonant frequency of a transducer with high Q . Another important consideration is that of the transient time taken either to reach full signal amplitude or reduce to zero from full amplitude. In many applications, laboratory based measurements and calibration procedures, a tone-burst, consisting of a complete number of sinusoidal oscillations, is preferred to a continuous wave. The primary reason for this is so that any reflected or scattered components within the acoustic field can be identified and separated from the principal signal. Depending on the proximity of the nearest reflecting body and the frequency of the acoustic signal, the echo-free time may allow only a very small number of cycles to be contained within the tone-burst. For this reason it is very important to minimise the transient time at the beginning and end of the tone-burst, where measurements from the steady state signal cannot be made. Therefore, for experiments of this nature, both the source transducer and the measurement transducer are required to have a low Q .

1.3.2 Propagation of Underwater Acoustic Waves

The fundamental mechanism by which acoustic waves are able to propagate in water and other similar dense media is that of particle displacement. The time dependant particle displacement from the equilibrium position, ξ , causes localised changes in the density of the fluid, ρ , which in turn causes localised changes in pressure, p . Each of these quantities oscillates with an identical frequency to that of the wave being propagated. The higher frequency limit of propagation can be calculated for a media, based on the closest atomic spacing and the Nyquist sampling theorem [35].

The speed with which the sound travels is determined by the choice of medium. A more detailed discussion of the speed of sound in water is given in Section 1.3.2.1. The speed of sound, c , relates the acoustic frequency, f , with the wavelength, λ , as described in Equation (1.3.1). By varying the frequency an appropriate wavelength for the given application can be obtained:

$$c = f \lambda \quad (1.3.1)$$

The speed of sound in the medium, c , the acoustic pressure, p , and the particle velocity, $\dot{\xi}$, give rise to a number of important quantities. The first of these is the acoustic impedance, Z :

$$Z = \rho c \quad (1.3.2)$$

The acoustic impedance is important when considering the propagation of an acoustic wave from one medium to another as will be discussed in Section 1.3.2.2.

The second quantity is intensity, I :

$$I = \left\langle p \dot{\xi} \right\rangle = \frac{p^2}{Z} \quad (1.3.3)$$

The intensity can also be considered as the energy flowing through a unit area per unit time [35]. The acoustic power, P , passing through an area can be derived from the integral of the intensity over the area, S :

$$P = \int I dS \quad (1.3.4)$$

From a measurement of intensity, the source level, $S.L.$, of a projector can be derived. The $S.L.$ is a standard measure of characterising the signal strength of a transducer with respect to another and is derived from the measured acoustic intensity at a distance of 1 m from the source. The reference intensity is that generated by a pressure of 1 μPa .

$$S.L. = 10 \log \left(\frac{I}{I_{ref}} \right) \quad (1.3.5)$$

Water is able to support two methods of mechanical wave propagation; longitudinal (or compressional) and transverse (or shear). The respective mechanisms by which these methods facilitate propagation are depicted pictorially in Figure 1.3.1, where each dot represents an acoustic particle. The most efficiently transmitted and widely used of these propagation forms is the longitudinal mode, upon which the work reported here is based.

1.3.2.1 Speed of Sound in water

The speed with which sound propagates through water has been the subject of much research beginning, as previously mentioned, with the experiments of Colladon and Sturm [3]. The work of Wilson [42,43] in the middle part of the 20th century was important in establishing the influence of pressure and temperature on the speed of sound in water. A period of refinement then occurred with a series of equations being put forward, each offering improved or extended consideration of either depth, pressure or salinity [44–48].

The current international standard approved by the United Nations Educational, Scientific and Cultural Organization (UNESCO) is that derived by Chen and Millero [49]. However, two more simple equations have since been developed by Mackenzie [50] and Coppens [4], which both allow adequate calculation of sound speed as a function of temperature, depth and salinity. The requirement of depth as an input parameter for each of these equations, as opposed to the pressure required by the UNESCO standard, is additionally attractive. The equation proposed by Mackenzie is valid for a range in temperature of 2 to 30 °C, a range in salinity of 25 to 40 parts per thousand and a range in depth from 0 to 8000 m. The equation given by Coppens is valid for a range in temperature of 0 to 35 °C, a range in salinity of 0 to 45 parts per thousand and a range in depth from 0 to 4000 m.

Due to its requirement for depth rather than pressure as an input parameter and capability to cope with fresh water where the salinity is 0 parts per thousand, the equation proposed by Coppens [4] is used throughout this work.

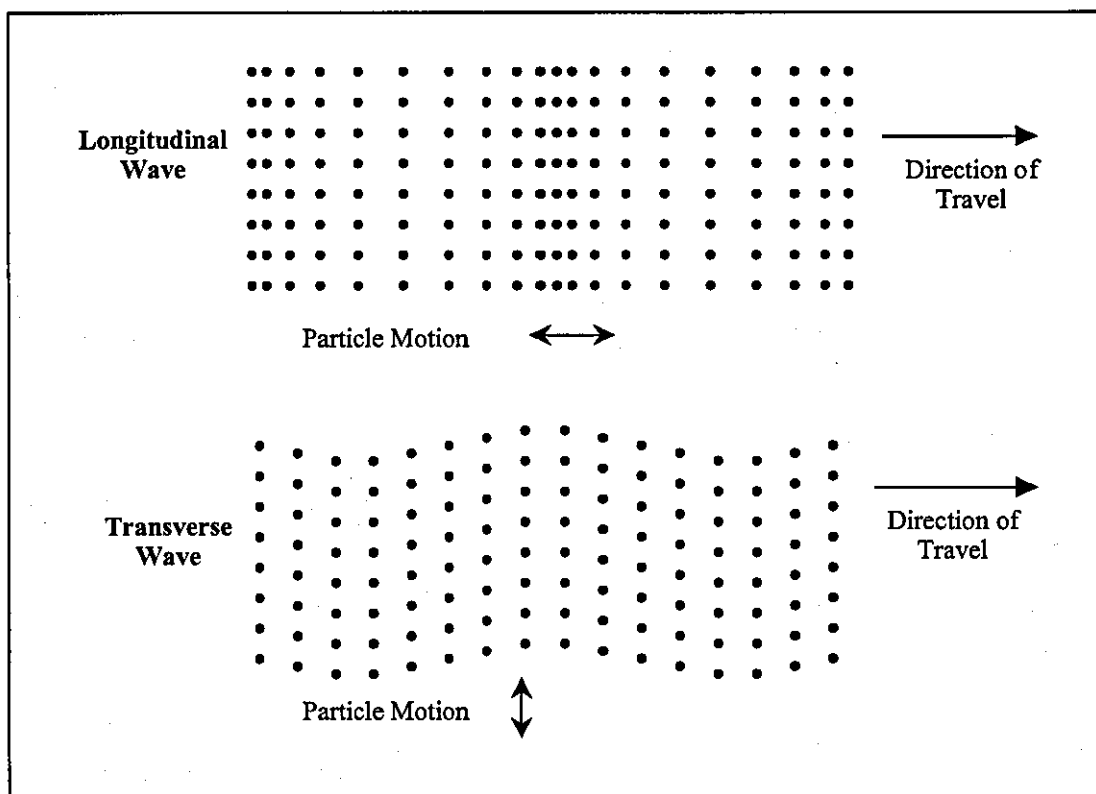


Figure 1.3.1: Longitudinal and Transverse Wave Propagation

1.3.2.2 Boundary Considerations

In many applications of underwater acoustics, such as medical imaging and pulse-echo submarine detection, it is necessary to consider the influence of a boundary on a propagating acoustic wave. In the context of this work, a boundary is defined as the meeting of two media types, where a change in acoustic impedance is experienced. Typical boundaries considered within this work include water-air interfaces, tank wall interfaces and those between the water and intentionally submerged objects.

At a boundary, a proportion of the acoustic wave will be transmitted across the interface whilst the remainder will be reflected. Analysis begins with the case of a planar wave incident on a planar interface. Here, the reflected components of the pressure wave, p_r , can be derived from the pressure amplitude of the incoming wave, p_i , and the respective acoustic impedances of the two media, Z_1 and Z_2 [35].

$$p_r = p_i \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right) \quad (1.3.6)$$

Meanwhile, the transmitted component, p_t , is given by:

$$p_t = p_i \left(\frac{2Z_2}{Z_2 + Z_1} \right) \quad (1.3.7)$$

The case where the incidence between the direction of the acoustic wave and the boundary is not normal introduces refraction, which requires Snell's Law to be considered. Snell's Law describes the ratio of the angle of incidence, θ_i , to the angle of transmission, θ_t , with respect to the relative speeds of sound in each media, c_1 and c_2 [51]:

$$\frac{\sin \theta_t}{\sin \theta_i} = \frac{c_2}{c_1} \quad (1.3.8)$$

The transmitted and reflected pressure amplitudes can therefore be calculated for the general case where the angle of incidence may not be normal. These are given in Equation (1.3.9) and Equation (1.3.10) respectively.

$$p_r = p_i \left(\frac{Z_2 \cos \theta_i - Z_1 \cos \theta_t}{Z_2 \cos \theta_i + Z_1 \cos \theta_t} \right) \quad (1.3.9)$$

$$p_r = p_i \left(\frac{2Z_2 \cos \theta_i}{Z_2 \cos \theta_i + Z_1 \cos \theta_t} \right) \quad (1.3.10)$$

Given that the intensity of an acoustic wave is proportional to the square of the pressure, the intensity reflectivity, $\frac{I_r}{I_i}$, can be derived from the pressure reflectivity, $\frac{p_r}{p_i}$, the ratio of the amplitudes of the reflected and incident pressure, p_r and p_i :

$$\frac{I_r}{I_i} = \left(\frac{p_r}{p_i} \right)^2 \quad (1.3.11)$$

The intensity reflectivity and pressure reflectivity coefficients for a range of material types at normal incidence in water are given in Table 1.3.1 [35].

Material	Normal intensity reflectivity	Normal pressure reflectivity
Air	1.0	1.0
Water	0	0
Castor Oil	0.020	0.14
PMMA (Perspex®)	0.37	0.61
Aluminium	0.85	0.92
Brass	0.93	0.96

Table 1.3.1: Intensity and pressure reflectivity of different materials in water

The interference between the incoming acoustic wave and the part of the wave reflected by the boundary often causes a field of complex phase and amplitude. The phenomena of the reflection and interference of an acoustic wave at a boundary is often referred to as scattering.

In many experimental scenarios it is desirable to minimise scattering from those boundaries that cannot be removed, such as tank walls or measurement transducers.

Two approaches are generally taken in the design of acoustic tank walls to minimise the potential disruptive influence of scattered sound. These are a careful choice of anechoic material with close impedance matching to water and a geometric shape designed to deflect what reflected component remains at an angle away from the normal. Approaches to minimise the perturbation caused by measurement transducers are discussed in Section 3.4 and a review of the measurement of acoustic scattering is discussed in more detail in Section 2.2.1.

1.3.3 Detection of Underwater Acoustic Pressure Waves

The development of the hydrophone represents the most significant landmark in underwater acoustic measurement technology. The hydrophone is the most prevalent measurement transducer in use around the world, both in marine and medical environments. According to Robinson [52], the ideal hydrophone would have the following properties:

- a) Small Size
- b) High Sensitivity
- c) Omni-directional
- d) Stable
- e) Broadband frequency response
- f) Non-perturbing structure
- g) Linear sensitivity

Given the wide range of wavelengths employed in underwater acoustics, specific hydrophones are designed and manufactured for particular frequencies or pressure levels. The aim of the designer is always to minimise the physical size whilst providing an acceptable sensitivity and frequency response. Consequently distinct types of hydrophone have been developed for different frequency ranges. Examples of typically shaped hydrophones include spherical or ball, needle and membrane.

Ball hydrophones are generally used in the measurement of low sonic and ultrasonic frequency acoustic fields, typically less than 200 kHz. It is common for the active element within a ball hydrophone to be constructed from an electrostrictive ceramic,

although internal resonance modes within the element and the backing material can lead to unpredictable directional and frequency responses. Dimensions can range drastically, but it is desirable for the diameter to be smaller than the acoustic wavelength.

More importantly in the measurement of medical acoustic parameters are the needle and membrane hydrophones, due to their suitability for high frequency acoustic measurements. In a needle hydrophone, an active element of piezo electric polymer is supported on the end of a needle approximately 1 mm in diameter. One major advantage of a polymeric element, such as polyvinylidene fluoride (PVDF) is its close acoustic impedance matching with water, which requires less backing and insulation material. This gives less distinct resonances within the device. Such devices are typically used at frequencies greater than 1 MHz [35].

The design of membrane hydrophones differs significantly from that of those mentioned previously. Due predominantly to the very short acoustic wavelengths encountered at elevated frequencies, the active element is required to be very small, usually less than a fraction of a millimetre. Therefore the element is positioned at the centre of a 100 mm diameter PVDF (Mylar[®]) membrane, stretched over an annular ring. The PVDF, in addition to having a close impedance matching with water, is manufactured in range of thicknesses of less than 25 μm , and is therefore considered 'acoustically invisible'. A detailed analysis of membrane hydrophones is given by Preston *et al.* [53].

Throughout this work, the term 'hydrophone' is used to represent any submersible device for measuring acoustic pressure.

1.3.3.1 Decibels

The application of the decibel system is widespread throughout airborne and underwater acoustics for a variety of reasons. Within airborne acoustics, perhaps the most significant reason is that the human ear is known to behave as a logarithmic detector. Within underwater acoustics, the reasons include the large range of signal amplitudes of the order of 10^{12} , and the fact that ratios of signal amplitudes are often of more interest than absolute quantities [41].

A decibel is derived from the ratio of a measured power, P , to that of a reference power, P_{ref} , as given in Equation (1.3.12).

$$dB = 10 \log \left(\frac{P}{P_{ref}} \right) \quad (1.3.12)$$

The intensity level, $I.L.$, is calculated in the same way as the source level for a given projector and is defined as

$$I.L. = 10 \log \left(\frac{I}{I_{ref}} \right) \quad (1.3.13)$$

Given that acoustic intensity is proportional to the square of the pressure, the sound pressure level, $S.P.L.$, is defined as:

$$S.P.L. = 20 \log \left(\frac{P}{P_{ref}} \right) \quad (1.3.14)$$

In underwater acoustics, the standard reference pressure is taken to be $1 \mu\text{Pa}$, which equates to an intensity of $6.76 \times 10^{-19} \text{ W/m}^2$.

1.4 CLOSURE: IDENTIFICATION OF RESEARCH NEED

In many marine applications, the accuracy limitations of acoustic measurements are approximately ± 1 dB (about $\pm 10\%$). These are generally quite acceptable for many measurements made in ocean waters [41]. The reason for this accuracy level is attributed to the effects of pollutants, bubbles, pressure and temperature distribution, physical chemistry and other inhomogeneities. However, the significant advances in the application of acoustics in medicine during the latter half of the 20th century have required acoustic measurements of an increased accuracy.

The development of techniques such as extra corporeal shock wave lithotripsy has illustrated the potential destructive influence of high amplitude pressure waves on human tissue. There is, therefore, considerable concern within the medical community to ensure the safe application of those therapeutic and imaging techniques where tissue damage is highly undesirable [35]. Considerable effort has therefore been directed towards the development of appropriate hydrophones or other measurement transducers to enable accurate characterisation of the fields generated by medical ultrasound equipment. This is necessary to achieve the levels of confidence required to ensure safe clinical use.

The National Physical Laboratory, NPL, in Teddington is the agency responsible for maintaining the primary calibration standards for underwater acoustics in the UK. In providing a calibration service able to cope with the demand from industry, it is usually necessary to include a number of secondary dissemination standards to relieve the pressure that would otherwise be placed on the primary standard. However, the current requirements from industry are for hydrophone calibration services of an accuracy comparable only to those obtainable from the primary standards. There is, therefore, the need for improvement in the measurement uncertainty of the primary standard for underwater acoustics of at least an order of magnitude, to enable the calibration of equipment to the level necessary for the implementation of a dissemination structure.

As a consequence of these requirements, the UK Department of Trade and Industry (DTI) National Measurement System Programme for Quantum Metrology 2001-2004 proposes a 'new generation of fundamental standards for acoustics based on optical methods' [54]. At the heart of this lies the desire to link acoustical standards more directly to the unit of length through measurement of particle displacement or velocity. The specific objective stated is:

"to lay the foundations for the development of new optically-based primary calibration methods for realising the pascal in air and water with accuracies a factor of at least two better than those which currently can be achieved using conventional techniques."

The programme also describes the need to overcome the accuracy limitations of the traditional calibration methods, particularly at frequencies below 500 kHz, for both single point measurements and whole-field mapping.

Additionally, the manufacturers of underwater acoustic source transducers are keen to characterise the spatial and temporal pressure distribution of the fields generated by their equipment. Hence the development of fast, reliable whole-field mapping techniques would be of significant benefit to this community. Similarly, it is conceivable that users of acoustic source transducers in medicine would benefit from knowledge of the spatial distribution of a range of acoustic parameters.

The work described in this thesis is aimed at addressing the needs of both the underwater acoustic calibration community and the manufacturers of underwater acoustic transducers, by developing a method of accurately measuring acoustic parameters in a non-perturbing way. As will be demonstrated by the literature review presented in Chapter 2, a variety of optical metrology methods have previously been applied to underwater acoustic measurements. Whilst many of these offer the potential for measurement of acoustic parameters, each has inherent drawbacks which restrict their application. Therefore, sufficient scope exists for the development of a complementary technique to quickly record acoustic data in a manner other techniques are not capable of.

Chapter 2

Literature Review

2.1 INTRODUCTION

The detailed literature review presented in this chapter builds on the background information presented in Chapter 1. It is based around publications on underwater acoustic measurements and measurement devices other than the conventional hydrophones described in Chapter 1. These include the capacitance probe, force measurement devices and methods for establishing the spatial distribution of acoustic fields, such as hydrophone arrays and the ultrasound beam calibrator. Certain investigations into acoustic scattering from submerged objects and other media boundaries are also reviewed.

The science of underwater acoustic calibration is explored, with particular reference to the two techniques used as part of the UK primary standard capability; three transducer spherical wave reciprocity, for frequencies between 2 kHz and 500 kHz, and the NPL Laser Interferometer, for frequencies between 500 kHz and 20 MHz.

Significant attention is paid to a review of the application of a range of optical metrology methods which have been used in underwater acoustic measurement. These include diffraction, schlieren, electronic speckle pattern interferometry, holographic interferometry, particle image velocimetry, laser Doppler anemometry and laser Doppler velocimetry. An assessment is made of each of these techniques, detailing their advantages and limitations.

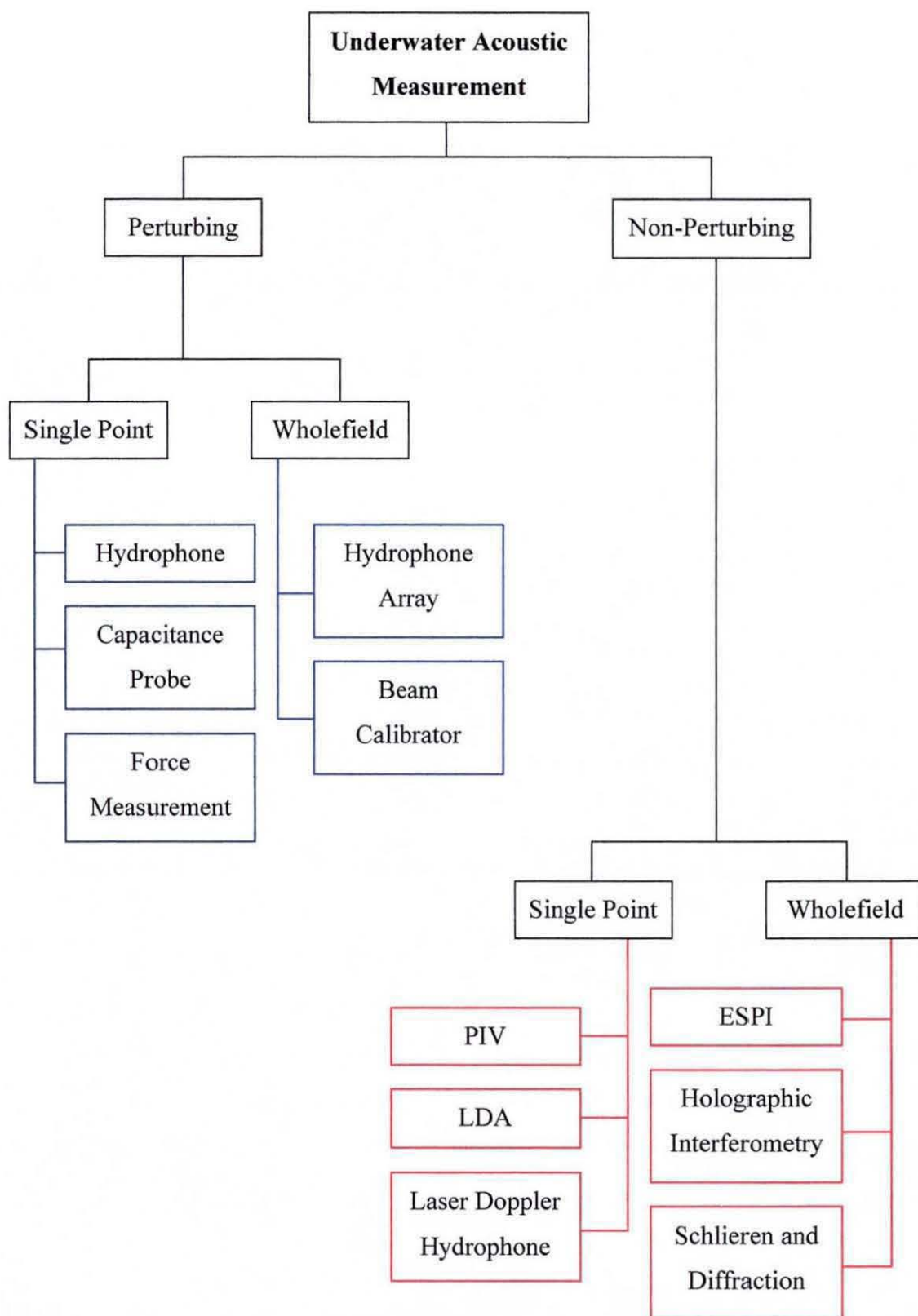


Figure 2.1.1: Schematic Overview of Literature Review

2.2 UNDERWATER ACOUSTIC MEASUREMENTS

As has been mentioned previously, the majority of underwater acoustic measurements are made using a hydrophone. Such devices are well established within the underwater acoustic community and well documented throughout this work. Presented here is an overview of a range of other submersible devices which have been employed in the measurement of acoustic parameters.

The capacitance probe is a rugged device which utilises the localised particle displacement within an acoustic field to vary the distance between two charged parallel plates. The voltage output is proportional to the displacement, from which the pressure can be derived [35]. The technique was first suggested as a method for recording acoustic measurements in liquids by Filipczynski in 1969 [55] and the durable nature of these devices has enabled measurements from the notoriously hostile environment of a lithotripsy field to be made [56]. However, distortions have been observed in the shock wave pulse measured by a capacitance device when compared to a membrane hydrophone. This has been attributed to transverse waves generated in the capacitance plates of the device [57]. Whilst this device can withstand high acoustic pressure amplitudes, it is a physical and thus perturbing device which only records the average pressure amplitude across a small area within the field.

A range of force measurement techniques have been employed to measure underwater acoustic fields, each of which utilises the principle of momentum transfer as their basis. The large target radiation force balance works by entirely intercepting the acoustic beam and measuring the force exerted upon it. From this measured force, the acoustic power can be derived [35]. The suspended sphere radiometer is used to determine the localised values of acoustic intensity, where the sphere is small enough to be subjected to a consistently distributed force. Dunn *et al.* first suggested the use of a sphere radiometer as a primary calibration method in 1977 [58]. Clearly, devices of this nature will perturb the acoustic field and provide only an average measure across the intercepting area. An extensive review of these and other underwater acoustic measurement techniques including a comparison of the relative merits of each is presented by Zeqiri [59]. Optical techniques are also included in the

discussion presented by Zeqiri, but in this work these are considered separately in Section 2.4.

Each of these techniques provides either a measure of acoustic pressure or intensity at a single point or an integration of the total power over an area as in the case of the large target radiation force balance. It has been established that the need exists in certain applications for measurements of the spatial and temporal distribution of acoustic parameters. Conventional methods of monitoring the spatial distribution of an acoustic field involve recording discrete pressure measurements at positions in three-dimensions within a field.

Various approaches can be taken to realise this, including taking repeated measurements using a single device or establishing a suitable array including many hydrophones. Both these techniques have shortcomings that restrict their application in many instances. For example, the time and skill required to accurately position and record multiple measurements using a single hydrophone makes the technique impractical for taking measurements over a large volume or with a dense spatial resolution. In contrast, a three-dimensional array of transducer elements will enable measurements to be made in rapid time, but the cost involved in the purchase of many hydrophones makes it unsuitable for many applications. In addition, the presence of physical devices and their supporting structures are known to introduce perturbation into the measurement volume.

The ultrasound beam calibrator is an example of a system offering a compromise between many of the conflicting requirements in order to facilitate spatially distributed measurements at frequencies between 500 kHz and 20 MHz [60]. Here a 21-element membrane hydrophone made from PVDF is mounted within an acoustic field and pressure measurements are recorded by each element. The position and orientation of the acoustic source is then modified and measurements repeated. The ultrasound beam calibrator offers a solution where field perturbation and the time required to record measurements are both minimised.

2.2.1 Measurements of Acoustic Scattering

The study of sound scattered by impeding obstacles or interfaces was first investigated by Rayleigh [5,6]. Whilst Rayleigh concentrated only on the influence of scattering bodies of small dimensions with respect to the acoustic wavelength, a more extensive experimental study was undertaken by Faran [61]. In his work, he detailed the influence of acoustic waves incident on solid cylindrical and spherical scatterers, taking into consideration the diameter of the object, the acoustic wavelength and the respective speed of sound in the media and scattering material. Repeated measurements were made of a 64 μ s duration, 1 MHz acoustic tone-burst generated by a transducer with a low Q, using a hydrophone. Graphical images depicting the scattering patterns of a range of cylinders of different dimensions and materials were presented.

One of the earliest applications of non-perturbing optical technology to the measurement of scattered acoustic fields was documented by Kheifets, who presented images depicting the scattered acoustic fields generated by the presence of solid obstructions and periodic gratings in an unnamed liquid [62]. The holographic technique utilised to create such images is described in more detail in Section 2.4.3.

A review of theoretical and experimental studies on underwater acoustic scattering from single and multiple bodies was reported by Zhen in 2001 [63]. A comprehensive mathematical description of acoustic scattering by a range of geometric shapes such as spheres, infinite cylinders and ellipsoids was presented and a host of other scenarios were reviewed and analysed.

2.3 UNDERWATER ACOUSTIC CALIBRATION TECHNIQUES

In the UK, NPL are responsible for maintaining the primary standards for underwater acoustics in the frequency range 2 kHz to 20 MHz. Two systems are employed to facilitate the calibration of hydrophones; three transducer spherical wave reciprocity for frequencies between 1 kHz and 500 kHz and the NPL Laser Interferometer for frequencies between 500 kHz and 20 MHz. Experimental validation studies have been carried out in the overlapping frequency range from 200 kHz to 1 MHz and, in general, demonstrate agreement within 0.4 dB or better [64].

Primary standards for underwater acoustic calibration at a range of frequencies employed around Europe are reviewed in a collaborative work by Robinson *et al.* [65,66,67] and in the United States by Preston *et al.* [68]. A similar study has recently been published by Enyakov *et al.* comparing calibration standards in Russia and China [69].

In all calibration procedures, it is desirable for experiments to be undertaken in controlled volumes of deionised water, where any potential scattering or perturbing influences with the exception of the hydrophone being calibrated are removed [35].

2.3.1 Three Transducer Spherical Wave Reciprocity

The primary method for the calibration of hydrophones in the frequency range 2 kHz to 500 kHz is three transducer spherical wave reciprocity. This standard was introduced by the International Electrotechnical Commission in 1977 [18] and adopted as a British standard in 1979 [19].

The process involves three transducers, of which one is required to be a reciprocal device with transmitting and receiving sensitivities related by a constant factor. Two transducers (1 and 2) can be checked to confirm the likelihood of each behaving in a reciprocal manner by comparing the input current, i , and output voltage, e , of each device in transmitting a signal from one device to the other and vice-versa.

$$\frac{e_2}{i_1} = \frac{e_1}{i_2} \quad (2.3.1)$$

During the process of three transducer spherical wave reciprocity, three measurement stages are completed, during which, each device is used as a transmitter and a receiver [41]. Transducers are arranged in pairs and the ratios of the output voltages and input currents are calculated. If hydrophone 3 is the reciprocal transducer, the sensitivity of hydrophone 1, M , is given by:

$$M = \sqrt{J \frac{d_{12} d_{13}}{d_{23}} \frac{Z_{12} Z_{13}}{Z_{23}}} \quad (2.3.2)$$

where d_{xy} represents the separation distance between transducer x and transducer y . Note that in Equation (2.3.2) Z_{xy} refers to the ratio of the output voltage e_y to the input current i_x and not the acoustic impedance as it does throughout the remainder of this work. J is the reciprocity parameter relating the transmitting and receiving sensitivities of the reciprocal transducer. For a spherical wave this is given by:

$$J = \frac{2d_0}{\rho f} \quad (2.3.3)$$

where d_0 is the reference distance (1 m), ρ is the density of water and f is the acoustic frequency.

Typical uncertainties within the NPL primary standard in the frequency range 2 kHz to 500 kHz are ± 0.5 dB at 95% confidence levels [70]. Results of the European inter-laboratory comparison demonstrate the NPL method to differ from the grand mean averaged over all frequencies and hydrophones of 0.3 dB [66].

2.3.2 NPL Laser Interferometer

The application of optical interferometry to the measurement of acoustic displacement was first suggested by Drain *et al.* in 1977 [71] and subsequently refined by NPL in 1986 [72], before being adopted as the primary standard for calibrating hydrophones in the frequency range 500 kHz to 15 MHz [73] in 1987. This frequency range was extended upwards for routine calibration to 20 MHz although successful measurements have been made at frequencies from 200 kHz [64] to 60 MHz [74]. Calibration of membrane hydrophones is now possible at these advanced frequencies, although the relative uncertainty is increased from 0.046 at 20

MHz to 0.250 at 60 MHz at 95% confidence [75]. The procedure is one where a measurement of acoustic displacement is made, from which the pressure can be derived using the expression given in Equation (2.3.4). This requires an assumption that the source and the transducer are separated by sufficient distance to mimic far field conditions where the radiating acoustic wave approximates a plane progressive wave [35]. The pellicle and optical apparatus are then replaced with the hydrophone under inspection. The voltage output from the hydrophone is then calibrated against the pressure measurements derived from the interferometer.

$$p = 2\pi Z f a \quad (2.3.4)$$

The NPL Laser Interferometer is shown schematically in Figure 2.3.1 and is based on the traditional Michelson Interferometer [73]. The principle of operation involves comparing the phase of the light returning from the reflective pellicle in the target arm with that returning the fixed distance of the reference arm.

A number of features are incorporated in the design of the interferometer to enable a measurement of the pellicle displacement to be made. A Pockels cell is included as part of a feedback loop to compensate for any spurious vibration encountered by the system. The Pockels cell responds only to low frequency vibration, allowing the ultrasonic displacement to be measured. A number of quarter wave plates (denoted by $\lambda/4$) are included; those either side of the Pockels cell allow the reference and target beams to be separated by their polarisation and those in the respective arms of the interferometer prevent reflected light from re-entering the laser cavity and changing the laser output.

The target beam is focussed onto the rear of a 3 or 5 μm thick PVDF pellicle, similar in dimensions to the membrane hydrophone previously described. The PVDF is coated with 25 nm of gold or aluminium, which allows it to behave as an optical reflector whilst exhibiting acoustic transparency. An aluminium coated PVDF pellicle is shown in Figure 3.6.8. The displacement of the pellicle due to the acoustic disturbance, a , the intensities of the target and reference beams, I_T and I_R respectively, and the phase difference between the two beams, f , influence the output

voltage of the system, V [73]. The refractive index of the medium is represented by n .

$$V = I_r + I_s + 2\sqrt{I_r I_s} \cos\left(\frac{4\pi na}{\lambda} + \phi\right) \quad (2.3.5)$$

If the intensity of each beam can be considered constant, Equation (2.3.5) can be simplified to that given in Equation (2.3.6) by the use of a scalar, V_0 , representative of the nominal voltage amplitude of the output signal:

$$V = V_0 \cos\left(\frac{4\pi na}{\lambda} + \phi\right) \quad (2.3.6)$$

To increase the sensitivity, the system is adjusted so that the phase, ϕ , equals $\lambda/2$, enabling further simplification:

$$V = V_0 \sin\left(\frac{4\pi na}{\lambda}\right) \quad (2.3.7)$$

The most significant drawback of the pellicle arrangement is the scattering caused by the aluminium annulus across which the membrane is supported. This restricts the time available for acoustic measurements to be made before the principal signal is corrupted by interference with scattered signal components. For a laser spot positioned centrally on a 100 mm diameter pellicle, reflections from the aluminium annulus, 50 mm away, will arrive within 34 μ s. This means that whilst over 600 cycles can be detected at the pellicle surface prior to contamination at 20 MHz, this value decreases to just 15 cycles at 500 kHz (depending on the Q of the source transducer). It is for this reason that the NPL Laser Interferometer is not in regular use below frequencies of 500 kHz.

The NPL Laser Interferometer benefits from a direct traceability to the primary length standard (based on the optical wavelength) and its lack of requirement for particular transducer characteristics. Measurement uncertainty is between ± 0.3 and ± 0.5 dB at 95% confidence depending on frequency and hydrophone properties [64].

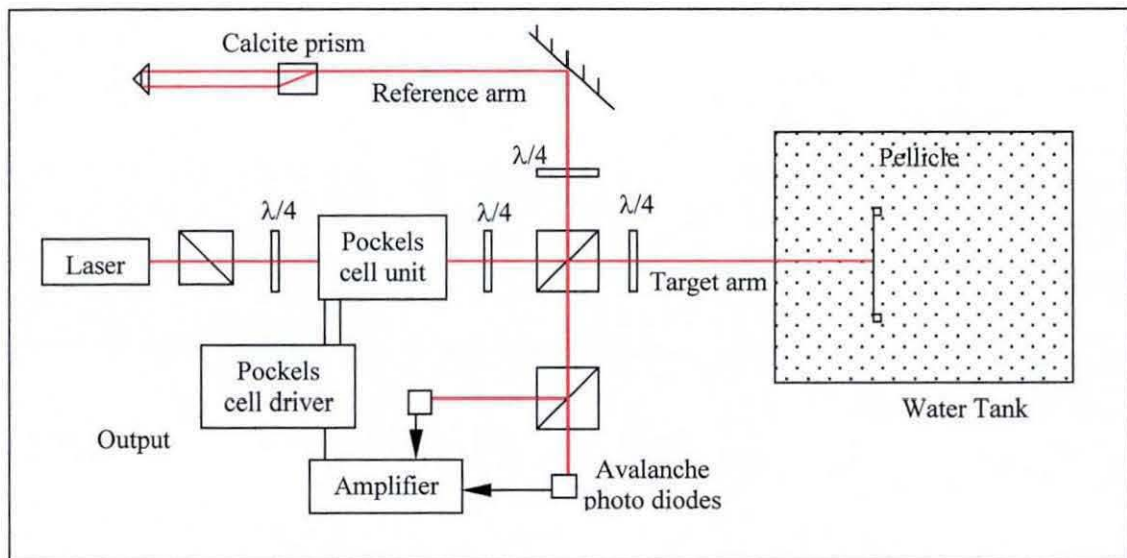


Figure 2.3.1: Schematic Arrangement of NPL Laser Interferometer

2.4 APPLICATION OF OPTICAL METROLOGY TECHNIQUES TO UNDERWATER ACOUSTIC MEASUREMENT

The NPL Laser Interferometer is one example of the many instances where optical metrology techniques have been applied to measure underwater acoustic parameters. Many such applications have offered a departure from the need to perturb the acoustic field by the presence of either a transducer or other secondary element, such as the pellicle in the case of the NPL Laser Interferometer, by utilising the interaction of the acoustic field on the properties of the incident light. Perturbation is a form of scattering brought about by the manner in which the acoustic particles oscillate in transmitting the wave. The reflection and interference caused by the boundary of the water with the casing of a physical measurement transducer is likely to corrupt the field and influence the measurement made by the device. For this reason, continued research into non-perturbing optical measurement methods is viewed with strategic importance within underwater acoustics [54].

2.4.1 *Diffraction and Schlieren Methods*

A great many researchers have engaged in the prediction, measurement, modelling and understanding of the interaction between light and sound. Observations as to the changes which occur during interaction between the two energy forms were recorded in the early half of the 20th century [76,77], although it was the work of Raman and Nath which established a sound theoretical basis for understanding [78]. The same authors then extended their description of the observed diffraction effects as a function of the respective wavelengths of the sound and light for normal incidence to include the case where the two beams are not normal [79]. In 1947, Willard developed apparatus for visualising ultrasonic waves based on the phenomenon referred to as “Debye-Sears Ultrasonic Light Diffraction” [80].

Diffraction is a phenomenon observed throughout optics and acoustics where a wave can be seen to divert from its original course by a change in the refractive index of a medium through which it passes. The presence of an acoustic field introduces localised oscillations in density, which cause the refractive index of the medium to change. These discrepancies in refractive index cause the path of a light beam

passing through the medium to be bent or 'diffracted' [81]. A comprehensive description of the theory of this acousto-optic interaction is presented by Klein and Cook [82]. The topic of ultrasonically induced optical diffraction has been the subject of many reviews, two of which were presented by Haran [81] and Monchalin [83]. A more recent summary of high frequency acoustic measurements by optical techniques was authored by Cook [84].

The Schlieren method of optical analysis was originally suggested by Foucault in 1858 [85] and first used as a means of assessing the uniformity of large astronomic objective lenses [86]. The method involves eliminating the undiffracted or 'zeroth order' light passing through an arrangement of optical elements and observing the presence of additional orders of diffracted light, indicative of inhomogeneities within the lenses under interrogation. If the lenses are known to be uniform, however, a potentially inhomogeneous sample can be examined by its inclusion. The practical apparatus required to undertake such experiments can take many forms, although a common arrangement is depicted in Figure 2.4.1.

The advent of coherent light sources enabled a refinement in optical diffraction measurements such that Blomme and Leroy were able to establish the second and third order approximation methods for characterising the diffracted light [87,88]. The same authors also investigated the changes in the polarisation of the light induced by interaction with acoustic fields [89]. This followed similar work by Jerrard, who made measurements of acoustic intensity from birefringence observed in liquids and solutions traversed by ultrasonic waves [90]. Here the author claimed that the random orientation of the molecules within a media caused it to behave in an optically anisotropic manner until an ultrasonic wave was introduced causing an orientation structure and hence birefringence in the diffracted light. Whilst each of these techniques offered the ability to provide information regarding the spatial distribution of an acoustic field, the techniques were only able to provide qualitative data.

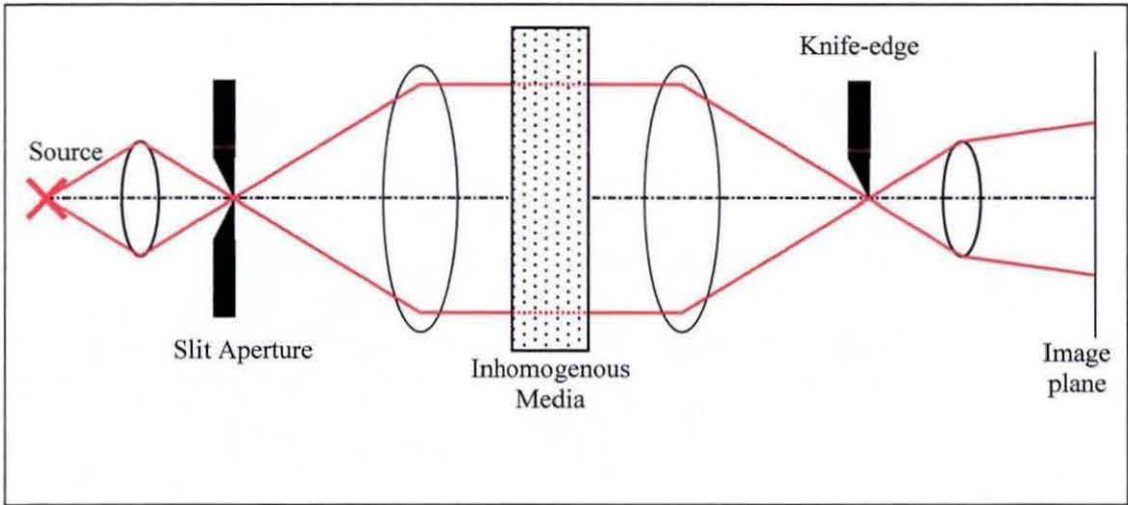


Figure 2.4.1: Arrangement used in Schlieren methods

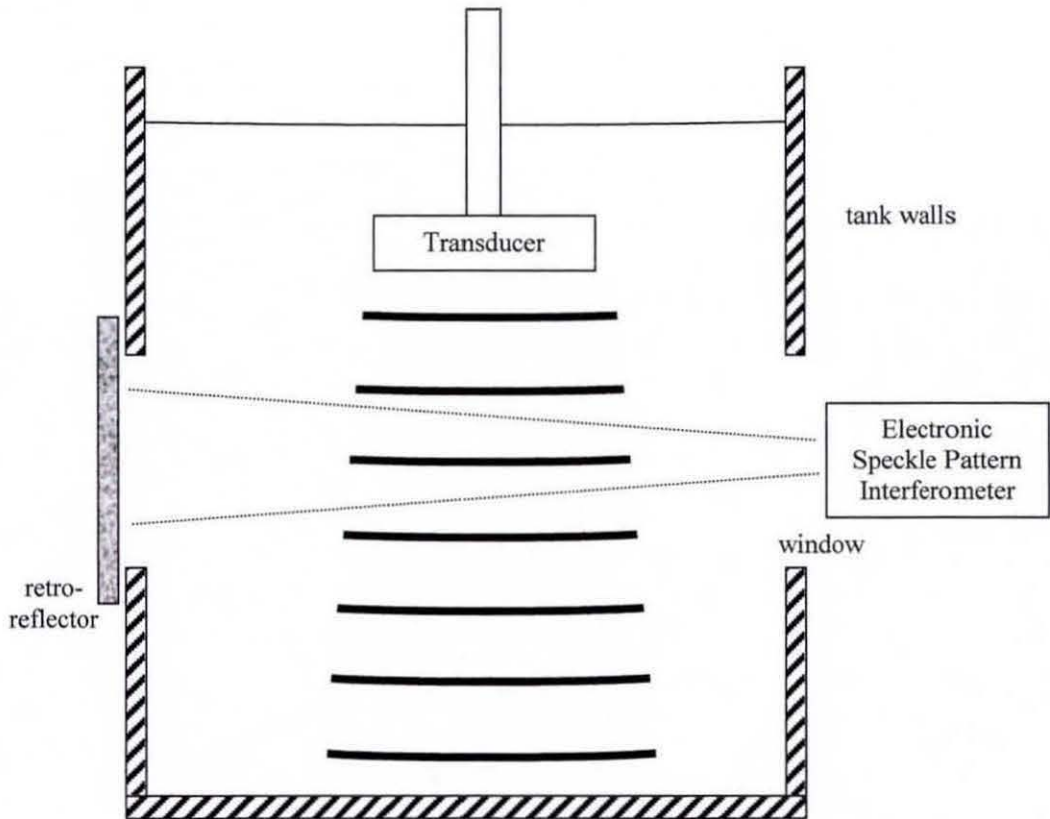


Figure 2.4.2: Experimental arrangement for recording ESPI measurements from underwater acoustic fields

A departure from the conventional diffraction measurements of light intensity came when Reibold and Kwiek began to measure the amplitude as opposed to the intensity of the light, enabling the complex nature of the various diffracted orders to be investigated. This progression, combined with advances in high-powered computer processing equipment enabled the development of light diffraction tomography [91]. In this process the magnitude and phase of the acoustic wave were established by filtered back projection using discrete convolution of the diffracted light at multiple angles through the field. By this method, a single point measurement of pressure could be derived. Further development of the technique was then documented [92–95] such that in their review of 1995, Reibold and Kwiek described light diffraction tomography as being a capable tool for mapping ultrasonic fields up to 5 MHz in frequency [96].

2.4.2 Electronic Speckle Pattern Interferometry

Electronic Speckle Pattern Interferometry (ESPI) was first reported by Leendertz and Butters in 1973 [97]. The technique, which is sometimes known as TV-Holography, has been evolved using a range of optical geometries allowing out-of-plane displacement, in-plane displacement and spatial derivative measurements using pulsed or continuous wave laser light sources. The fundamental principle is based on the measurement of the phase of coherent light scattered from an optically rough surface (one where the surface height variation is of the order of a wavelength of the light used) [98,99].

Indeed the conventional interpretation of phase differences measured in studies in air is of a movement in the position of the scattering target. However, any quantity known to influence the refractive index of the media through which the optical beam travels, such as temperature or pressure, will also introduce phase changes in the scattered light. The visualisation of thermal distributions using ESPI was first reported by Dupont *et al.* [100] and a further study of free convection heat transfer in liquids is presented by Spagnolo *et al.* [101].

Of greater interest with regard to this work is the detection of pressure induced refractive index changes. Having extensively studied refractive index changes

induced by airborne acoustic fields emanating from vibrating objects such as loudspeakers using ESPI [102,103], the Applied Optics Group at Norwegian University of Science and Technology successfully implemented the observation of underwater acoustic fields using the same technology [104]. A depiction of the experimental arrangement used is given in Figure 2.4.2. In a more specific study, Rustad demonstrated the suitability of ESPI for studying the acoustic field generated by a 3.25 MHz continuous wave medical ultrasound probe, with spatial resolution of better than 100 μm [105].

In a similar approach to that taken by Reibold *et al.* for light diffraction studies, phase stepping and tomographic reconstruction techniques have been applied to measurements of sound fields in air [106,107]. The application of a pulsed laser source has enabled transient acoustic waves to be recorded and tomographically reconstructed from ESPI measurements [108].

2.4.3 Other Interferometry

ESPI represents a subset of the much larger group of optical interferometric techniques, many of which have been applied to the measurements of underwater acoustic parameters. As in the case of the NPL Laser Interferometer described in Section 2.3.2, the traditional family of interferometers are conventionally used to measure displacement. The principle of interferometry is one where deviation between two optical wavefronts is measured by the interference observed between the two [98]. Typically, light from a coherent source is amplitude divided into two beams by a beam splitter. One beam, the reference arm, travels a set distance through a consistent media, whereas the other arm follows a path whose optical path length is subject to change with time. An initial condition is recorded which is used as a reference. Any difference between this reference and subsequent measurements indicate a change in one or more parameters that influence the optical path length. Many interferometric arrangements have evolved to suit a number of different applications. Some typical arrangements are depicted in Figure 2.4.3, indicating how acoustic fields might be observed.

In the Michelson Interferometer, depicted in Figure 2.4.3 (a), the difference in optical phase introduced by the measurement arm results in the two recombined wave fronts forming an interference pattern at the detection plane [109]. Therefore, a change in the refractive index within the test cell will lead to a changing fringe pattern being recorded at the image plane.

The Mach-Zender Interferometer arrangement, depicted in Figure 2.4.3 (b), is popular because it offers the opportunity to measure an inhomogeneity with the beam only passing once through the media [109]. This reduces uncertainties and noise within the measurement as well as the complexity of post experimental data analysis.

The Jamin Interferometer, depicted in Figure 2.4.3 (c), is a more refined version of a similar arrangement known as the Rayleigh interferometer. Despite its benefits it remains in less widespread use than the Rayleigh, but lends itself particularly well to measurements of media refractive indices [109]. This enables a measurement of the refractive index of a sample traversing an arm of the interferometer to be made, with respect to the reference arm. Another variation involves both interferometric arms traversing the acoustic wave separated by a known distance along the axis of the wave. The influence of the acoustic wave in refracting or accelerating the optical beam will be determined by the phase of the acoustic wave at that point. By positioning the two optical beams such that the interference pattern at the image plane remains constant, the wavelength of the acoustic wave (or a multiple thereof) can be measured.

In 1977, Jones and Bergquist reported a Michelson interferometer and a Jamin interferometer designed to monitor pressure variations transmitted through oil [110]. Various practical issues were addressed and resolved, and measurements were completed for acoustic frequencies of less than 10 kHz. It was found that the Michelson interferometer was able to detect small pressures at the higher frequencies whereas the Jamin interferometer performed well at frequencies less than 300 Hz.

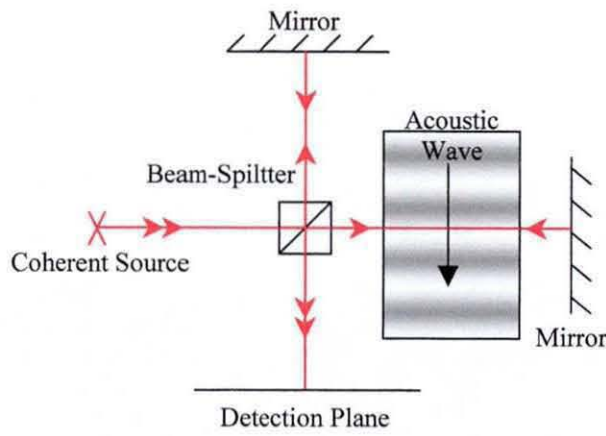


Figure 2.4.3 (a): Michelson Interferometer

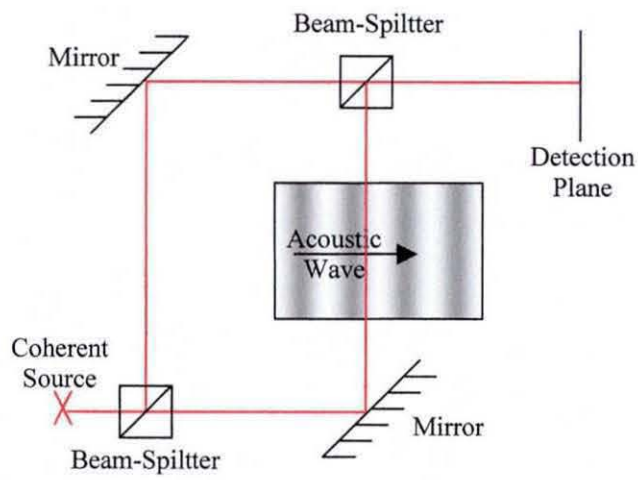


Figure 2.4.3 (b): Mach-Zender Interferometer

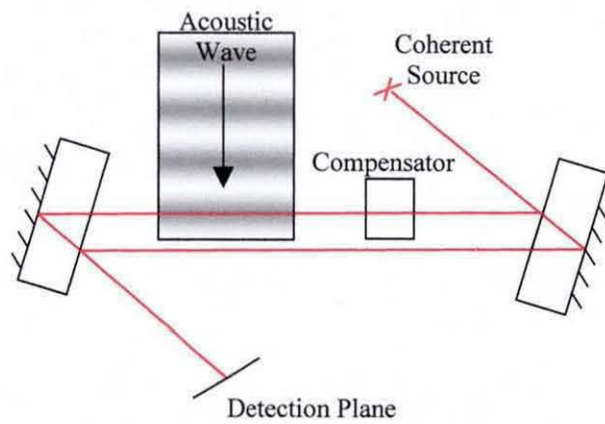


Figure 2.4.3 (c): Jamin Interferometer

Figure 2.4.3: Three typical interferometric arrangements

Also included in this group is holographic interferometry, first discovered by Gabor in 1948 [111], from which ESPI has evolved. When used to image solid objects, the technique involves recording the interference pattern formed by a coherent beam reflected from the target and a reference beam on high-resolution film [98]. When the interference pattern is illuminated by the same reference beam, a reconstruction of the imaged object is observed. The interference pattern recorded on the high resolution film enables excellent spatially resolved phase and amplitude information of the light reflected from the object to be preserved, giving the appearance of a three dimensional object when reconstructed.

Holographic Interferometry was first suggested as a tool for analysing acoustic fields by Kheifets in 1973 to address the need for an optical technique capable of measuring low frequency acoustic oscillations of less than 100 kHz [62]. In his arrangement, Kheifets recorded the interference between a continuous wave target beam passed through an acoustic volume and a reference beam, which was not subject to any rarefying conditions. As has been mentioned in Section 2.2.1, the author also presented holographic images illustrating the acoustic scattering caused by a series of obstructions. The major disadvantage of this technique was the fact that the result represented the integral of both the refractive index with distance along the optical path and with time. This required the inclusion of a Bessel function within the analysis. Kwiek and Reibold overcame this necessity by eliminating the time integral using a pulsed laser source emitting pulses of light of 20 ns duration, which is small with respect to the acoustic wave. This enabled transient acoustic waves of 200 ns duration and 20 MHz frequency to be recorded [112].

2.4.4 Particle Image Velocimetry

Particle Image Velocimetry (PIV) is a technique typically applied to measurements of gaseous and liquid based fluid flows [113]. The method involves illuminating a volume using a laser light source and imaging particulates suspended in the fluid at two instants separated by a known time increment. The size of the particulates must be sufficiently large to scatter the light, yet small enough to ensure that they faithfully follow the flow of the fluid such that any measurements recorded of their relative position are representative of the molecules of the fluid. The technique

benefits from its ability to monitor the passage of particles over an area rather than at a single point. In order to establish the plane in which the particles are moving, the laser light is typically manipulated into a light sheet as depicted in Figure 2.4.4.

The ability of PIV to generate quantitative measurements of particle displacement with time has enabled the successful measurement of underwater acoustic parameters. Hann and Greated reported the application of PIV to image the 'dumbbell' shaped exposures caused by the oscillation of the acoustic particles with time, from which the amplitude can be measured and acoustic pressure derived [114]. The exposure time used to record each image was equivalent to several periods of acoustic oscillation and when each exposure was separated by a duration sufficient for the scattering particle to travel a distance greater than twice its acoustic amplitude, both the mean and acoustic particle velocities could be obtained [115].

Subsequent development and analysis of the technique enabled the measurement of acoustic amplitudes of the order of half a millimetre with an error of approximately 5% [116]. The system was shown to benefit from its ability to resolve acoustic amplitudes from randomly orientated sound fields, although limitations in the measurement of high intensity sound fields were stated. A review of the application of PIV techniques to the measurement of particle oscillation within acoustic fields is presented by Campbell *et al.* [117].

2.4.5 Laser Doppler Anemometry

Laser Doppler Anemometry (LDA) is another technique used to interrogate the passage of seeding particles through a volume. Traditionally used for measurements of fluid flow, the technique involves amplitude dividing a coherent light beam into two 'arms'. Each arm is then converged using a lens and directed to cross at their foci. A schematic of a typical set-up is given in Figure 2.4.5. A particle passing through this focal region will scatter light from each of the beams. A Doppler frequency shift is imparted onto the light from each beam determined by the incident angle of the light and the viewing angle. The difference of the frequencies of the light from the two beams, known as the Doppler frequency difference, is measured [118].

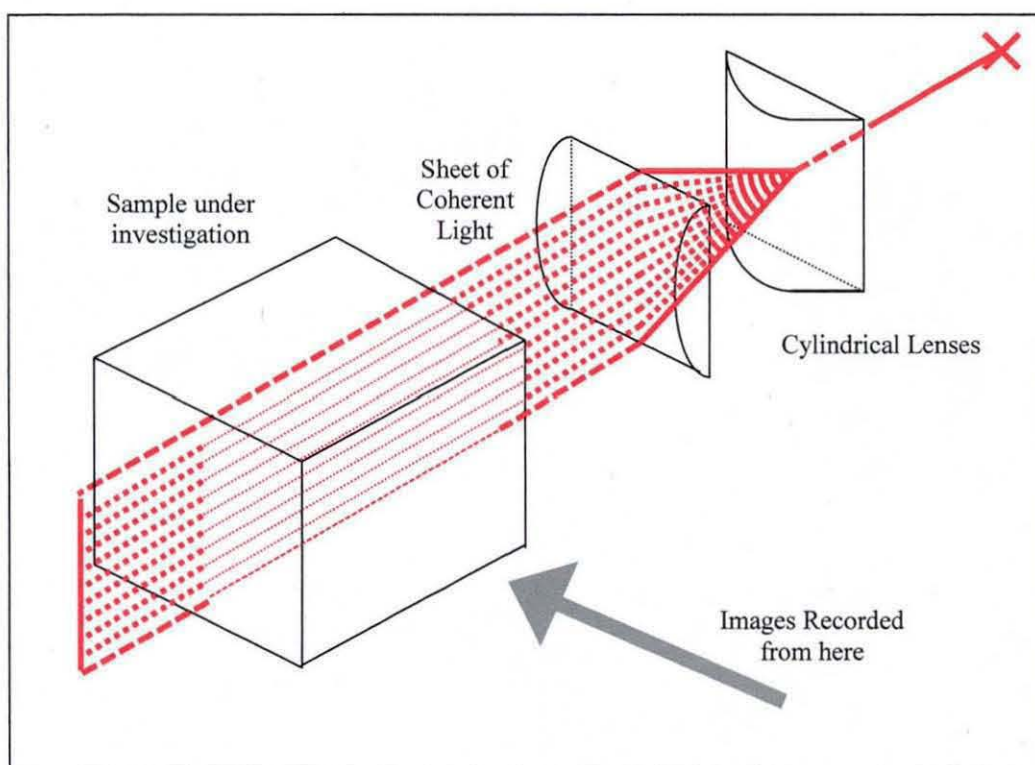


Figure 2.4.4: Optical arrangement for recording PIV data

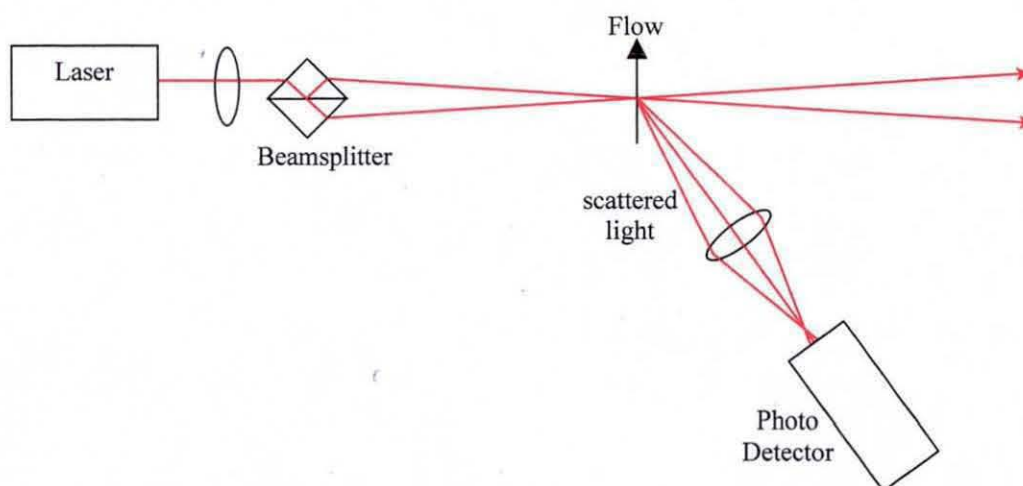


Figure 2.4.5: Schematic of a Laser Doppler Anemometer [118]

An equally valid means of describing the operation of an LDA system is to consider the Young's interference fringes that would be present should the cross over volume be viewed on a screen. The separation of these fringes is determined by the beam angles and the wavelength of the light. The passage of a particle through a parallel fringe pattern would result in maximum light being scattered from the bright fringes and minimum from the dark fringes. The rate at which the particle traverses the fringes determines the frequency with which the intensity of the scattered light oscillates. The mathematics of this description can be shown to be identical to that of the Doppler frequency difference [118].

LDA was first applied to measurements of acoustic fields by Taylor in 1976 [119]. By detecting the light scattered by the vibrating particles within an acoustic field, a non-perturbing method of measuring the localised acoustic particle velocity was devised. The author also considered the relationship between acoustic frequency and the particle diameter required to ensure the particles faithfully followed the motion of the fluid for a range of particulate densities in air and water. It was theorised that this technique would be reliable at frequencies up to 50 kHz in air and higher in water.

Vignola *et al.* developed the technique to a position where measurements of particle displacements of 5 nm could be made from a 1.8 kHz frequency standing wave generated in a water filled tube, with a bandwidth of 10 kHz [120]. In addition to the particle motion caused by fluid flow or acoustic oscillation, the influence of Brownian motion was investigated, but although a broadening of the spectral peaks was observed, it was considered to be insufficient to seriously restrict the technique. Contemporary advances have negated the need for seeding of the volume with signal processing techniques, such as photon correlation, enabling particle velocity measurements to be made directly from natural particulates within a fluid [121–123]. A number of subsequent studies aimed at recording acoustic particle velocity from monotonic [124] and, more recently, complex acoustic fields [125] in air and water have been completed, predominantly at the University of Edinburgh. One additional study of interest is that of Galloway *et al.* who report the potential for application of LDA systems at frequencies greater than 100 kHz [126].

The major drawback in using LDA at extended frequencies is the acousto-optic interaction experienced by the optical beam passing through the acoustic field. It is known that a propagating acoustic pressure wave will cause localised changes in density, which will directly influence the refractive index of the media. Given that the optical beams are required to pass through the acoustic field prior to their crossing, it follows that the optical path length of each beam will not remain constant. More importantly, the difference between the optical path length of each beam, since it is this that forms the basis of the measurement, cannot be guaranteed to remain constant. It is convenient to consider this effect as causing the interference fringe pattern in the crossover region to move, which will influence the properties of the light scattered from within this region. Due to this acousto-optic influence the measured heterodyne frequency of the scattered light cannot be simply attributed to particle motion in the crossover region. This magnitude of this effect has been demonstrated theoretically and experimentally to be related to both the wavenumber and propagation distance of the laser light and the angle of incidence between the acoustic and optical beams [127,128]. At high sound frequencies and large propagation distances, the acousto-optic effect has been demonstrated to dominate the signal measured from scattering particles [129]. This causes an artificially high apparent particle motion measurement.

This phenomenon is of greater significance in underwater acoustics than airborne due to the increased changes in refractive index typically experienced. Whilst the piezo-optic coefficient for air ($\approx 2 \times 10^{-9} \text{ Pa}^{-1}$ [130]) is greater than that for water ($\approx 1.5 \times 10^{-10} \text{ Pa}^{-1}$ [131]), the pressure experienced for a given acoustic displacement are greater in water than air since the acoustic impedance of water is much greater.

In summary, the application of LDA for acoustic particle velocity measurements in air is effective since the particle displacement is several orders of magnitude greater than any fringe pattern motion caused by refractive index changes in the arms of the interferometer. The same is not true, however, for measurements in water, where the displacement of the particles is negligible compared to the fringe pattern motion caused by the refractive index changes.

2.4.6 Laser Doppler Velocimetry

Laser Doppler Velocimetry (LDV), sometimes known as laser vibrometry, is a well-established tool used primarily to record velocity measurements from the scattering elements of solid surface targets [132]. The principle of operation and the equipment used in LDV experimentation is intrinsically the same as that of LDA; the major difference being the use of the two beams between which the frequency difference is observed. In LDV, the two beams created from the laser source by the beam splitter are diverted such that only one is used to illuminate the target. The other ‘reference’ beam follows a path through a homogeneous medium usually sufficiently long enough to compensate for any coherence length discrepancy before being recombined with the target beam. The standard commercially available LDV equipment, based on the laser vibrometer proposed by Pickering and Halliwell [133], detects the frequency shift in back scattered light from the target. The geometry used is based on that of the Michelson interferometer.

Since the frequency of the returning light is too high to be measured directly by any opto-electric detector, it is mixed with the reference beam to create a measurable heterodyne frequency. Signals generated in this way are directionally ambiguous due to the heterodyne frequency representing the difference in frequency between the two beams. For this reason a frequency shift produced by a Bragg cell, diffraction grating or rotating target is included in one of the arms to offset the resultant heterodyne or beat frequency from zero. The photodetectors provide an output proportional to the intensity of the incident light. This is then demodulated to provide a voltage output proportional to the velocity of the target.

Throughout the work reported here, two Polytec LDV systems were deployed, each consisting of an optical head and an electronic controller unit: The OFV-302 standard optics head and OFV-3000 controller were used together to record velocities at frequencies lower than 150 kHz and the OFV-056 Scan head and OFV-3001-S controller for frequencies up to 1.5 MHz. A schematic representation of the key internal components of the OFV-302 standard optics head is given in Figure 2.4.6 and photographs of the respective units are shown in Section 3.6.1.

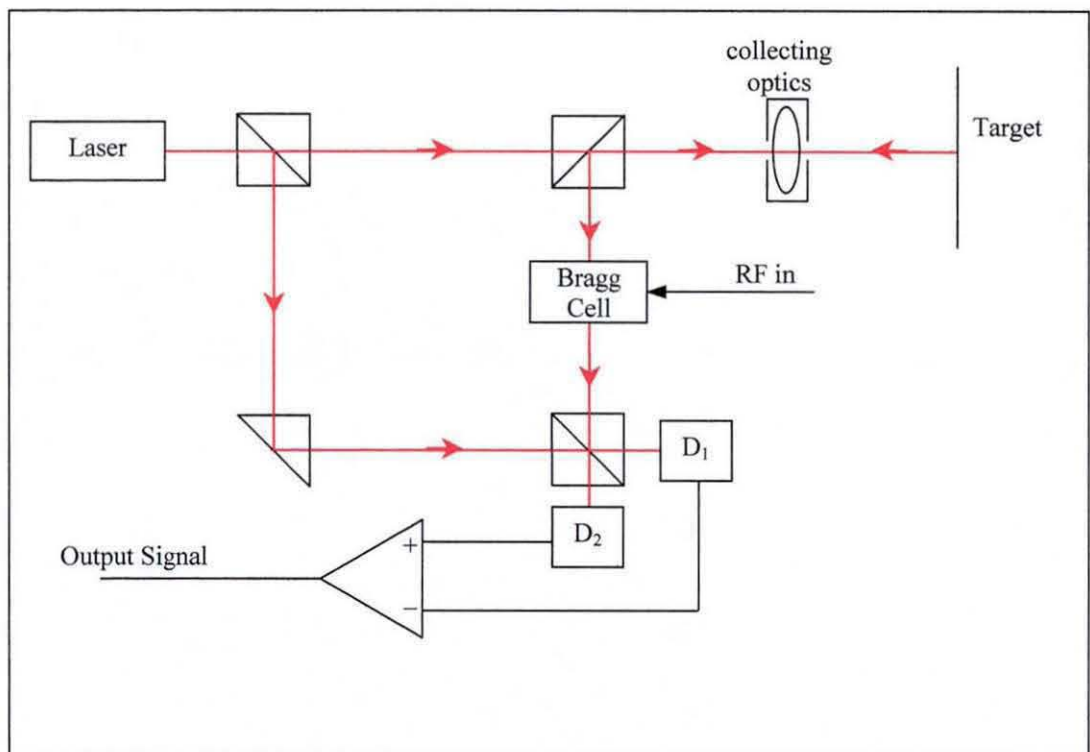


Figure 2.4.6: Internal Workings of LDV Optical Head

Laser Doppler Velocimetry has been applied to the measurement of underwater acoustic parameters in a number of different approaches taken by many researchers. One of the earliest usages of LDV in acoustics was reported by Huang and Achenbach, who successfully monitored the passage of a surface wave during its propagation over an aluminium plate [134].

Clearly, unlike metallic solids, the properties of water permit interrogation from within the medium using LDV, as in the case of the laser Doppler hydrophone reported by Crickmore [135,136]. In this arrangement, the target beam is passed through the volume and focused in a particular region of interest. The frequency of the light scattered by particulates within this region is then modulated by the motion of the particle. Crickmore makes reference to perhaps the most significant uncertainty present within such measurements, the acousto-optic influence on the path length of the target beam during its propagation through the volume.

In a hybrid system based on the principle of operation of the NPL Laser Interferometer, Huang and Yeubing reported a method for deriving underwater acoustic particle velocity through measurements from a suspended pellicle [137]. The technique was found to benefit over the NPL Laser Interferometer from increased simplicity and its ability to resolve acoustic signals from extraneous low frequency vibrations. This technique has been assessed alongside the NPL Laser Interferometer and results from a direct comparison are included in Section 3.6.2.1.

Much of the work reported in the subsequent chapters of this thesis is aimed at utilising the acousto-optic interaction, a source of uncertainty in many applications, to record measurements from underwater acoustic fields. Recently, studies at the University of Technology and Economics, Dresden have enabled measurements of the sound fields generated by loudspeakers, whistles, organ pipes and oscillators to be visualised in air. It is understood that this work is yet to be published.

2.5 CLOSURE

This chapter has detailed a range of measurement techniques, each of which have been applied to the measurement of underwater acoustic parameters. In general, the measurement methods in widespread use require a physical device to be placed within the field. This is likely to induce perturbation into the field and alter the acoustic characteristics. Recent advances in optical technology have enabled laser based methods to be utilised in the measurement of acoustic parameters. These are intrinsically non-perturbing, although it has been demonstrated that recording single point pressure measurements remains subject to large uncertainty.

The relative merits and drawbacks of each of the techniques discussed are summarised in Table 2.5.1, based on analysis of the reviewed literature.

It can be concluded, therefore, that there is a need for the further development of non-perturbing optical methods for the advanced measurement of underwater acoustic fields, to complement or surpass the techniques described here.

Technique	Merits	Drawbacks
Hydrophone	cheap, robust, reliable, portable	perturbing influence, limited bandwidth, resonant device
Capacitance Probe	wide bandwidth, high sensitivity, portable	perturbing influence, integration of pressure over plate area
Force Measurement	simple, robust	perturbing influence, can only measure time averaged intensity
Hydrophone Array	quick, robust	expensive, perturbing influence
Beam Calibrator	quick, robust, reliable	potential perturbing influence, only measure a single line section
PIV	non-perturbing, additional seeding not required	requires expensive equipment and complex post-processing
LDA	non-perturbing, additional seeding not required	requires expensive equipment, acousto-optic effect can inhibit measurement accuracy
Laser Doppler Hydrophone	non-perturbing	acousto-optic effect can inhibit measurement accuracy
NPL Laser Interferometer	highly accurate, reliable	potentially perturbing, requires controlled environment
ESPI	non-perturbing, simple, reliable, wholefield	path length integrals, temporal resolution limited by camera sample rate
Holographic Interferometry	non-perturbing, good spatial resolution	path length integral, poor temporal resolution
Schlieren and Diffraction	non-perturbing, wholefield, simple	predominantly qualitative measurement, path length integral

Table 2.5.1: Overview of Underwater Acoustic Measurement Techniques

Chapter 3

Characterisation of Equipment

3.1 INTRODUCTION

A variety of mechanical and electrical equipment is required to generate or detect an acoustic signal. This chapter begins by describing the manner in which the acoustic signals were generated, specifying the equipment employed.

The laboratory based experiments described within this work involve recording measurements from controlled, repeatable acoustic fields. Underwater acoustic transducers are used to facilitate the generation and detection of these signals. The source and detector transducers used in this work are characterised in this chapter. Conductance and susceptance plots are used to characterise each of the source transducers and frequency dependent sensitivity plots are presented for each of the hydrophones. Where appropriate, information regarding the calibration of the equipment is included. The calibration of underwater acoustic equipment enables traceability to primary standards, which themselves are defined in terms of laboratory based procedures.

Much of the work described in this thesis involves the application of Laser Doppler Velocimetry. Two Polytec LDV devices were used and each is characterised in this chapter. A comparison between the Polytec LDV and the NPL Laser interferometer is also included. The performance of a pellicle used as part of the NPL Laser Interferometer when suspended in a focused acoustic field is also assessed.

3.2 ELECTRICAL SIGNAL GENERATION

The mechanical source transducers used throughout this work were piezo-electric devices which required a dynamic voltage to generate an acoustic pressure wave. For reasons considered in more detail in Section 4.3.2, tone-burst acoustic signals were used extensively throughout this work. These consisted of a finite number of complete cycles at a given frequency followed by a period sufficiently long enough for the reverberating acoustic wave to die away.

Two electrical signal generators were used in tandem to generate the required sinusoidal voltage tone-bursts. A Philips PM5134 function generator was used to create a square wave signal oscillating at a frequency equivalent to the required repetition rate of the acoustic tone-bursts – usually 50 Hz. This signal was used as an input trigger for the Hewlett Packard 8111A pulse/function generator, which provided a predetermined finite number of sinusoidal oscillations of 10 volts in amplitude. The phase of each tone-burst began and ended at zero, enabling a linear acoustic field to be generated. The frequency range of each signal generator was sufficient to cater for each of the acoustic fields generated within this work.

In many applications of underwater or medical acoustics, amplification of this signal would be required to drive the acoustic source at an acceptable level. However, due to the comparatively short propagation distances required of the generated acoustic signal, the drive voltage provided by the HP 8111A pulse generator was found to be sufficient.

3.3 UNDERWATER ACOUSTIC SOURCE TRANSDUCERS

As has been previously mentioned in Chapter 1, the range of commercially available underwater acoustic source transducers is vast and varied, depending on the specific intended application. Within the work reported in this thesis, attention was focused on the frequency range from a few kHz to 1 MHz. This was due to a number of factors including the necessity to eliminate reflected signal components, described in more detail in 4.3.2 and the limited bandwidth of the LDV systems used to detect the signal. Consequently, a range of underwater acoustic source transducers were required to provide signals of an appropriate frequency, duration and beam shape.

3.3.1 Characterisation of Underwater Acoustic Source Transducers

Each of the transducers used within this work is detailed in the following sections using measured electrical parameters. A full explanation of the theory of this electrical analysis is beyond the scope of the work reported here, but a comprehensive methodology for characterising acoustic transducers using their equivalent electrical circuits is presented by Wilson [40]. Here, the author details methods of establishing motional resonance frequencies from plots of susceptance against conductance.

The receiving sensitivity of each of the measurement transducers used were established at a given frequency from the sensitivity plots presented. These were obtained through calibration procedures undertaken at NPL.

3.3.1.1 Piezo Electric Sounder

Early experimentation was carried out using a piezo electric sounder encased between two rubber sealed Perspex sheets, pictured in Figure 3.3.1. The sounder was attached to a length of aluminium tube, which was used to position the device within the water tank. An analysis of the electrical properties of the device was undertaken to establish the presence of any resonance frequencies, at which the generation of an acoustic signal would be achieved more efficiently. A plot of the susceptance against the conductance is given in Figure 3.3.2, from which the primary resonance can be identified at 78 kHz and the secondary resonance at 33 kHz.

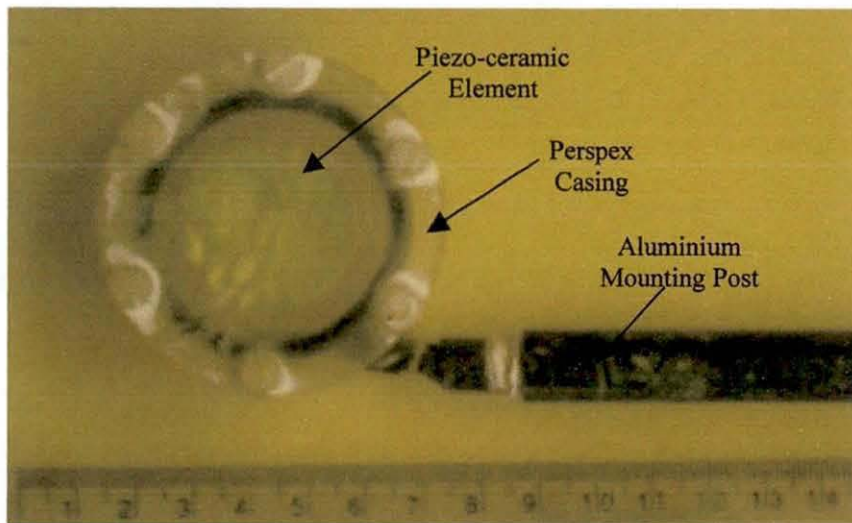


Figure 3.3.1: Piezo electric sounder

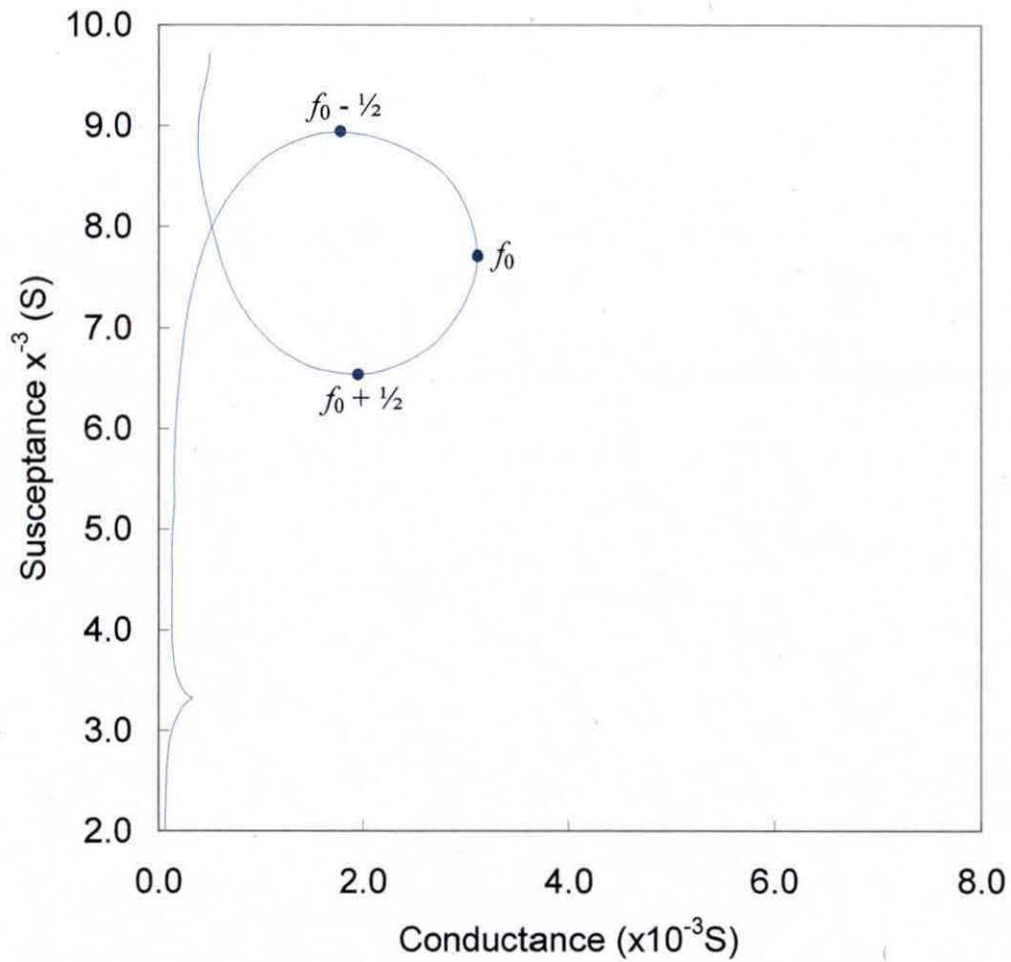


Figure 3.3.2: Susceptance against Conductance for Piezo electric sounder

3.3.1.2 Met-Optic Plane Piston Transducer

One source which was widely used throughout this work to generate acoustic signals at 180 kHz was the Met-Optic plane piston transducer. A picture of this device, held in an aluminium mounting designed for the experiments described in Chapter 9 is given in Figure 3.3.3. Unfortunately the manufacturers of this device are no longer trading and consequently, acquiring information regarding its construction has not been possible. The susceptance against conductance plot given in Figure 3.3.4 demonstrates the presence of a number of resonances. The most significant of these are found at 60 and 180 kHz. Consequently, this device was predominantly used to generate 180 kHz acoustic pressure waves. Spatial measurements described in this thesis show the shape of the field distribution to be approximately planar at 180 kHz.

3.3.1.3 Panametrics Immersion Transducers

Three Panametrics immersion transducers were utilised in the experimentation undertaken at high frequencies (≥ 500 kHz). These transducers were regularly used as auxiliary sources in NPL hydrophone calibration procedures, where a comparison between a reference and a test hydrophone require a repeatable acoustic field. These transducers are damped which enables them to have a very low Q . Each was chosen to generate a field with specific characteristics:

Panametrics V389: This transducer was used to generate 500 kHz converging acoustic waves. The casing of the device had an outer diameter of 38.1 mm and the concave front face caused the wavefront to focus 54.6 mm in front of the transducer.

Panametrics V3438: This was also a focused transducer intended to generate acoustic signals of 1 MHz frequency. The transducer was 25.4 mm in diameter and the concave front surface caused the acoustic wavefront to converge at a very tight focus (≈ 1 mm), 25.4 mm from the apex of the face.

Panametrics V302: This transducer was also 25.4 mm in diameter and used to generate a 1 MHz acoustic wave, similar to the V3438, although the shape of the field generated was planar as opposed to focused.

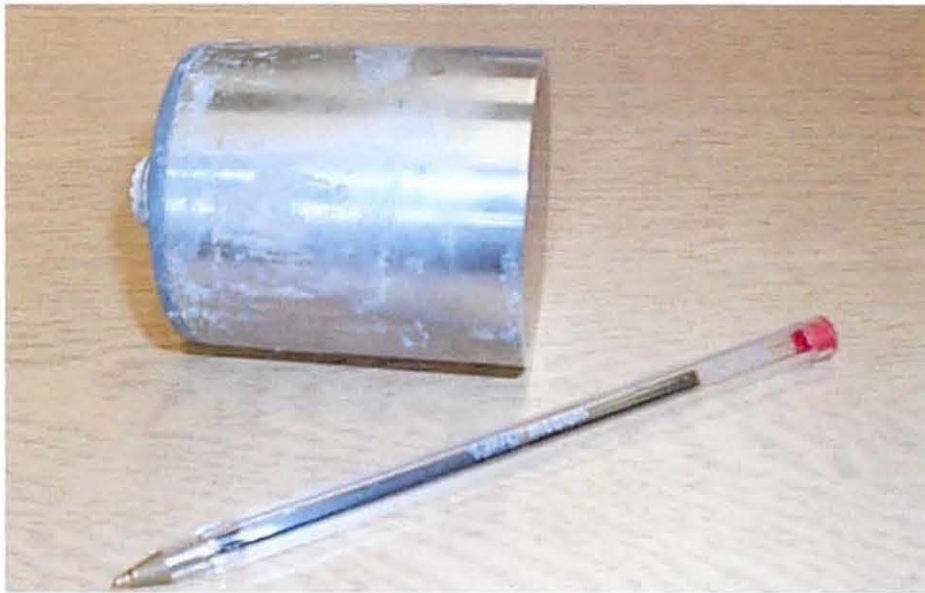


Figure 3.3.3: Met-Optic Plane Piston Source Transducer with 180 kHz resonance

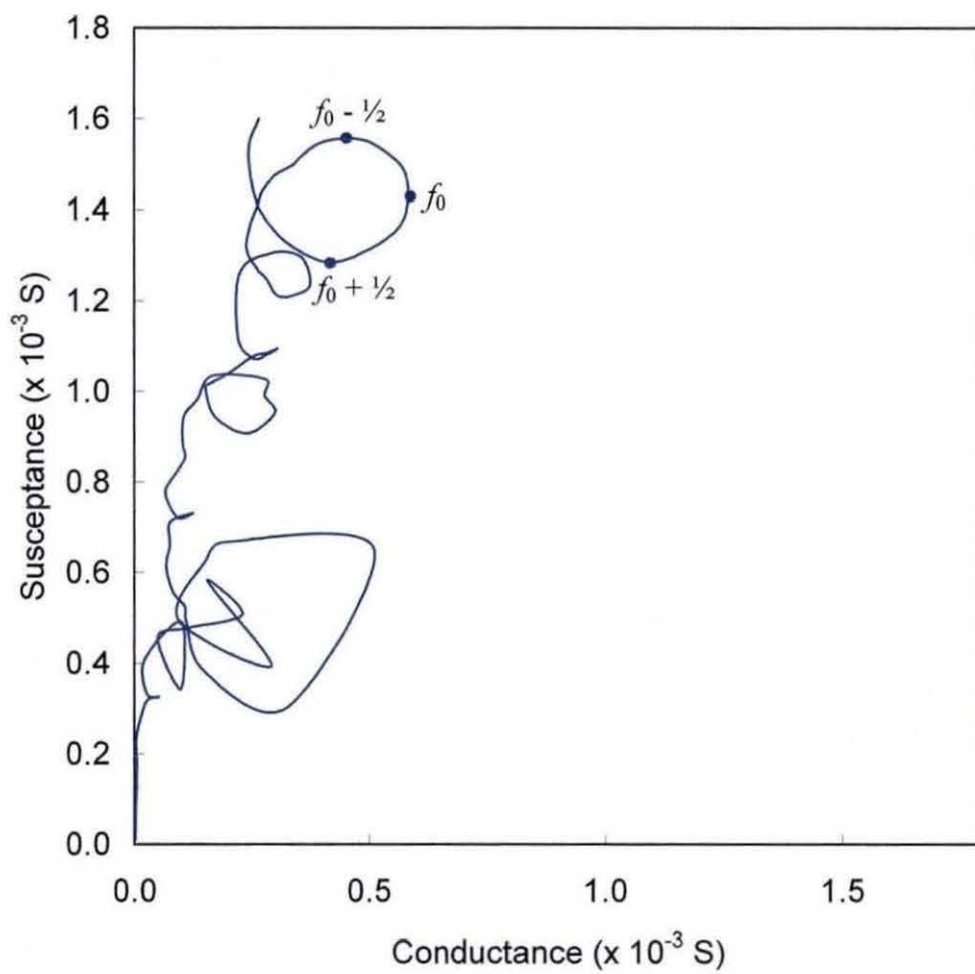


Figure 3.3.4: Susceptance against Conductance for Met-Optic Transducer

3.4 UNDERWATER ACOUSTIC MEASUREMENT TRANSDUCERS

Underwater acoustic measurement has been the subject of much research and as such has formed the motivation for the work undertaken and reported in this thesis. In analysing and assessing the relative merits of novel measurement methods, it was important to reference the results obtained to known standards. Two hydrophone devices were used to perform this function and are discussed in this section.

3.4.1 Characterisation of Underwater Acoustic Measurement Transducers

The construction of each of the transducers used in this work was such that the response of each was highly frequency dependent. Therefore the most significant characterisation required for their use throughout this work was a measure of their sensitivity at a particular frequency. Although the spectrum of an entire monotonic tone-burst consists of many more components in addition to the fundamental frequency, discussed in more detail in 4.3.2. For this reason, the steady state portion of the tone-burst, where only a signal frequency is present, was used in measurements where possible. This enabled the sensitivity at a particular frequency to be used to derive pressure from the voltage output from the hydrophone.

3.4.1.1 25.4 mm diameter ball hydrophone

The 25.4 mm diameter ball hydrophone, pictured in Figure 3.4.1, was chosen to measure acoustic signals below 100 kHz. The construction of this device was based around a lead zirconate titanate (PZT) ceramic sphere with a polyurethane casing.

The sensitivity plot, given in Figure 3.4.2, depicts the response of the device in the 10 kHz to 100 kHz frequency range. Due to the large sensitivity range across the bandwidth, the sensitivity is presented in decibels with respect to a reference sensitivity of 1 V/ μ Pa. As can be observed from this plot, the primary resonance can be found at 83 kHz, although an acceptable response was obtained at frequencies from 60 kHz to 100 kHz. The broadness of the primary resonance peak, demonstrated by the lower and upper half power points at 72 kHz and 82 kHz, enables the Q of the hydrophone to be calculated to be 8.3. The device was found to have an omni-directional response profile.



Figure 3.4.1: 25.4 mm diameter ball hydrophone

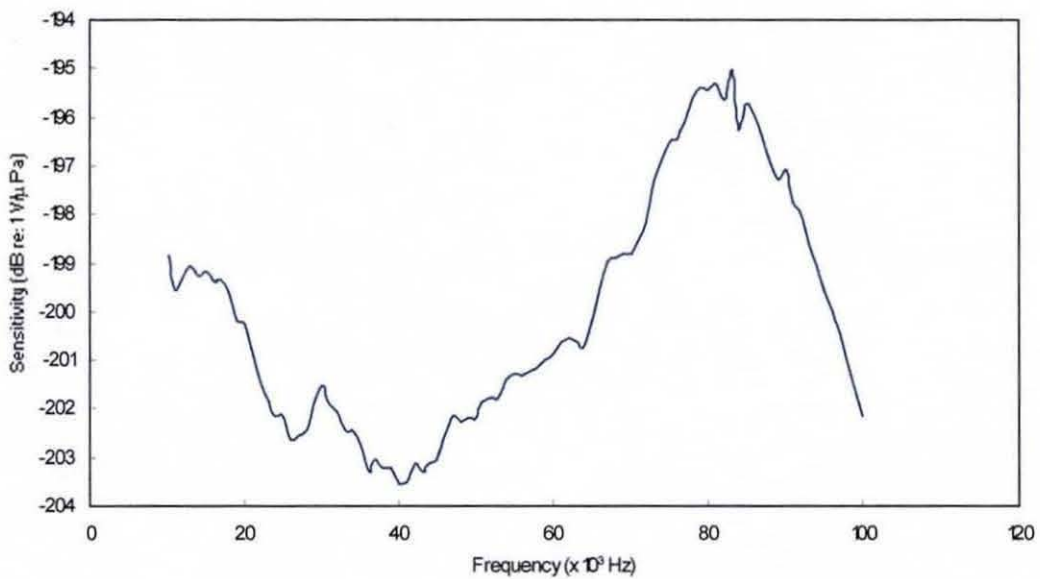


Figure 3.4.2: Frequency response of ball hydrophone

3.4.1.2 ITC 6128 Probe Hydrophone

For frequencies greater than the upper limit of the ball hydrophone, an International Transducer Corporation ITC 6128 test hydrophone, pictured in Figure 3.4.3, was used. The active element within this device is cylindrical, measuring 2 mm in diameter by 2 mm in length and is positioned approximately 5 mm from the tip of the polyurethane casing, orthogonal to the length of the unit. The casing, which is clearly substantially larger than the element, is included to offer a convenient means of mounting and positioning the element in a robust and reliable manner.

The working frequency range stated by the manufacturer of the device is 200 kHz to 600 kHz although the sensitivity in an extended bandwidth either side of these limits was found to be acceptable for measurements to be made. The hydrophone was calibrated at NPL and the resultant sensitivity plot is given from 10 kHz to 1 MHz in Figure 3.4.4. From this, the principal resonance can be identified to lie at 550 kHz. The half power points either side of this peak were found to occur at 525 kHz and 595 kHz respectively. This enables the Q of the ITC 6128 hydrophone to be calculated to be 7.9.

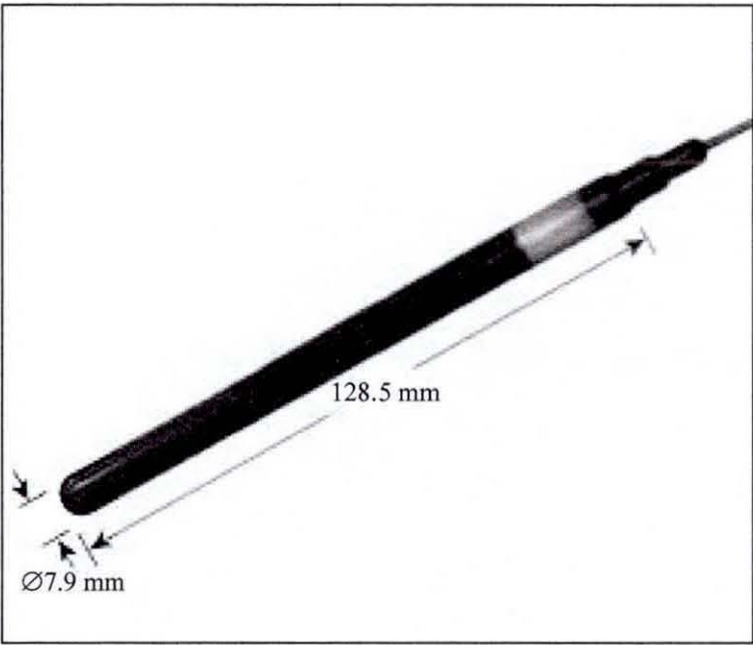


Figure 3.4.3: ITC 6128 hydrophone [138]

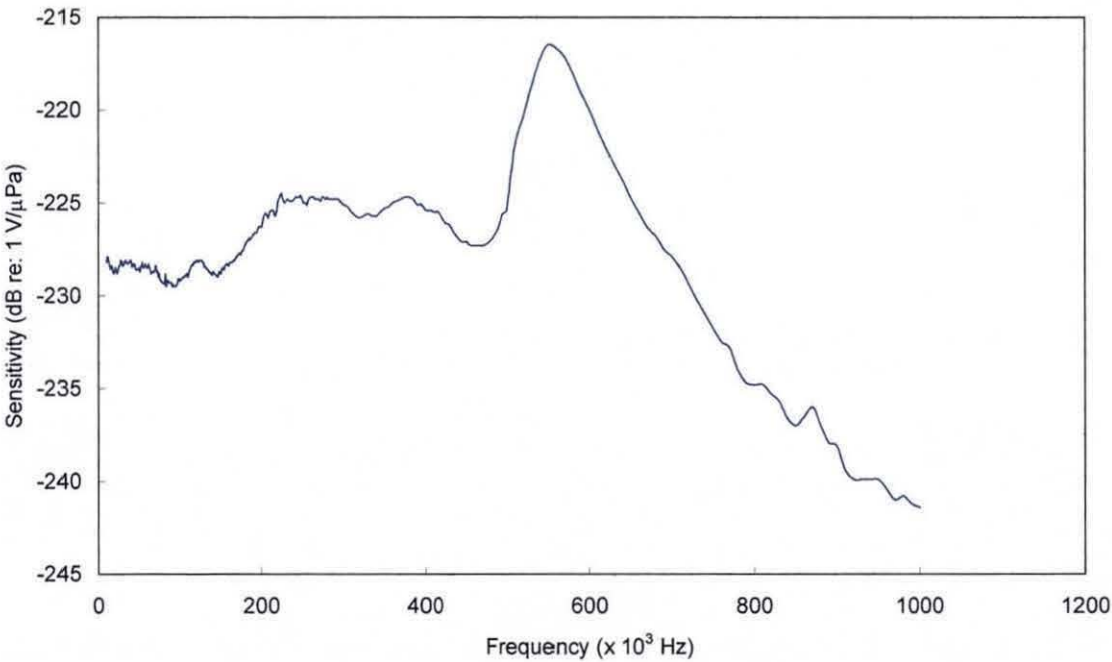


Figure 3.4.4: Frequency response of ITC 6128 test hydrophone

3.5 DATA ACQUISITION

In each of the experiments described in this thesis where a time resolved measurement is recorded, with the exception of those from the scanning LDV, the signal was displayed on an oscilloscope. The most commonly used oscilloscope was a LeCroy 9314 CL digital oscilloscope. This device enabled up to four signals to be sampled at a frequency of up to 40 MHz and displayed or mathematically manipulated in real time. Each signal recorded from an acoustic tone-burst, the most prevalent acoustic signal used in this work, was pre-triggered from the initial detection of the acoustic signal by approximately 10% of the measurement duration and a portion of signal greater than the duration of the tone-burst recorded.

Summed averaging of typically 100 sweeps was completed, each triggered in the same way such that the phase of the tone-burst remained consistent. Although a real-time frequency analysis capability was available within the functionality of the oscilloscope, this was not utilised, rather, only the time resolved signals were recorded. This decision was taken to conserve the memory required to store the measured data and increase the speed with which the averaging process could be calculated by the oscilloscope.

Perhaps the most significant advantage of using the LeCroy 9314 CL oscilloscope was the ability to export measured signals to a PC using the integrated floppy drive with ease. The generated files were saved in ASCII text format, which enabled straightforward processing in software such as *Microsoft Excel* or *Matlab*. All frequency analysis was undertaken using the Fast Fourier Transform (FFT) algorithm in *Matlab*.

3.6 OPTICAL MEASUREMENT METHODS

As has been reported in Section 2.4, the application of optical metrology methods has been widespread within underwater acoustics. Two particular optical measurement tools were employed in the work detailed in this thesis: Laser Doppler Velocimetry and Laser Interferometry. A comprehensive analysis of the vibrometer and interferometer devices that enable the application of these techniques is beyond the scope of this work, but reference is made to the general features and idiosyncrasies which define and limit their performance.

3.6.1 *Laser Doppler Velocimetry*

Two Polytec LDV systems were used in this work; the standard optic vibrometer for measurements at frequencies below 150 kHz and the scanning vibrometer for measurements at frequencies up to 1.5 MHz. Both these devices are characterised and reference is made to their calibration in the following sections.

3.6.1.1 *Characterisation of Polytec Standard Optic Vibrometer*

A commercially available LDV system, the Polytec Standard Optic Vibrometer, was used extensively throughout this work. It consisted of an OFV-302 standard optical head inside which the components described in Section 2.4.5 are positioned and an OFV-3000 controller used to convert the output signal from the optical head into a voltage proportional to the measured velocity. The optical head is pictured in Figure 3.6.1 and the controller in Figure 3.6.2. Five sensitivity settings were available to scale the velocity signal into a measurable voltage output signal. These were 1, 5, 25, 125 and 1000 mm/s/V, although wherever possible the 1000 mm/s/V setting was used to prevent the built in frequency filters from modifying the signal.

The other significant setting required for each measurement was the tracking filter, which could be set to either off, slow or fast. This was concerned with accounting for periods of signal drop-out, where the returning light was insufficient to be detected. Signal drop-out was interpreted by LDV as an instantaneously repositioning of the target to an infinite distance, with infinite velocity. This was not found to be a prevalent issue within this work and consequently this filter was switched off.



Figure 3.6.1: Polytec OFV-302 Standard Optical Head



Figure 3.6.2: Polytec OFV-3000 LDV Controller

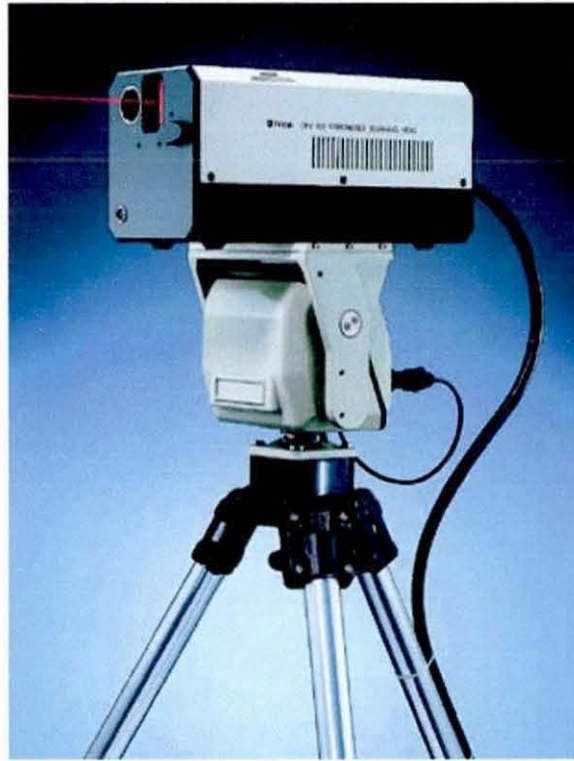


Figure 3.6.3: Polytec OFV-056 Scan Head [139]



Figure 3.6.4: Polytec OFV-3001-S controller and Data Management System [139]

3.6.1.2 Characterisation of Polytec Scanning Vibrometer

The Polytec 'Laser Scanning Vibrometer' is an optical metrology tool designed for recording measurements of surface velocity from multiple positions on a vibrating target. The unit consists of an OFV-056 Scan Head, depicted in Figure 3.6.3, and an OFV-3001-S LDV controller, shown in Figure 3.6.4. A 2-dimensional array of points is established with relation to a reference image provided by a CCD video camera positioned within the scanning head. The PSV software, described in more detail in Section 5.3.2, is then able to control the scanning mirrors to direct the laser beam at each point sequentially, where a measurement of velocity with time is taken. In standard mode, the real and imaginary components of the FFT of the velocity-time signal (with predetermined time range and sampling rate) are recorded and saved to disk by the controlling software.

In addition to the scanning capability, this LDV system could be used as a single point device similar to the standard optic LDV system with an increased frequency range.

3.6.1.3 Calibration of Polytec Vibrometers

Polytec, the manufacturers of the two LDV systems used throughout this work, have worked closely with the German National Standards Agency, the Physikalisch-Technische Bundesanstalt (PTB) to establish a method of calibrating their instruments enabling traceability to primary standards [139].

The calibration of a vibrometer is achieved using a comparison procedure with a known mechanical vibrator would be problematic since no transfer standard vibrator exists which can match the dynamic range of the vibrometer. Consequently, the calibration procedure employed makes use of the fact that the measurement system is based on a He-Ne laser, considered to be a stable length standard, and measures only the performance of the electronic components used to convert the Doppler frequency shift into an alternating signal. Test signals are generated at frequencies throughout the working range of the LDV system and the sensitivity profile is adjusted

accordingly. To gain an absolute calibration, however, at least one direct comparison with a mechanical oscillation standard must be undertaken.

Understandably, this calibration is undertaken to establish the fidelity of velocity measurements made from an oscillating target. This is in contrast to much of the work described throughout this thesis, although the principle behind the calibration makes it applicable regardless of the application.

When establishing the sensitivity of the Polytec vibrometers, the fact that the instruments are not based upon a resonant system means that they do not exhibit resonances within their response spectra in the same way as a physical device such as a hydrophone does. For this reason it cannot be considered to have a Q as such, but its wide bandwidth enables a near instantaneous response to be obtained. Various frequency filters are available within the LDV electronics, which can enhance the signal to noise ratio if applied correctly [139]. These filters are specified by a 3rd order low pass Bessel function, based on a specified cut-off frequency, f_c , as depicted in Figure 3.6.5. With the cut-off frequency of the OFV-056 / OFV-3000 (standard optic vibrometer) set to 150 kHz, the maximum available option, it can be seen that in theory the response of the instrument would be very stable across a 100 kHz bandwidth.

An actual calibration of the OFV-056 / OFV-3001-S scanning vibrometer yielded the trace depicted in Figure 3.6.6. As can be seen from the spectrum, the frequency response of this instrument is very stable across a 1 MHz bandwidth, dropping by just 0.5 dB at its extremities. This is close enough to the theoretical 3rd order low pass Bessel function depicted in Figure 3.6.5.

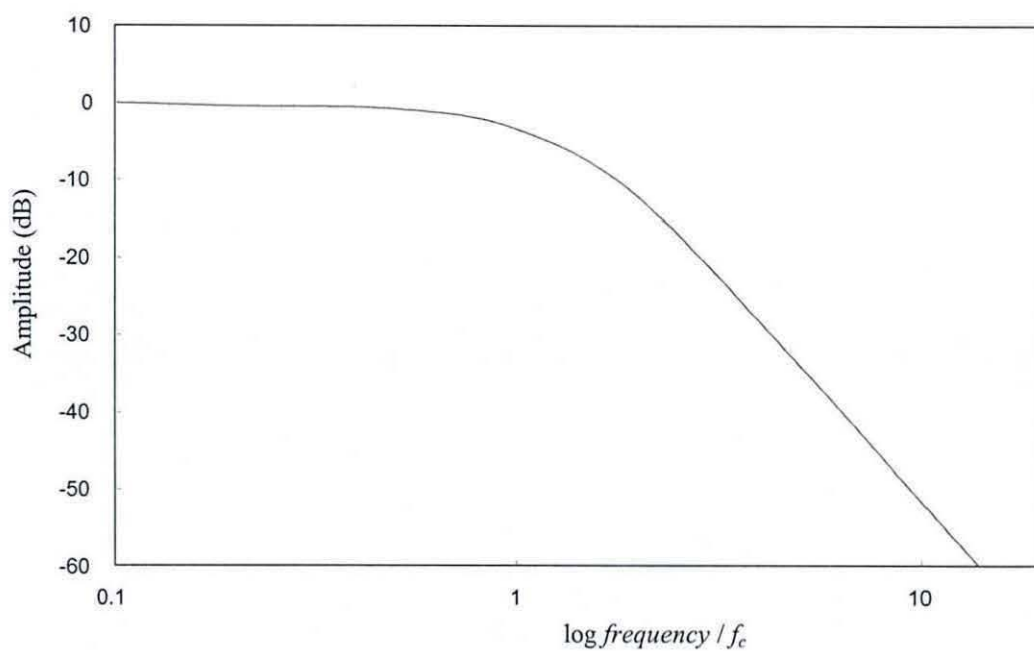


Figure 3.6.5: Amplitude frequency response of a 3rd order Bessel low pass filter

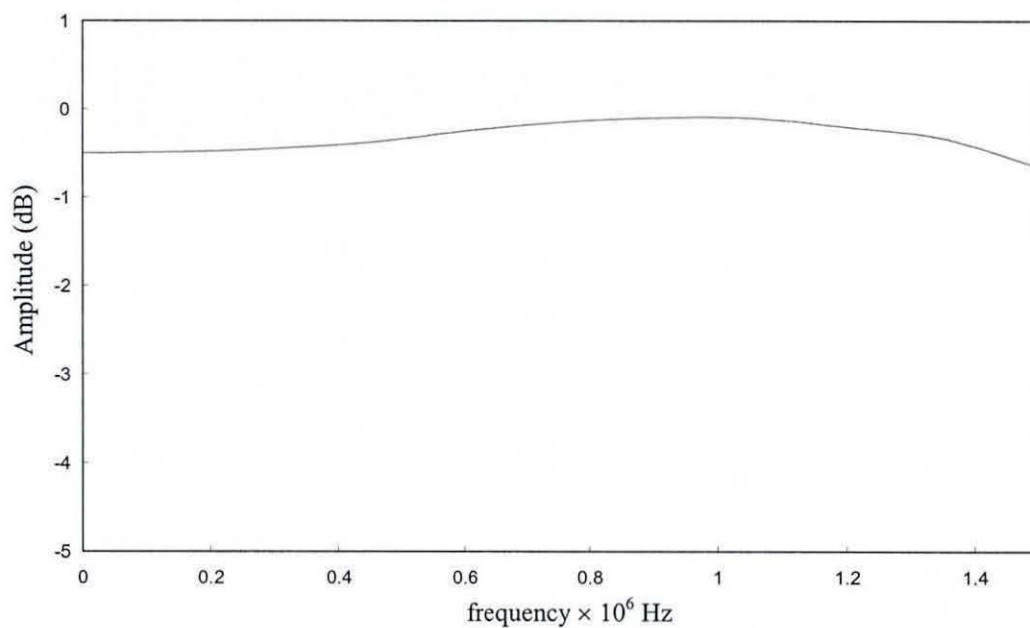


Figure 3.6.6: Normalised Frequency response of Polytec Scanning LDV

3.6.2 NPL Laser Interferometer

The development of the NPL Laser Interferometer (LI) has been well documented [73,35] and studies have been undertaken to establish its performance [74]. The principle of operation is described in Section 2.3.2, where the respective roles of the Michelson interferometer and the PVDF pellicle are described. As a means of establishing the performance of the NPL LI, measurements of an acoustic disturbance were compared with those measured by the Polytec OFV-056/OFV-3001-S LDV. Additionally, the response of the pellicle to an acoustic disturbance was investigated.

3.6.2.1 Comparison of LDV with NPL Laser Interferometer

As a means of assessing the relative performance of each of the optical measurement devices, a direct comparison was made between the LDV and NPL LI. Each instrument was used to measure the motion of a 100 mm diameter, 5 μm thick PVDF pellicle coated with 25 nm of gold, suspended within the acoustic field.

For reasons of practicality, simultaneous measurements were not possible, so a removable mirror placed on the axis of the NPL LI beam was used to direct the approach of the LDV beam. The beams were both focused onto the same point on the surface of the pellicle. A schematic of the arrangement used is given in Figure 3.6.7. Time histories of the surface velocity as measured by the LDV and displacement from the NPL LI were recorded for acoustic tone-bursts at two different frequencies and output levels. Comparisons were first made between the LDV velocity trace and the first time differential of the NPL LI displacement signal, and then between the NPL LI displacement trace and the first time integral of the LDV velocity signal. In each experiment, a calibrated membrane hydrophone was then substituted for the pellicle to record the pressure directly.

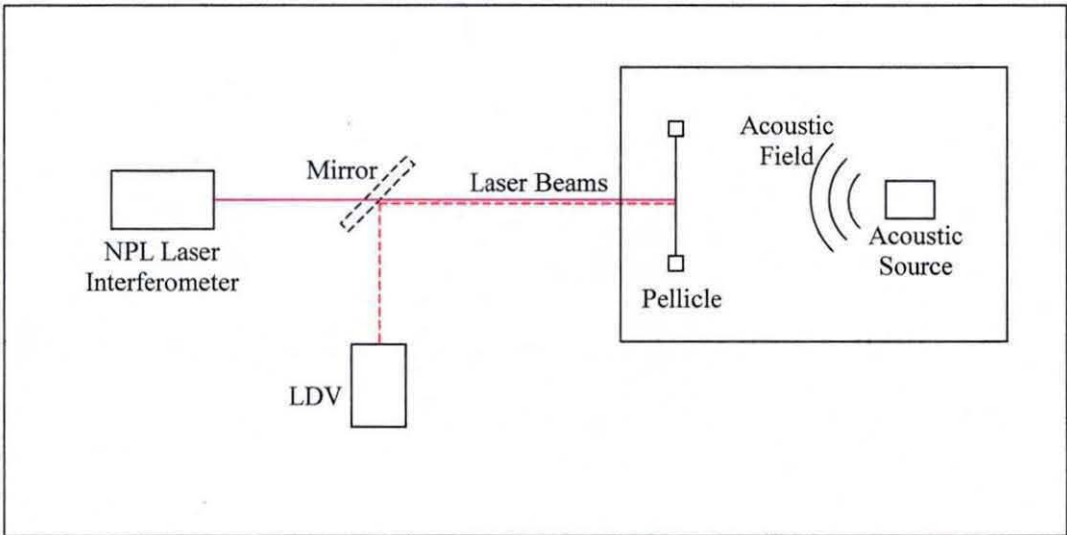


Figure 3.6.7: Measurements from a pellicle using NPL Laser Interferometer and LDV

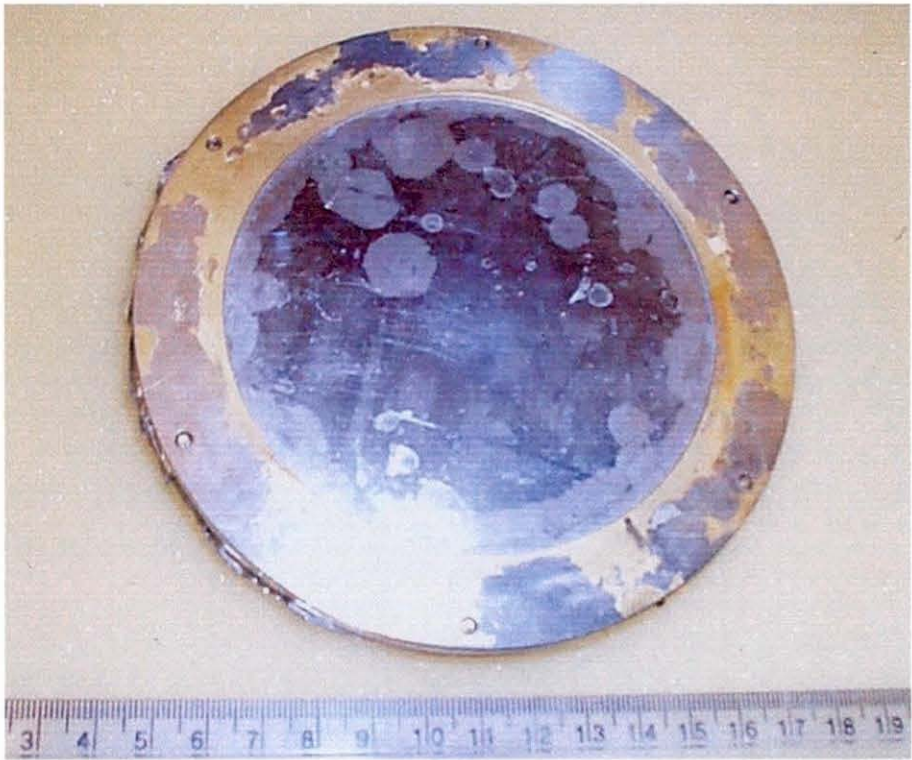


Figure 3.6.8: 100 mm diameter aluminium coated 5 µm PVDF pellicle

A three-way comparison was then made between the LDV, the NPL LI and the optical path displacement and velocity derived from a calibrated membrane hydrophone. Tone-bursts from a plane-piston transducer at 500 kHz and 1 MHz and a focused transducer at 1 MHz were used as the acoustic source. The lower working limit of the LI (0.2 MHz) and the higher limit of the LDV (1.5 MHz) limited the frequency range. Measurements were recorded for each condition using each device.

The output waveform from the NPL LI was differentiated with time to obtain the velocity, and the waveform from the LDV was integrated with time to obtain displacement. An integer number of cycles from a flat region of each measured tone-burst were extracted and Discrete Fourier Transforms (DFT) calculated. The magnitude corresponding to the fundamental frequencies of the DFT were used as a direct comparison, both for displacement and velocity. Since the two optical measurements could not be made simultaneously, two hydrophone measurements were made, with the element aligned with the position of the LDV laser beam in Hydrophone 1, and with the NPL LI in Hydrophone 2.

	Drive Voltage		Displacement (nm)	Velocity (m/s)
500 kHz Plane Piston Transducer	350 mV	Interferometer	11.59	36.94×10^{-3}
		LDV	12.02	38.47×10^{-3}
		Hydrophone 1	10.76	34.58×10^{-3}
		Hydrophone 2	10.35	33.88×10^{-3}
	450 mV	Interferometer	11.87	37.84×10^{-3}
		LDV	11.04	35.24×10^{-3}
		Hydrophone 1	11.44	36.51×10^{-3}
		Hydrophone 2	10.97	34.84×10^{-3}

Table 3.6.1: NPL LI and LDV measurements from 500 kHz plane piston transducer

As shown in Table 3.6.1, at 500 kHz, agreement between the two optical measurements is approximately 4% for the 350 mV drive voltage and 7% for the 450 mV. The two hydrophone measurements differ by approximately 4% in each case. This is an indication that there may have been discrepancies in the alignment of the devices in each set-up, thus it can be concluded that the agreement between the NPL LI and the LDV is similar to that of the two hydrophone measurements. Furthermore, it is an indication of one of the possible routine sources of uncertainty when using hydrophones.

	Drive Voltage		Displacement (nm)	Velocity (m/s)
1 MHz Plane Piston Transducer	350 mV	Interferometer	9.51	59.76×10^{-3}
		LDV	9.75	61.25×10^{-3}
		Hydrophone 1	9.31	58.32×10^{-3}
		Hydrophone 2	9.48	59.45×10^{-3}
	450 mV	Interferometer	10.39	65.55×10^{-3}
		LDV	10.36	65.16×10^{-3}
		Hydrophone 1	10.02	62.87×10^{-3}
		Hydrophone 2	10.11	63.42×10^{-3}

Table 3.6.2: NPL LI and LDV measurements from 1 MHz Plane Piston Transducer

For the plane piston transducer at 1 MHz, as shown in Table 3.6.2, the agreement is an improvement on the 500 kHz measurements; within 2.5% at 350mV and 1% at 450 mV. This improvement is reflected in the agreement between the two hydrophone measurements (1.8% and 1.9% respectively). Again, the LDV can be seen to compare equally as well with the NPL LI as with the 2 hydrophones.

	Drive Voltage		Displacement (nm)	Velocity (m/s)
1 MHz Focused Transducer	100 mV	Interferometer	25.59	141.45×10^{-3}
		LDV	7.99	50.56×10^{-3}
		Hydrophone 1	7.22	45.29×10^{-3}
		Hydrophone 2	20.62	129.44×10^{-3}

Table 3.6.3: NPL LI and LDV measurements from 1 MHz plane piston transducer

The results from the 1 MHz focused transducer shown in Table 3.6.3 show very poor agreement between the interferometer and the LDV measurements. The most likely reason for this is that the laser beam was not reflected from the position on the pellicle surface at the centre of the acoustic focus in each case. This is indicative of the problems experienced when using a tightly focused transducer since it is hard to find the focus and consequently difficult to align accurately. This reasoning is supported by the similar discrepancy between the two hydrophone measurements.

3.6.2.2 PVDF Pellicle

The performance of a pellicle similar to the ones used as part of the NPL Laser Interferometer primary calibration procedure described in Section 2.3.2 was investigated using the scanning LDV system. An example of a PVDF pellicle coated with a layer of aluminium is pictured in Figure 3.6.8, although the one used in the experiments reported here was coated in 25 nm of gold rather than aluminium. The displacement of the pellicle is assumed to be representative of the acoustic displacement since the close impedance matching of PVDF ($\approx 1.2 \times 10^5 \text{ kg/sm}^2$) with water ($\approx 1.5 \times 10^5 \text{ kg/sm}^2$) enables the pellicle to faithfully follow the motion of the immediately adjacent fluid. Investigations into the perturbing influence of a PVDF pellicle are reported in Section 7.3.2.

The primary calibration procedure for frequencies between 500 kHz and 20 MHz in the UK involves comparing a measurement of time-resolved pressure from a membrane hydrophone suspended in the field with a measurement of displacement from a point on the surface of the pellicle. Ideally the position of the laser beam on the pellicle should correspond directly to the position of the hydrophone element, but, due to the very small dimensions of the element (< 1 mm [35]), this is subject to uncertainty. This uncertainty in the alignment is manifest in the discrepancy between the measurements from the respective instruments presented in Section 3.6.2.1.

It is highly likely that discrepancies were present in each of the measurement scenarios, although the nature of the measured fields minimised the resultant measurement error in certain situations. For example in the case of a planar wavefront, the phase and amplitude of the pressure, and consequently the acoustic displacement, are known to remain constant at small displacements from the acoustic axis in a measurement plane, such as that described by the position of the pellicle. Subsequently, inaccurate alignment of the laser beam with the hydrophone element will not yield high levels of inaccuracy in the measurement. However, where the acoustic beam is specifically shaped, such as that generated by the Panametrics V3438 transducer, accurate alignment of the laser beam with the active element of the hydrophone is essential, as illustrated by the poor correlation in the results of Section 3.6.2.1.

For this reason, an assessment of the motion of the pellicle at positions away from the acoustic axis was undertaken. The scanning LDV described in Section 3.6.1.2 was used to record the time-resolved velocity of a 25 mm diameter circular area on the surface of the pellicle. The pellicle was suspended at the focus of a field generated by the Panametrics V3438 transducer. A tone-burst consisting of 10 complete cycles was generated at 1 MHz and the velocity at 745 discrete positions was measured. From the resultant spatially resolved data, images representing the velocity distribution at 4 instants in time separated by $0.2 \mu\text{s}$ were created. These are shown as colour scaled surface plots in Figure 3.6.9 and colour scaled images in Figure 3.6.10. Two additional images were also created depicting the magnitude and phase of the distributed velocity. These are shown in Figure 3.6.11 and Figure 3.6.12

and were obtained from the 1 MHz component of the magnitude spectrum calculated using Fast Fourier Transforms (FFTs) of the time-resolved data. The magnitude image is scaled using a normalised logarithmic scale where each value is divided by the maximum value within the image. More detail about the formation of these images is given in Section 5.3.4 of this thesis.

The resultant images demonstrate highly non-linear spatial distribution of the velocity amplitude at positions around the focus of the acoustic beam. As can be observed from the magnitude image given in Figure 3.6.11, less than 10 mm from the peak velocity found at the centre of the focus, the measured velocity amplitude was found to be reduced by 1 order of magnitude. This adds justification to the theory that misalignment of the respective measurement transducers was responsible for the poor correlation between the LDV, NPL LI and membrane hydrophone, proposed in Section 3.6.2.1. The discrepancy of approximately 0.3 observed between these measurements could be attributed to an alignment discrepancy of just 5 mm.

Another significant finding was the difference in phase observed throughout the measured region of the pellicle. Figure 3.6.12 depicts this phase distribution as concentric rings emanating from the central position of peak velocity amplitude. It is evident from this image that the phase of the velocity measured approximately 7 mm from the centre would lag that of the central measurement by π . Unfortunately the phase of the respective measurements made in 3.6.2.1 was not recorded, making it impossible to use the phase distribution to establish the precise location of the measurement.

Whether the magnitude and phase distribution measured using the scanning LDV system were a direct function of the acoustic displacement, or a function of surface waves generated in the PVDF by the acoustic excitation or a combination of both cannot be ascertained. However, it is anticipated that measurements of the acoustic distribution within the field undertaken later in this thesis will assist in establishing the cause.

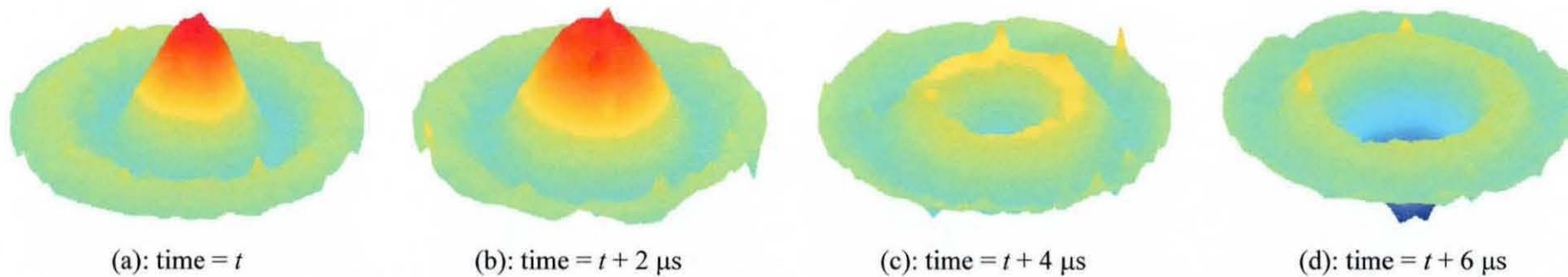


Figure 3.6.9: Colour scaled surface reconstructions of pellicle velocity

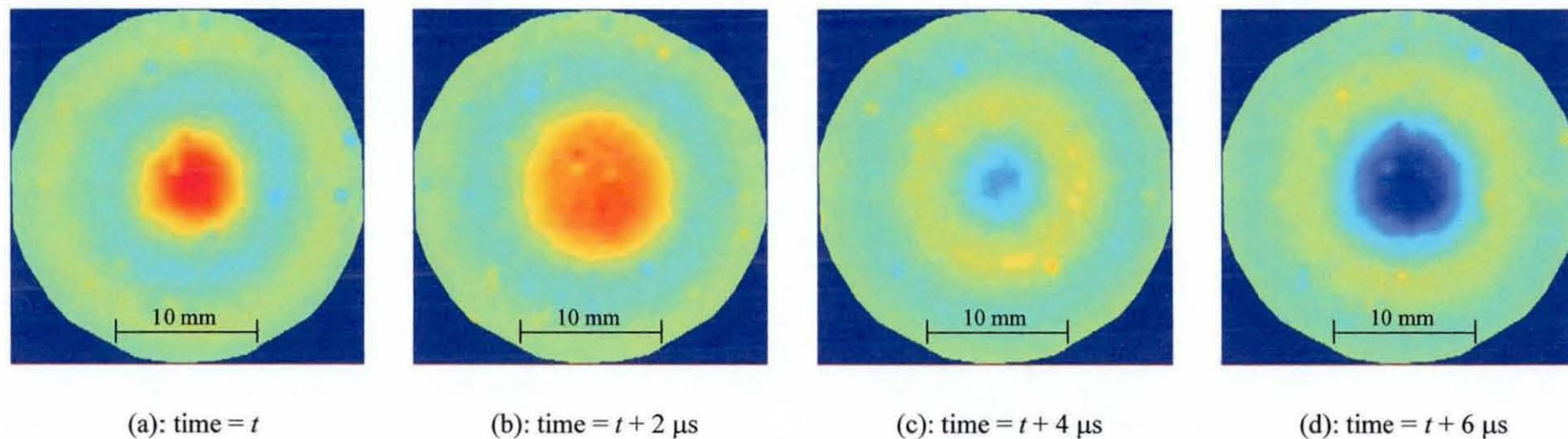
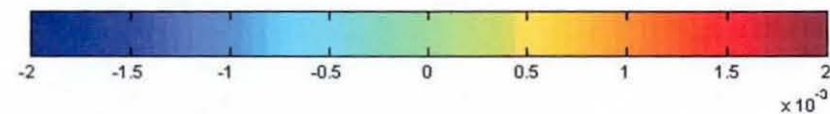


Figure 3.6.10: Colour scaled images of pellicle velocity (m/s)



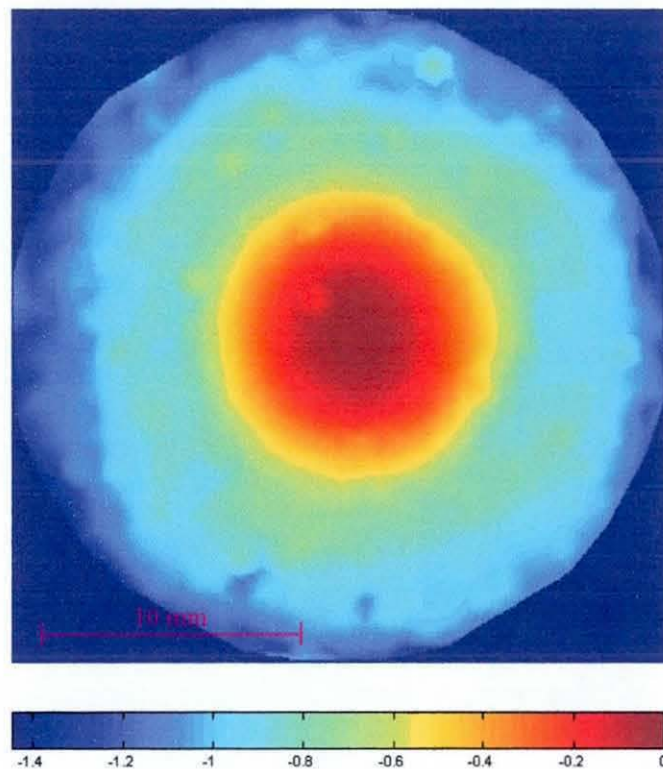


Figure 3.6.11: Normalised magnitude of velocity amplitude of pellicle in field

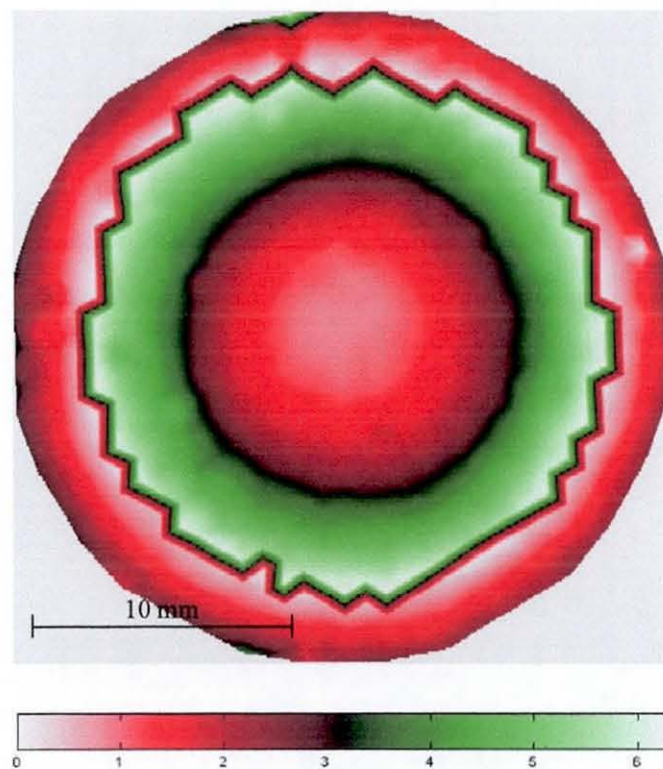


Figure 3.6.12: Phase distribution of pellicle in field

3.7 CLOSURE

This chapter has introduced the equipment that was used to carry out the experimentation reported in this thesis. Where possible, the source transducers were used on or around their resonance frequencies in order to maximise the pressure amplitudes generated from a given voltage supply.

The direct comparisons made between the results from the NPL Laser Interferometer and the Polytec LDV demonstrated excellent similarities of 4% and 7% for the two drive voltages at 500 kHz and 2.5% and 1% for the two drive voltages at 1 MHz. The measurements made concurrently using a membrane hydrophone showed agreement within 4% at 500 kHz and 1.8% and 1.9% at 1 MHz. This demonstrated the capability of the LDV to accurately record measurements of pellicle velocity. Results obtained from a similar comparison for a 1 MHz focused field illustrated the need to consider the spatial distribution of underwater acoustic fields. The discrepancy between the three measurement methods was an indicator of both the poor alignment of each transducer and the highly non-linear spatial distribution of the field. These are both important considerations when recording single point pressure measurements.

The assessment of the PVDF pellicle motion yielded results which also demonstrated the highly non-linear spatial distribution of the field generated by the Panametrics V3438 focused transducer at 1 MHz. These results also enabled the progress of a radiating wave to be monitored on the surface of the pellicle. From this the spatial distribution of both amplitude and phase across a 25 mm $\times$ 25 mm area was established.

Chapter 4

Non-perturbing Laser Doppler Velocimetry Measurements from Underwater Acoustic Fields in One-Dimension

4.1 INTRODUCTION

This chapter introduces the concept of recording measurements directly from underwater acoustic fields utilising the acousto-optic interaction between optical and acoustic wavefronts. The piezo-optic coefficient is used to describe the relationship between the pressure and refractive index of a media. A simple formula is presented to enable the piezo-optic coefficient to be calculated at different water temperatures.

Additionally, the principle of operation of laser Doppler velocimetry is explained in detail since this instrument is to be used to record measurements in the experimentation reported in subsequent chapters. Careful consideration is given to the interpretation of measurements made by this instrument, conventionally assumed to represent target surface velocity.

A theoretical analysis of the passage of a laser beam from an LDV through a simple acoustic field is presented. This mathematical description is then developed to cater for more complex acoustic fields and a general solution is derived.

The results of preliminary investigations are presented, where an LDV is used to record optical path length changes induced by an acoustic signal. Experimental conditions used include standing waves and tone-bursts. A discussion is presented which establishes the minimum acoustic signal frequency required to eliminate the presence of reflected signal components for a 10 cycle tone-burst and a given sized water tank.

Measurements were recorded from 2 and 6 cycle tone-bursts at 80 kHz and a 10 cycle tone-burst at 500 kHz. Results from these experiments are then compared with the rate of change of optical path length calculated from the integral of the refractive index at discrete positions derived from the pressure measured by a hydrophone.

Finally, the minimum resolvable pressure amplitude required to facilitate a measurement using the LDV and hydrophone is established for tone-burst acoustic signals at 80 kHz and 500 kHz.

4.2 THEORETICAL ANALYSIS

In order to gain an understanding of the method by which measurements of underwater acoustic parameters might be made using Laser Doppler Velocimetry, theoretical consideration is given here to the interaction between acoustical and optical beams. In addition, the principle of operation of Laser Doppler Velocimetry and the application of Laser Doppler Velocimetry to measurements directly from acoustic fields is investigated.

4.2.1 Piezo-Optic Coefficient

The influence of pressure on refractive index has been well documented beginning with the initial experiments recorded by Debeye and Sears [76] and Raman and Nath [140]. The piezo-optic coefficient, $\left(\frac{\partial n}{\partial p}\right)$, is a constant of proportionality relating refractive index with pressure and can be measured directly or deduced using theoretical assumptions [131]. The first experimental values were obtained by Raman and Venketaraman in 1939 [141], and further studies have been undertaken by Reisler and Eisenberg in 1965 [142]. A distinction is made between the isothermal and adiabatic forms of this coefficient, although it is noted that for water, the values of both these coefficients are very similar, as given in Table 4.2.1. For the experimentation described here, the adiabatic form is used since the acoustic period is too short for any heat transfer to take place [143].

	$\left(\frac{\partial n}{\partial p}\right)$	
Temperature	Isothermal	Adiabatic
(°C)	($\times 10^{-10} \text{ Pa}^{-1}$)	($\times 10^{-10} \text{ Pa}^{-1}$)
15	1.515	1.508
20	1.486	1.473
25	1.463	1.444

Table 4.2.1: Piezo-Optic Coefficients for Water ($\lambda = 633 \text{ nm}$) [131]

The value used throughout this experimentation is taken as $1.503 \times 10^{-10} \text{ Pa}^{-1}$ for an optical wavelength, $\lambda = 633 \text{ nm}$ (He-Ne Laser) and a water temperature, $T = 17.0^\circ \text{C}$. The working temperature range was measured to be between 16.0°C and 18.5°C with a median of approximately 17.0°C . This was obtained using a simple quadratic approximation given in Equation (4.2.1), representing the curve of best fit for the data given in Table 4.2.1,

$$\left(\frac{\partial n}{\partial p} \right) \approx 1.2 \times 10^{-14} T^2 - 1 \times 10^{-12} T + 1.638 \times 10^{-10} \quad (4.2.1)$$

Equation (4.2.1) represents a curve of best fit for the temperature dependant values of the piezo-optic coefficient presented in Table 4.2.1. These values were calculated using thermodynamic data and the equation for the dependence of refractive index on temperature and density proposed by Eisenberg [144].

4.2.2 Laser Doppler Velocimetry

As described in Section 2.4.5, Laser Doppler Velocimetry is traditionally a technique for making non-invasive measurements of surface motion or fluid flow [132]. By comparing the wavelength of the light emitted by the laser source with that scattered from the reflecting target, the LDV has been shown to be effective in measuring the rate of change of optical path length travelled by the light beam. The light incident on the LDV photo-detector is Equation (4.2.2).

$$E_T(t) = E_T \cos \left(\frac{2\pi}{\lambda} t + \varphi_T - 2ka_v \sin \omega_v t \right) \quad (4.2.2)$$

where λ is the wavelength of the laser light, E_T and φ_T are the respective amplitude and phase of the light incident at the detector when the path length is in its natural state, and a_v and ω_v are the respective amplitude and frequency of the optical path length change. When the heterodyne of the signal and the carrier frequency is demodulated, a time-resolved analogue voltage, representative of the rate of change of optical path length is produced.

4.2.3 Theoretical Analysis of LDV laser beam passage through an underwater acoustic field

If a laser beam is passed through an active acoustic field, the optical path length will be influenced by the changes in pressure. An LDV has the advantage over a first-order interferometer, such as a Michelson or Mach-Zender [51], of providing an output voltage dependent on velocity rather than displacement. This results in the response of the LDV being determined not only by the magnitude of the path length change, but also the frequency with which this change occurs, as will subsequently be demonstrated.

A quantifiable definition of what the optical beam from an LDV measures when it is passed through an acoustic field is derived by considering a line section through the field parallel to an axis, z , as depicted in Figure 4.2.1. A simple acoustic field can be considered as consisting of a perfectly planar continuous wavefront of single frequency, f , travelling parallel to an axis, x , normal to the line section. The time resolved pressure amplitude at a point along the line, $p_{(z)}(t)$, is described in Equation (4.2.3), where A and Φ represent the amplitude and phase respectively

$$p_{(z)}(t) = A \sin(2\pi ft - \Phi) \quad (4.2.3)$$

At any position along the laser line section through the simple plane wave, the pressure variation with time will be identical, as depicted in Figure 4.2.1. In practice this is unattainable and a plane wave will show a variation in amplitude and phase with distance along the line. However, as perfect plane wave conditions are approached, these amplitude and phase variations are minimised. Figure 4.2.2 shows an example of a field where the amplitude and phase of the instantaneous pressure distribution are not constant with distance along the laser beam line, and whilst the wavefront curvature is exaggerated for the purpose of visualising the effect, an amount of curvature is inevitable in any propagating acoustic wavefront. However, for the purposes of the analysis that follows, the simplified plane wave described in Equation (4.2.3), where the amplitude, A , and the phase, Φ , remain constant with distance along the line in z , is used as an adequate approximation.

The acoustic pressure amplitude and propagation distance are both considered to be sufficiently small to ensure the propagating wavefront behaves in an entirely linear fashion unlike high-pressure waves where distortions are introduced with distance travelled [38]. Hence, the phase is determined simply by the tangential distance from the acoustic source to the position of the laser beam, x_0 , the sound velocity in water, c , and the initial phase of the wave generated by the transducer, Φ_0 . In the majority of experimental cases, and indeed throughout this work, this is equal to zero, $\Phi_0 = 0$.

$$\Phi = \Phi_0 + \frac{cx_0}{2\pi f} = \frac{cx_0}{2\pi f} \quad (4.2.4)$$

The time-resolved refractive index at a point along the line, $n_{(z)}(t)$ is related to the pressure variation:

$$n_{(z)}(t) = n_0 + \left(\frac{\partial n}{\partial p} \right) p_{(z)}(t) \quad (4.2.5)$$

where n_0 is the ambient refractive index of the media. From this the optical path length, $l(t)$, can be described in Equation (4.2.6).

$$\begin{aligned} l(t) &= \int_{z_1}^{z_2} n_{(z)}(t) dz \\ &= l_0 + \int_{z_1}^{z_2} \left(\frac{\partial n}{\partial p} \right) p_{(z)}(t) dz \\ &= l_0 + \left(\frac{\partial n}{\partial p} \right) p_{(z)}(t) \int_{z_1}^{z_2} dz \\ &= l_0 + \left(\frac{\partial n}{\partial p} \right) p_{(z)}(t) \left[z \right]_{z_1}^{z_2} \\ &= l_0 + (z_2 - z_1) \left(\frac{\partial n}{\partial p} \right) p(t) \end{aligned} \quad (4.2.6)$$

where l_0 is the ambient optical path length equal to the product of the refractive index, n , and distance through the media, where z_1 and z_2 define the limits of the region of interaction between the laser beam and the acoustic field

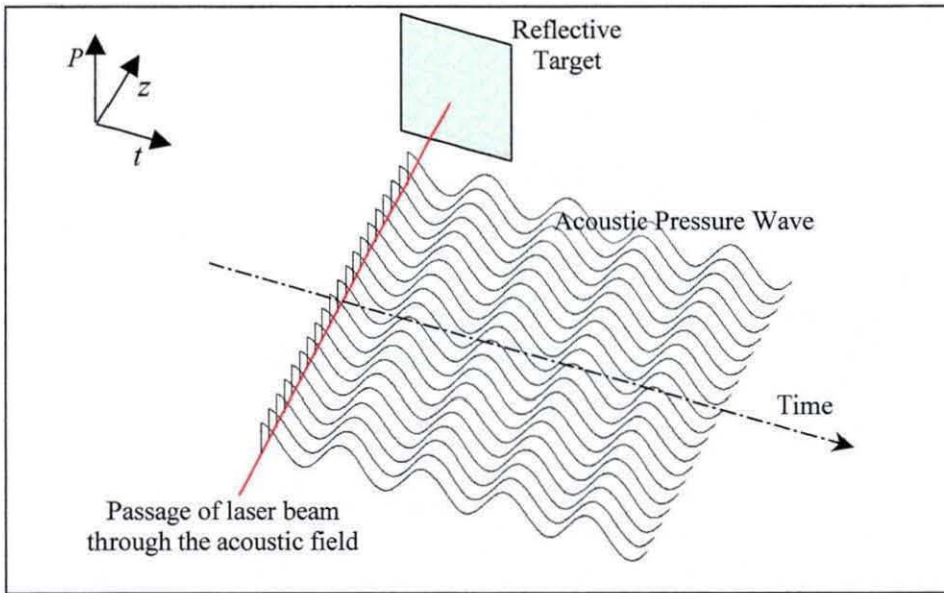


Figure 4.2.1: Pressure time variation of a line section through a simplified planar wavefront, where amplitude and phase are constant with distance through the field.

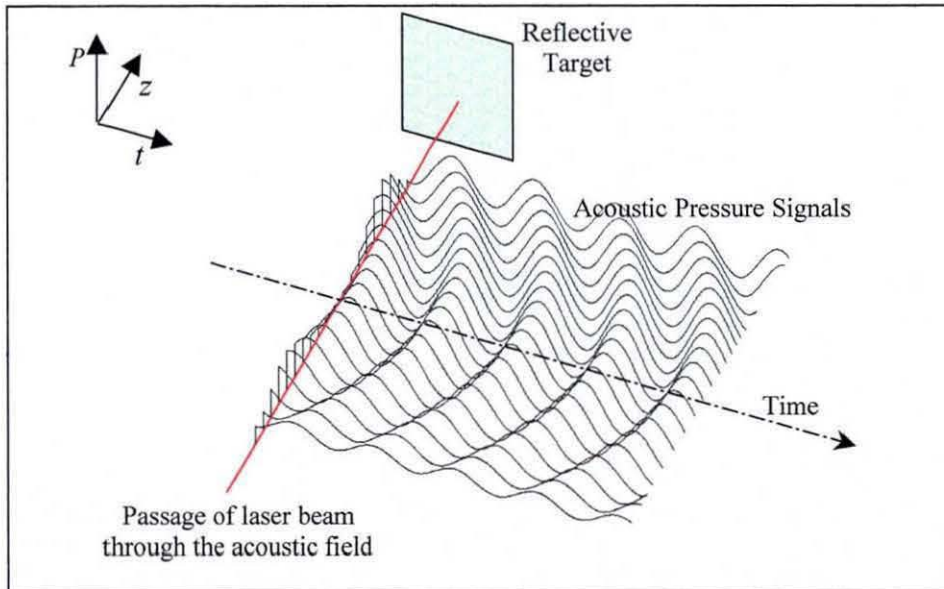


Figure 4.2.2: Pressure time variation of a line section through a curved wavefront, where amplitude and phase are an unknown function of distance through the field.

The rate of change of optical path, $\frac{dl(t)}{dt}$, is given by the first differential with respect to time of the optical path length.

$$\begin{aligned}\frac{dl(t)}{dt} &= (z_2 - z_1) \left(\frac{\partial n}{\partial p} \right) \frac{d(p(t))}{dt} \\ &= 2\pi f (z_2 - z_1) \left(\frac{\partial n}{\partial p} \right) A \cos(2\pi f t - \Phi)\end{aligned}\quad (4.2.7)$$

It is common for an LDV to detect the scattered light using collecting optics situated behind the same aperture through which the originating beam is projected, as was depicted in Figure 2.4.6. Consequently, the beam is required to be returned along its axis, which is typically achieved by reflection from a target. By ensuring that the target does not move, any detected change in path length can be attributed to changes in refractive index as opposed to a variation in the physical distance travelled by the laser beam. Hence the rate of change of optical path length measured by the LDV is double that given in Equation (4.2.7), resulting in the time-resolved output voltage from the LDV, $V(t)$, which is proportional to the rate of change of optical path length, given as,

$$V(t) = 4\pi f K (z_2 - z_1) \left(\frac{\partial n}{\partial p} \right) A \cos(2\pi f t - \Phi) \quad (4.2.8)$$

where K is the sensitivity scalar of the LDV electronics. This scalar determines the voltage output for a given measured rate of change of optical path length and takes the units of m/s/V. Five discrete settings were available on each of the LDV controller units used: 1, 5, 25, 125 and 1000 mm/s/V.

If the acoustic plane wave is generated by a plane-piston acoustic transducer of circular cross section, as is typically the case, further simplification can take place given the assumption that the field is perfectly planar. Here, the limits of the integral can be expressed in terms of the radius of the transducer, r , such that Equation (4.2.8) becomes

$$V(t) = 8\pi f K r \left(\frac{\partial n}{\partial p} \right)_s A \cos(2\pi f t - \Phi) \quad (4.2.9)$$

Equation (4.2.9), derived from analysis of a simplified planar acoustic wave, enables the general relationship between the controlling variables and the output voltage to be established. An increase in either the amplitude of the acoustic pressure, A , the radius of the transducer, r , the LDV sensitivity scalar, K , or the frequency of the acoustic excitation, f , will increase the amplitude of the output voltage accordingly. The frequency of the output voltage is determined by the acoustic frequency and the phase, Φ , is determined by the propagation distance x_0 .

4.3 EXPERIMENTAL METHODOLOGY

Preliminary investigations were undertaken to establish the potential for successfully recording measurements from an underwater acoustic field using Laser Doppler Velocimetry. Such experiments were undertaken initially in a $2\text{ m} \times 1.5\text{ m} \times 1.5\text{ m}$ water tank in the Centre for Underwater Acoustics at NPL in Teddington. Here the laser beam from a Polytec OFV-302 Standard Optics Head LDV was directed through an optical window and reflected from a gold coated PVDF pellicle, intended for use as part of the NPL Laser Interferometer primary calibration system [73]. The typical arrangement for recording displacement measurements from the pellicle is depicted in Figure 4.3.1. The pellicle was used since its gold coating offered excellent diffuse reflective properties underwater, where the light was returned in a narrow cone and hence was easily aligned with the collecting optics of the LDV. An acoustic transducer was then positioned such that a pressure field was projected across the laser beam, as depicted in Figure 4.3.2.

The output voltage from the Polytec OFV-3000 LDV controller was shown to recreate the major characteristics of the acoustic field as demonstrated by the similarities between the trace recorded from the oscillating pellicle, shown in Figure 4.3.3, and the LDV laser beam passing through the field, shown in Figure 4.3.4.

Figure 4.3.3 represents a measurement of the velocity of a point on the pellicle surface induced by the incident acoustic wave. The experimental set-up was similar to that depicted in Figure 4.3.1 and the transducer used was a Neptune Sonar plane-piston source, which generated a 50-cycle tone-burst at 110 kHz. The trace is characterised by the regions before and after steady state conditions are reached, where discrepancies in the phase and amplitude of the signal can be observed. These can be predominantly attributed to the Q of the transducer, which can be used as a measure of the response time of the transducer when energised and is described in more detail in Section 1.3.1.1.

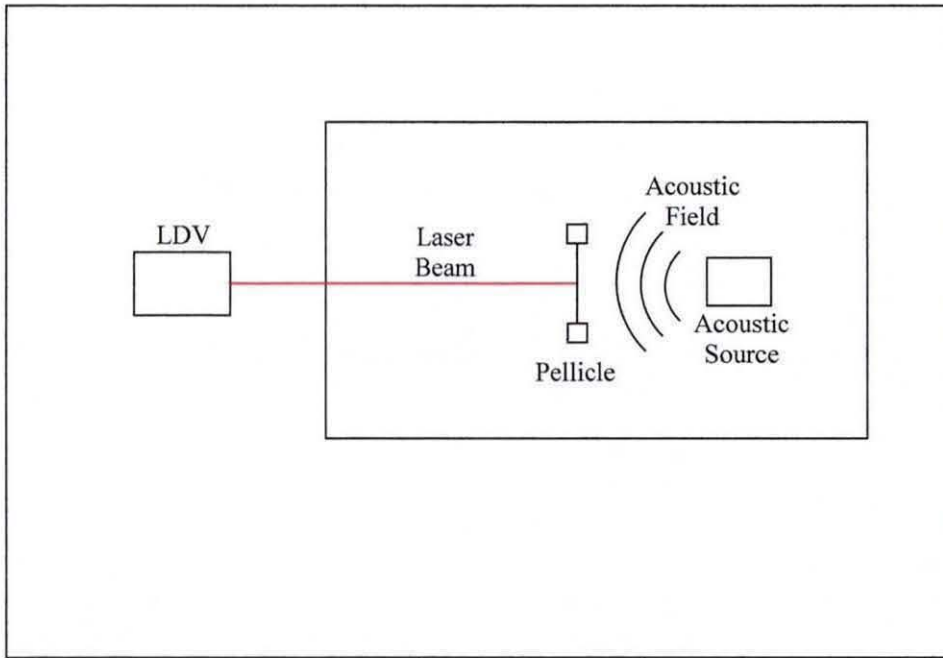


Figure 4.3.1: LDV laser beam measuring the acoustic deflection of a pellicle suspended within an acoustic field

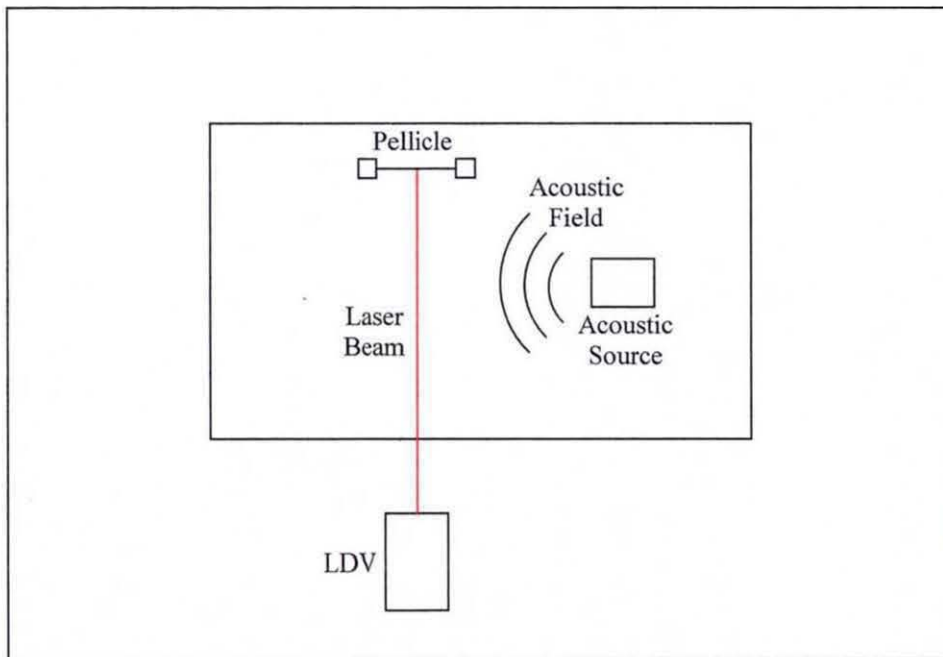


Figure 4.3.2: LDV laser beam passing through acoustic axis with normal incidence

Additionally in this case, since the acoustic wavelength at 110 kHz is not insignificant (≈ 13.5 mm) with respect to the radius of the pellicle (≈ 50 mm), acoustic reflections from the aluminium mounting of the pellicle begin to interfere with the original tone-burst at the measurement point after a fewer number of acoustic cycles than would be the case at higher frequencies. Consequently the trace shown appears noisier than it would otherwise be. However, the primary quantifiable features of the trace can be observed as the acoustic period (≈ 9 μ s) corresponding to the 110 kHz excitation frequency and the overall duration of the tone-burst (≈ 450 μ s), excepting the noisy transient regions at the beginning and end.

Figure 4.3.4 represents a measurement of the direct influence of the acoustic wave on the optical path length travelled by the LDV laser beam. It can be seen that the characteristics observed in the trace of Figure 4.3.3 are also evident in the trace of Figure 4.3.4. The acoustic period is consistent with the 110 kHz excitation frequency and the overall duration is also similar to that noted in Figure 4.3.3. The time delay prior to the arrival of the signal is dependent purely on the 'time of flight' taken for the acoustic wave to travel from the transducer to the laser beam position.

In general, the noise content during the steady-state of the acoustic signal is significantly reduced from that observed in Figure 4.3.3, primarily due to the fact that since a pellicle was not required to be positioned within the field, the primary source of interfering reflections was eliminated.

Despite the comparatively long tone-bursts used in each of these experiments (≈ 450 μ s, corresponding to a physical length of ≈ 0.7 m), the curved geometry of the tank walls, combined with the physical dimensions of the tank enabled the reflections from tank walls to be isolated and interference minimised. When the time axis of the measurement was expanded, the reflected signals could be identified, as depicted in Figure 4.3.5.

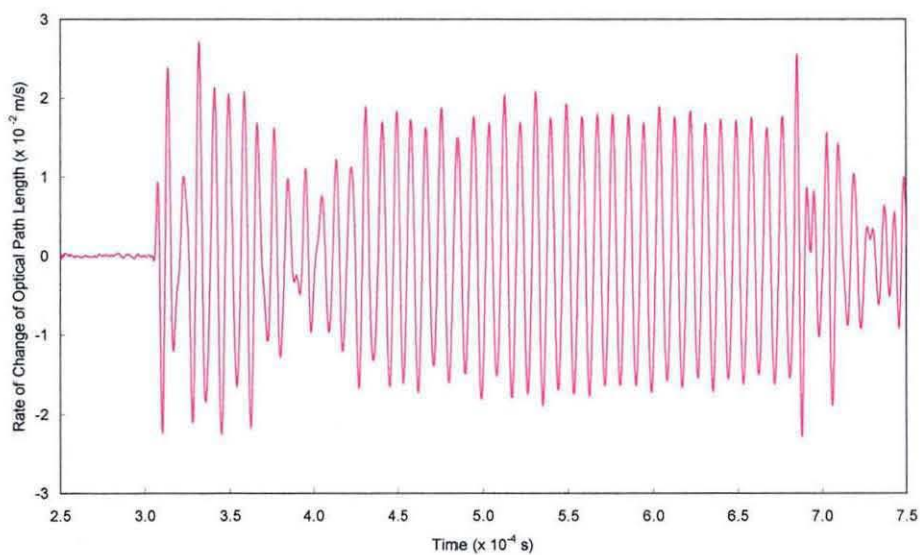


Figure 4.3.3: LDV measurement from a pellicle suspended within a 110 kHz acoustic field

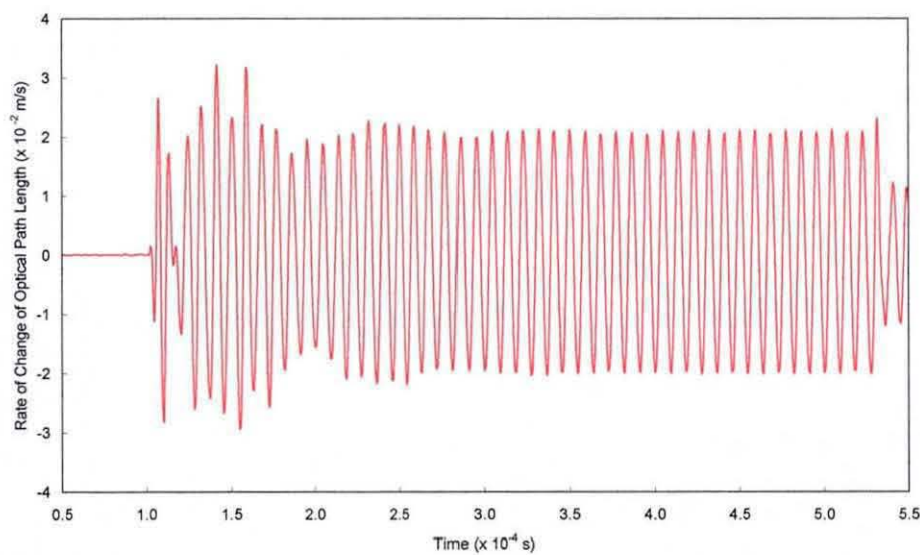


Figure 4.3.4: LDV measurement directly from a 110 kHz acoustic field

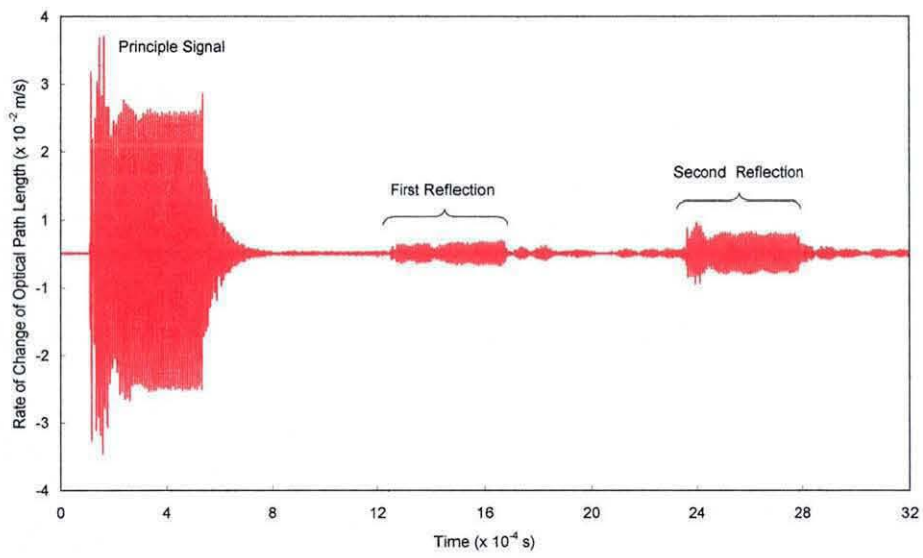


Figure 4.3.5: Reflected components of the acoustic beam detected by the LDV passing through the field

Analysis of the shape of the reflected signals, combined with the time delays present prior to their arrival and the respective spatial positions of the acoustic source and LDV laser beam enable predictions to be made as to the origin of the reflected components. The first additional component can therefore be attributed to a side lobe from the transducer reflected from both the water surface and tank floor and the second additional component can be attributed to a reflection of the main beam from the end wall of the tank.

In addition to the curved geometry of the tank walls, another benefit of using the facility at NPL was the PC controlled two-carriage positioning system, which could position acoustic devices with a resolution of 10 μm . Repositioning the respective transducers could be undertaken more quickly and efficiently than by hand operation and the sensitive tilt and rotate capability of the system enabled acoustic signal levels to be maximised.

4.3.1 Acoustic Standing-wave

The water tank used for interrogation by optical methods at Loughborough University was glass walled and had internal dimensions of $1.219\text{ m} \times 457\text{ mm} \times 295\text{ mm}$. Hence for a centrally positioned acoustic source, the shortest distance for a wavefront to travel to a surface and return to the source is 295 mm , which corresponds to an elapsed 'time of flight' of approximately $200\text{ }\mu\text{s}$. Since a means of generating tone-burst signals was not available at the time the experiments described here were undertaken, a continuous standing wave was identified as a feasible means of generating a consistent acoustic field, where reflections would not corrupt the measurements made.

The acoustic transducer was positioned at a desired nodal position and used to generate a continuous wave acoustic wavefront. The frequency of excitation was adjusted until the amplitude of the measured signal from the ball hydrophone positioned at a desired nodal position was minimised.

In order to establish a standing-wave with 6 anti-nodes along the length of the tank, the acoustic source was positioned 700 mm from the end of the tank to correspond with a desired anti-nodal position. A hydrophone was positioned approximately 400 mm away from the end of the tank to correspond with a desired nodal position. The minimum amplitude of the hydrophone signal was found to occur at a frequency of approximately 4.9 kHz .

The gold coated pellicle was replaced by a glass mirror, positioned outside of the tank as shown in Figure 4.3.6. The reason for this was two-fold; to eliminate any vibration caused from the motion of the water on the pellicle surface and to remove any perturbing influence the pellicle or its mounting may have had on the field. Care was taken in positioning the LDV optical head to ensure that only the optical beam reflected from the mirror was returned to the collecting optics, with superfluous reflections from the glass tank walls being diverted elsewhere.

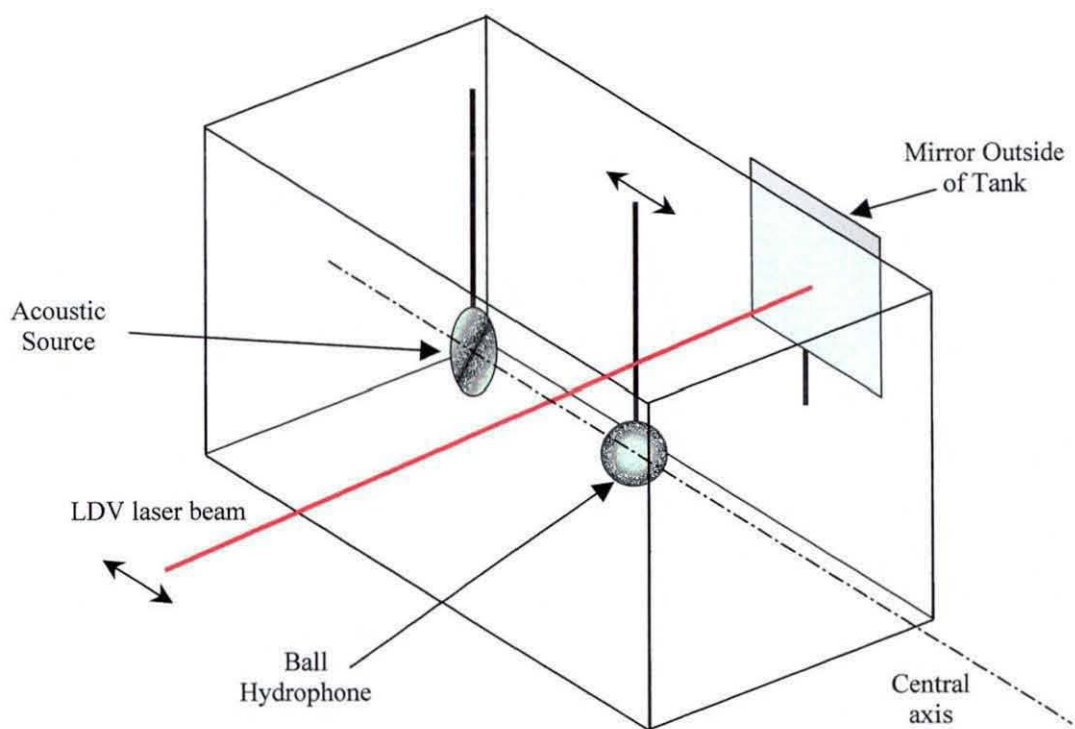


Figure 4.3.6: Arrangement for recording hydrophone and LDV measurements from a standing-wave acoustic field

Using the arrangement depicted in Figure 4.3.6, signals were recorded from a nodal position approximately 300 mm from the end of the tank, using the calibrated hydrophone and the LDV and displayed on a LeCroy 9314CL Digital Oscilloscope. The signals were then scaled to obtain pressure data for the hydrophone and velocity or 'rate of change of optical path length' for the LDV. A typical trace for both the hydrophone and LDV is given in Figure 4.3.7. For the geometry of the tank and acoustic field used, it is assumed that time taken for the light to travel from the laser to the reflecting mirror and return to the collecting optics is negligible in comparison to the period of the acoustic wave being measured. The passage of the light would be complete in 3.3 ns, compared with the acoustic period of 2.0 μ s. In 3.3 ns, the acoustic wave would travel only 4.9 μ m, equating to a phase shift of 10 mrad.

If it is assumed that the pressure variation at any point within the volume is perfectly sinusoidal, then it is evident that the hydrophone provides a more faithful reproduction of the pressure signal than the LDV. This seems a reasonable assumption since the amplitude of the acoustic pressure generated by the source is not sufficient to induce non-linear propagation over the distances involved. It should be noted, however, that the pressure variation at a point close to the tank wall boundaries is likely to oscillate with a less pure sinusoid than at a point in the centre of the tank. Therefore, since the LDV measures an integral of the refractive index with distance, these lower quality signals contribute to the reduction in purity of the output voltage sinusoid, as observed in Figure 4.3.7.

A consistent phase difference of approximately π is present throughout the trace. This is to be expected since the rate of change of optical path length, as measured by the LDV, is proportional to the first time differential of the refractive index variation, caused by the pressure variation, which is measured by the hydrophone.

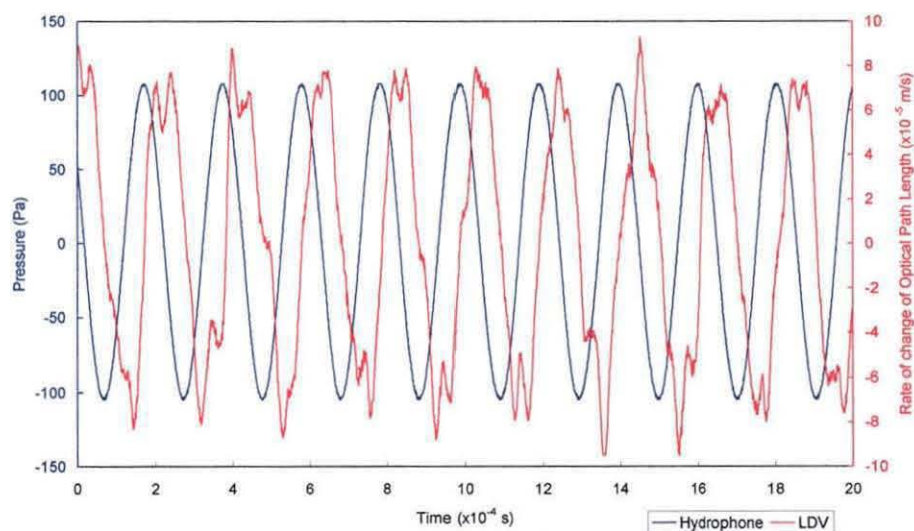


Figure 4.3.7: Hydrophone and LDV measurements from a 4.9 kHz acoustic standing wave

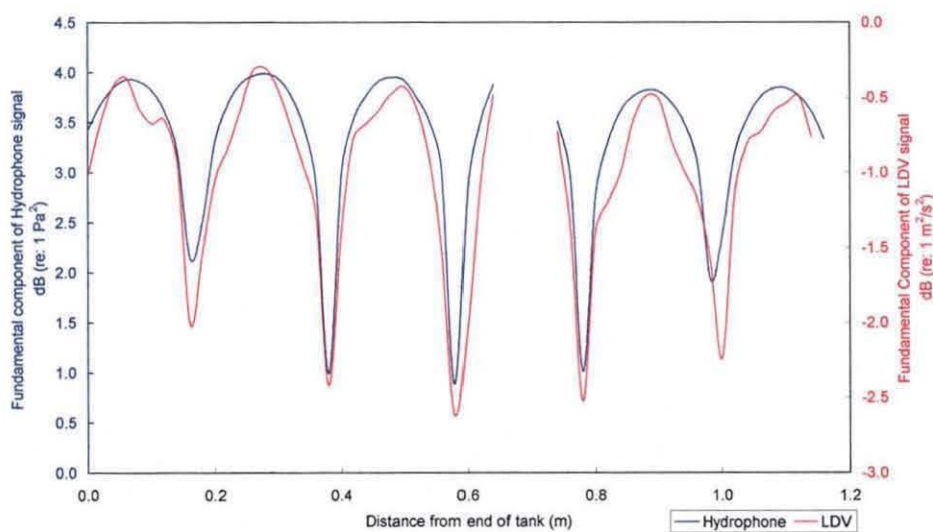


Figure 4.3.8: Component of Power Spectrum at Fundamental Frequency versus distance along tank for Hydrophone and LDV

To assess the pressure distribution within the standing-wave volume, signals were recorded at 20 mm intervals along the length of the tank using both measurement transducers. The hydrophone measurements were taken along the central axis of the tank and the LDV measurements were taken with the laser beam passing through the central axis with normal incidence, as shown in Figure 4.3.6. In order to obtain a measure of the amplitude of the respective measurements, a Discrete Fourier Transform (DFT) was taken of a complete number of cycles from each signal. The component at the fundamental frequency was then plotted for each measurement position and is given in Figure 4.3.8.

The two distributions of the amplitude of the standing-wave with distance along the tank measured by both the hydrophone and the LDV are consistent in shape and conform to that anticipated from the experimental set-up. The absence of both traces between 0.64 m and 0.74 m is because this was the position of the acoustic source, which made it physically impossible to either position the hydrophone or pass the LDV laser beam through the field.

Whilst the hydrophone provides a measurement of the pressure variation at a point, the LDV provides a voltage proportional to the change in optical path length travelled by the laser beam, as described in Section 4.2.3. When applied to the experimental standing-wave described here, the voltage output from the LDV given in Equation (4.2.9) can be simplified to that given in Equation (4.3.1)

$$\begin{aligned}
 V(t) &= 4\pi f K w \left(\frac{\partial n}{\partial p} \right) A \cos(2\pi f t - \Phi) \\
 &= 1.16\pi \left(\frac{\partial n}{\partial p} \right) A \cos(8.8 \times 10^3 \pi t - \Phi)
 \end{aligned} \tag{4.3.1}$$

Here the width of the tank used, w , measured to be 295 mm, is used as the length of the interaction region for a frequency, f , of 4.9 kHz. The sensitivity scalar, K , was specified as 5 V/mm/s, chosen to maximise the output voltage for the measured rate of change of optical path length without causing the signal to over-range.

The amplitude, A , of the standing wave is a function of distance from the end of the tank and, with the exception of the regions immediately bordering the tank walls mentioned previously, is assumed to be independent of distance across the tank. This assumption is made on the notion that a mode of mechanical oscillation had been established consisting of 7 anti-nodes and 6 nodes along the length dimension of the tank. The phase, Φ , is also related to the distance from the end of the tank, but is not considered here since it does not influence the amplitude, and hence the component of the power spectrum used to create the graph shown in Figure 4.3.8.

4.3.2 Acoustic Tone-Burst

Due to the limitations of standing waves in terms of the finite frequency bands that can be supported and the homogeneity of phase distribution, calculations were undertaken to establish the potential for recording measurements from tone-burst acoustic fields. In assessing this possibility, the following considerations were taken into account:

- a) The minimum number of acoustic cycles required to reach steady-state conditions is dependent on the Q of the transducer and a finite number of complete cycles are required to perform the necessary mathematical interrogation of the signal. For this reason, the minimum desirable number of cycles contained within a tone-burst, N , is taken to be 10. The number of cycles, together with the wavelength of the acoustic field, (governed by the acoustic frequency) determines the physical length of the tone-burst as given in Equation (4.3.2), where d_{tb} and t_{tb} are the physical length and duration of the tone-burst respectively, c is the speed of sound in water and f is the acoustic frequency.

$$\begin{aligned} d_{tb} &= \frac{Nc}{f} \\ t_{tb} &= \frac{N}{f} \end{aligned} \tag{4.3.2}$$

- b) The length of the tone-burst must be sufficiently short in relation to the nearest reflecting wall or surface in the tank, such that the original tone-burst fully passes the measurement transducer before the first reflection arrives. The tank was

always filled such that the height of water was greater than the width of the tank. The position of the nearest wall is given in Equation (4.3.3) in terms of the distance from the nearest edge of the source to the wall, d_w , and the time taken for an acoustic wave to travel this distance, t_w , where w is the width of the tank and r_0 is the radius of the acoustic source.

$$\begin{aligned}d_w &= \frac{w}{2} - r_0 \\t_w &= \frac{w}{2c} - \frac{r_0}{c}\end{aligned}\tag{4.3.3}$$

From this, the distance travelled by the first reflection of the acoustic wave to arrive at a point in the centre of the tank and the time taken to do so, d_r and t_r , respectively, can be derived. Equation (4.3.4) expresses these, where d is the distance from the acoustic source to the measurement transducer.

$$\begin{aligned}d_r &= \sqrt{4d_w^2 + d^2} \\t_r &= \frac{1}{c} \sqrt{4d_w^2 + d^2}\end{aligned}\tag{4.3.4}$$

- c) The final factor that requires consideration is the ‘near-field’ of the acoustic transducer. Plane-piston transducers are designed to create plane wave acoustic fields in the far-field. However, in the region closest to the emitting face, referred to as the near-field, the interference from acoustic waves generated by the face and edges of the transducer combine to destruct the planar wave front. An approximation of the distance from the acoustic source to the demarcation between the complex near-field and the simpler far-field is given in Equation (4.3.5), where d_f is the distance from the acoustic source to the demarcation point, and t_f is the time taken to travel this distance.

$$\begin{aligned}d_f &= \frac{r_0^2 f}{c} - \frac{c}{f} \\t_f &= \frac{r_0^2 f}{c^2} - \frac{1}{f}\end{aligned}\tag{4.3.5}$$

The three defining parameters are plotted in Figure 4.3.9 for three different frequencies, 50 kHz in (a), 90kHz in (b) and 130kHz in (c), for the laboratory tank of width, 295 mm. The shaded regions denote the positions where all desirable conditions are met. It can be demonstrated from Figure 4.3.9 that at frequencies below 90 kHz, there is no overlapping region, which means that reflections are likely to interfere with the signal before sufficient steady state cycles have passed the measurement transducer.

When considering these requirements, it can be seen that ideally the width of the tank should be as large as possible to maximise the time taken before the arrival of the first reflection. In addition, the frequency should be as high as possible to minimise the length of the tone-burst. However, the Polytec OSV-3000 LDV controller has an upper frequency limit of 150 kHz, which restricts the potential for high frequency measurements. It is also known that the acoustic transducers have highly resonance-based responses, which dictate the frequencies of oscillation which can be measured.

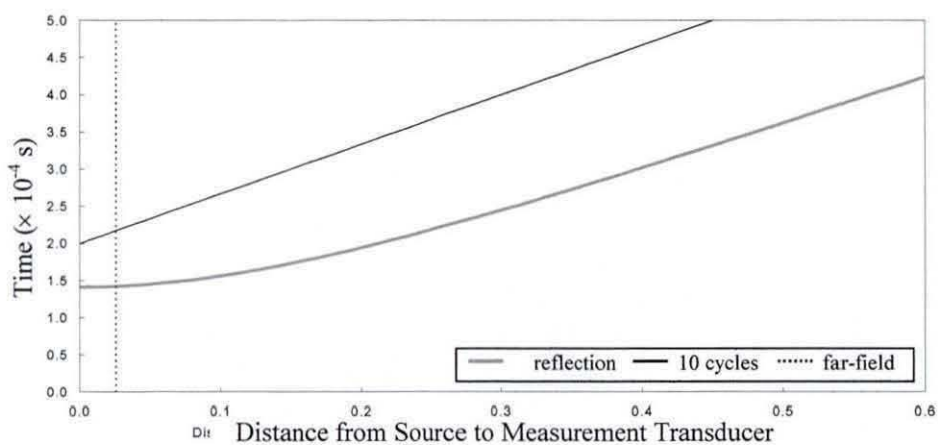


Figure 4.3.9 (a): Frequency = 50 kHz

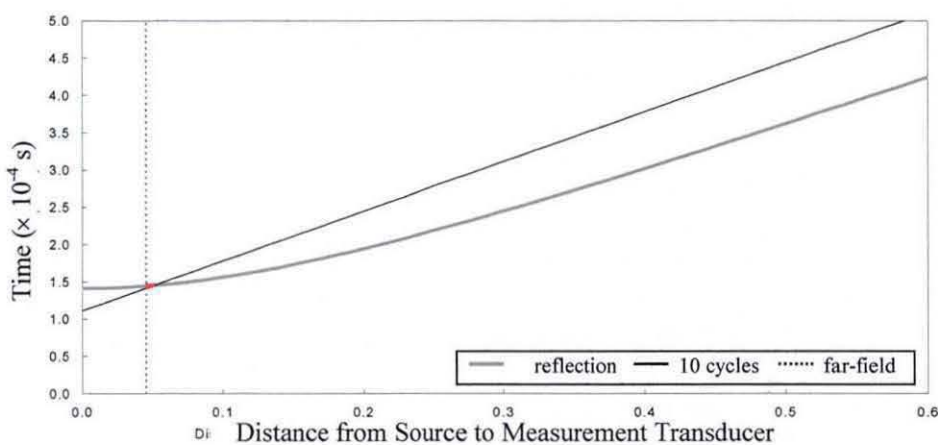


Figure 4.3.9 (b): Frequency = 90 kHz

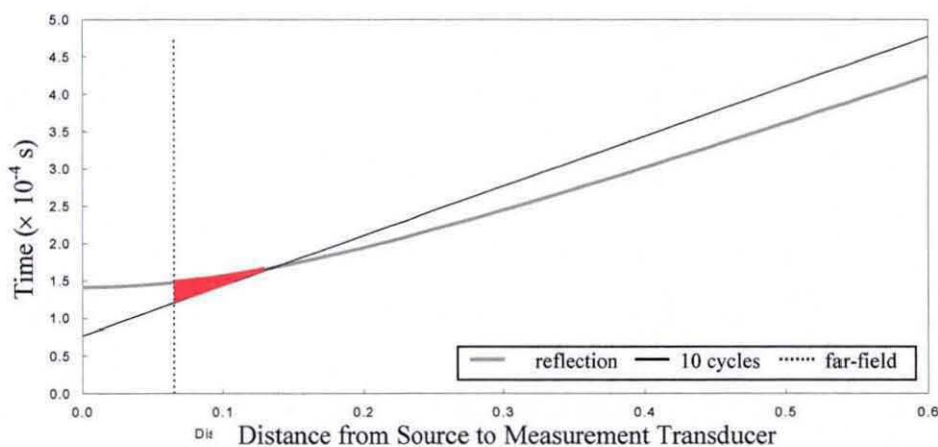


Figure 4.3.9 (c): Frequency = 130 kHz

Figure 4.3.9: Relative positions required for steady state acoustic fields to be measured in the Loughborough University tank

4.3.2.1 Measurements from an 80 kHz Acoustic Tone-Burst

One such plane-piston transducer used extensively in the laboratory was found to have a sharp resonance at 80 kHz. This was excited by the Hewlett Packard HP8111A pulse/function generator in tandem with the Philips PM5134 function generator to create a single frequency tone-burst containing a finite number of cycles, N . A time delay of approximately 50 ms was included between each tone-burst to allow the reflections of the tone-burst to fully die away before the emission of the next pulse. This minimised any interference between successive bursts. The time taken for a burst to die away is determined primarily by the boundary conditions of the tank, specifically the percentage of the incident acoustic energy that is reflected as opposed to absorbed or transmitted by the wall. For the experiments described here, the boundary consisted of a flat glass plane, which reflects a high percentage of the incident acoustic energy, meaning the reflections take longer to die away than those from a more absorbent boundary, such as those of the NPL tanks described previously.

Experiments were undertaken using 2 and 6 cycle tone-bursts. Whilst neither of these tone-burst durations represented ideal experimental conditions, the restrictive dimensions of the available tank limited the tone-burst length. A 2 cycle tone-burst duration was chosen since it would be completed prior to the arrival of any reflections, although it was appreciated that the high Q transducer would not reach steady state output conditions within the time. A 6 cycle duration was considered a reasonable compromise between permitting steady state conditions to be reached and keeping reflected signals to a minimum.

Each acoustic tone-burst was measured using the 25 mm diameter ball hydrophone (calibrated in Section 3.4.1.1) positioned on the central axis of the acoustic field and a double pass of a Polytec OFV-302 / OFV-3000 LDV through the field, reflected from a fixed target outside the volume, as shown previously in Figure 4.3.6. An average of 100 successive, independent tone-bursts triggered from the source input signal was recorded by each measurement transducer using a LeCroy 9314CL Digital Oscilloscope for each tone-burst duration. Figure 4.3.10 depicts the 80 kHz 2-cycle tone-burst measured by the hydrophone in (a) and the LDV in (b).

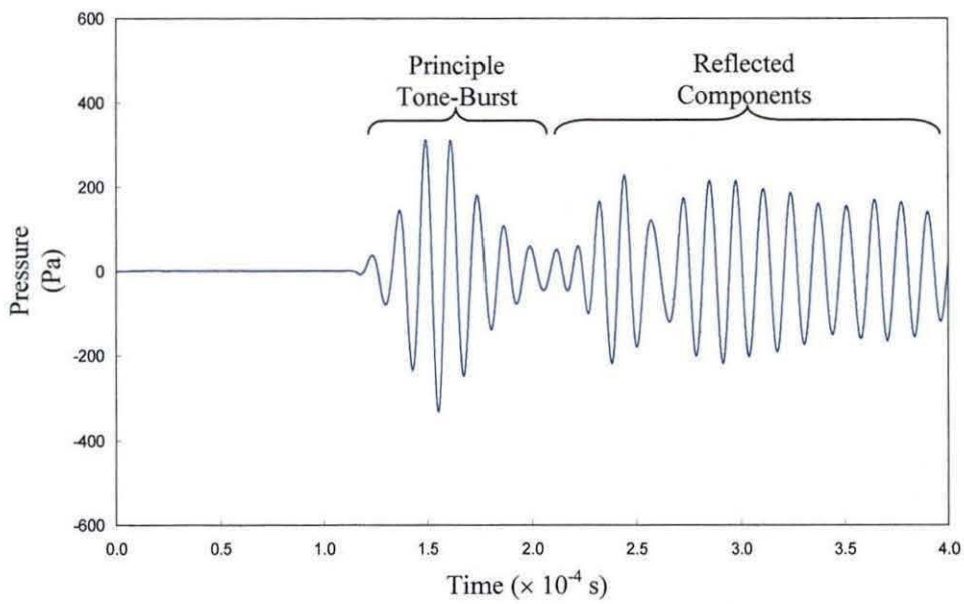


Figure 4.3.10 (a): Hydrophone Measurement

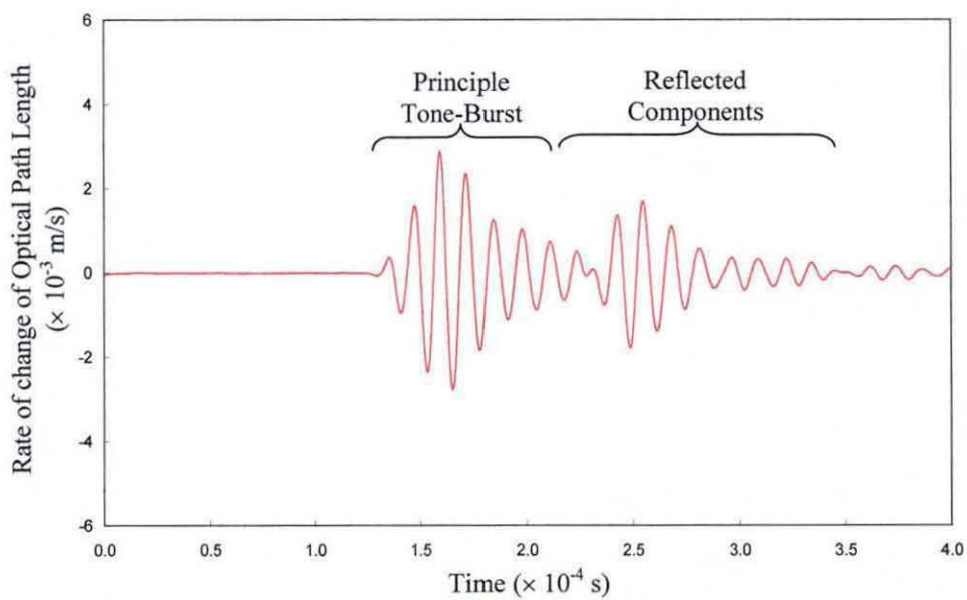


Figure 4.3.10 (b): LDV Measurement

Figure 4.3.10: Two-cycle 80 kHz tone-burst measurements

The distance of separation between the source and the measurement transducer can be calculated for both the hydrophone and the LDV by measuring the delay prior to the initial detection of the acoustic signal and multiplying by the speed of sound, c . Despite manual attempts to position the LDV laser beam at the centre of the hydrophone in-situ prior to removal, this distance is calculated to be 169 mm for the hydrophone, and 184 mm for the LDV. For a two-cycle tone-burst, the distance of the measurement transducer from the source at which measurements can theoretically be recorded without interference from reflected components of the acoustic field is calculated to be between 40 mm and 578 mm. Hence, both the respective transducer positions lie within the acceptable limits.

However, in each trace, the original acoustic tone-burst is not entirely detached from the reflected components that follow. This is due to the issues associated with the number of cycles required by the transducer to reach steady-state conditions, and consequently the reverberation time of the transducer before its surface returns to a motionless state. Reflected signals are present in both traces although the amplitude of those measured by the hydrophone is significantly larger than that of the LDV. This may be attributed to the fact that in addition to the physical reverberation of the transducer, the hydrophone element continues to resonate for a time after the tone-burst has passed. Alternatively, the phase of the pressure within the reflected signals along the line section interrogated by the LDV is such that when integrated it begins to be cancelled out through destructive interference.

For the case of the 6-cycle tone-burst depicted in Figure 4.3.11, where (a) represents the hydrophone measurement and (b) represents the LDV measurement, the distance of separation between the source and the measurement transducer was similarly calculated to be 169 mm and 184 mm, respectively. However, the calculated acceptable limits for this separation were calculated to be 40 mm and 143 mm, implying that measurements would not be able to be made without reflections interfering with the original signal. This is observed in each trace by the fact that the separation between the original and reflected components of the acoustic tone-burst in Figure 4.3.11 is not as great as was the case in Figure 4.3.10. Again, as was experienced in the 2-cycle measurements, the amplitude of the reflected portion of

the acoustic signal measured by the hydrophone is significantly greater than that measured by the LDV.

In each tone-burst example, the distance of separation between the source and the measurement transducer is observed to differ by 15 mm between the hydrophone and the LDV. Whilst the laser beam from the LDV was directed at the centre of the in-situ hydrophone prior to its removal from the field, the system was aligned by hand resulting in the accuracy of positioning to be estimated as ± 2 mm. Another possible contributing factor is the fact that the apparent centre of the hydrophone, i.e. the finite position within the hydrophone at which the voltage output is representative of the pressure variation, does not necessarily coincide with the geometric centre of the device [41].

At high frequencies, where the phase of the pressure wave changes significantly across the physical dimensions of a transducer, the apparent centre appears close the edge of the device nearest to the source of the acoustic wave. Only when the frequency is low and hence the phase remains relatively constant across the hydrophone will the apparent centre coincide with the geometric centre. It should be noted that the LDV provides a signal proportional to the first time differential of the hydrophone signal (assuming plane wave conditions), which introduces a phase difference of π .

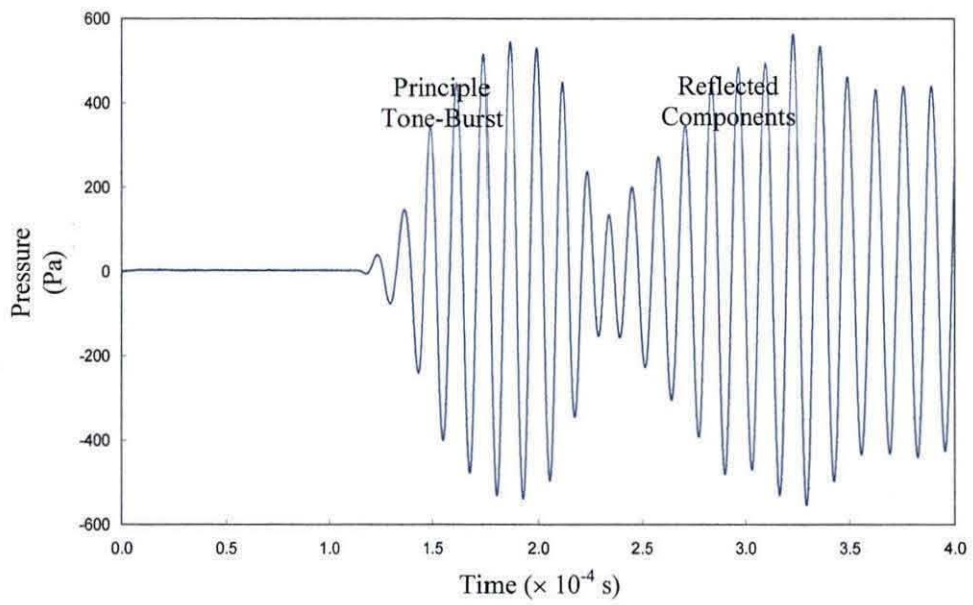


Figure 4.3.11 (a): Hydrophone Measurement

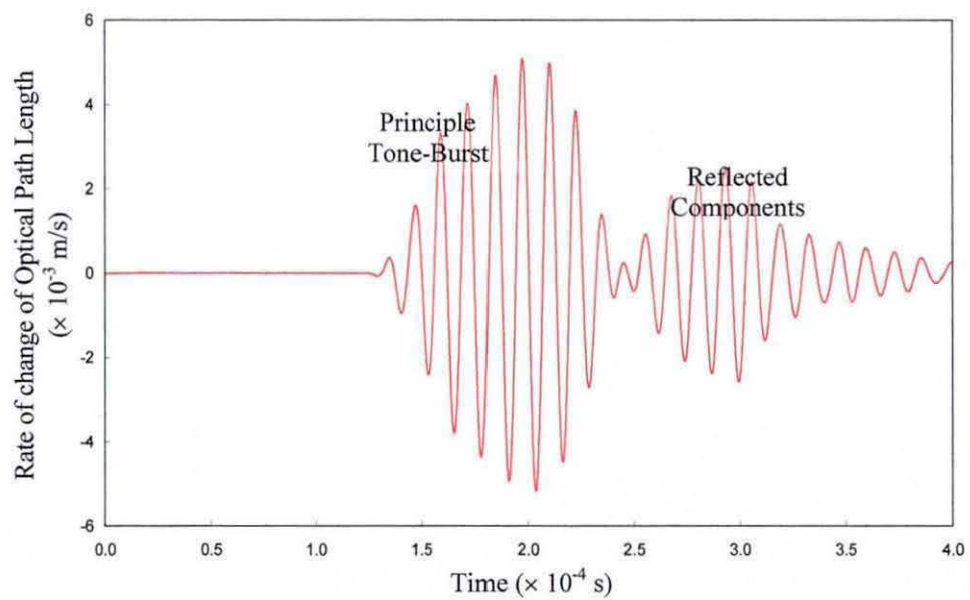


Figure 4.3.11 (b): LDV Measurement

Figure 4.3.11: Six-cycle 80 kHz tone-burst measurements

Despite the presence and influence of the reflected components of the acoustic tone-bursts and taking into account the variation in the actual position of the measurement transducer, both measurement transducers demonstrate the capability of identifying the spatial position of pressure amplitude and phase. The LDV has a number of advantages over the hydrophone. Firstly, the separation of the laser beam and the source can be calculated more accurately, since the laser beam has a smaller diameter than the hydrophone, typically 1 mm compared to 25 mm. Secondly, the response of the LDV, given in Section 3.6.1.3 is consistent across the frequency range, whereas the response of the ball hydrophone is characterised by the resonance at approximately 80 kHz, illustrated in Figure 3.4.2. Finally, and perhaps most crucially, the LDV does not perturb the field in any manner by its presence, unlike the hydrophone. The hydrophone does, however, have the benefit of providing a signal proportional to the integrated pressure over the much smaller volume of its active element, which approximates to the pressure at a point at its centre.

4.3.2.2 Calibration of a Line Section through an 80 kHz Acoustic Tone-Burst

In order to make further assessment of the integrated refractive index measured by the LDV, eleven discrete hydrophone measurements were taken at regular intervals along the path of the LDV laser beam positioned to interrogate a 5-cycle acoustic field. A 5-cycle tone-burst was chosen as a compromise between a sufficiently short tone-burst to minimise reflected interference and a longer duration enabling the transducer to reach steady state conditions. Each measurement consisted of an average of 100 successive independent tone-bursts triggered from the source input signal. A schematic of the experimental arrangement is given in Figure 4.3.12.

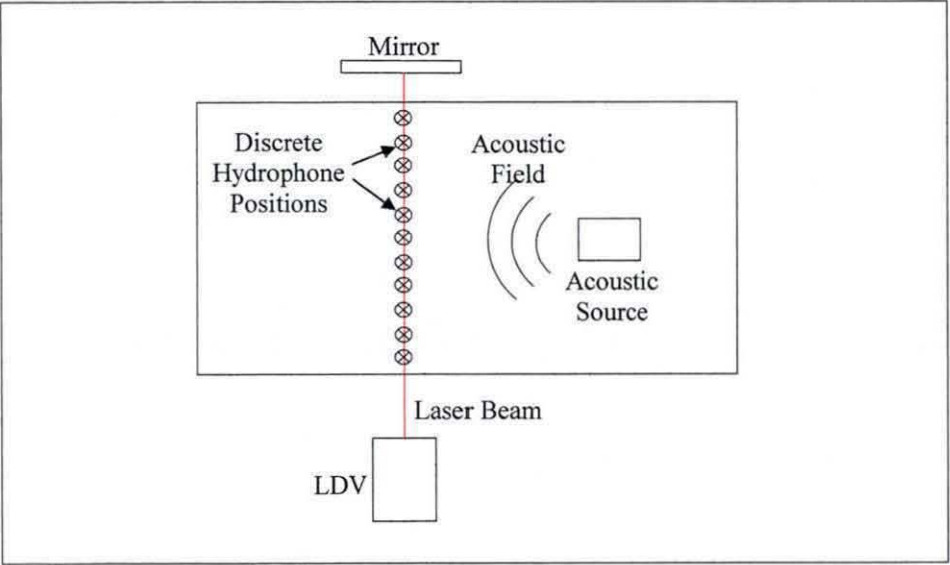


Figure 4.3.12: Discrete Hydrophone Measurements along a line section

Each trace was recorded and scaled using the piezo-optic coefficient to obtain the refractive index with time at each measurement position. These traces were then integrated with distance along the line, factored by 2 to account for the double pass of the beam through the field, and differentiated with respect to time to provide a quantity representative of the rate of change of optical path length with time, as given in the theory detailed in Section 4.2.3. This was compared with an average of 100 repetitions of the rate of change of optical path length from the LDV for the same line section. Both traces are depicted, with the signals plotted in the time domain in Figure 4.3.13 and frequency domain in Figure 4.3.14.

The most significant observation from this comparison is that the original 5-cycle tone-burst can be readily identified in the LDV trace but not in the integrated hydrophone signal. This is primarily due to the 'ringing' effect of the hydrophone in each individual measurement, which, when integrated with distance, results in a signal where the original and reflected components of the tone-burst cannot be isolated. The time taken for the amplitude of the signal to reach a steady state describes the transient 'rise time', although since neither the hydrophone nor LDV measurement truly reaches steady state, it cannot be derived from this measurement.

It is noticeable from the comparison given in Figure 4.3.13 (a) that there is phase difference between the two measured signals. From an examination of the initial detection of the signal by each measurement transducer, given in Figure 4.3.13 (b), it is evident that the signals are detected at different temporal positions, with the hydrophone signal leading the LDV signal by approximately $10.4 \mu\text{s}$, which equates to a phase difference of 1.2 rad.

The speed of sound at a depth of 150 mm in fresh-water at 16.5°C is 1471.1 m/s [4], which corresponds to a distance travelled of 15.3 mm as explained in Section 1.3.2.1. The diameter of the hydrophone ball was 25 mm and the LDV laser beam was manually aligned to pass through the centre-line of the ball position. If the beam were positioned exactly perpendicular to the acoustic axis and passed through the exact centre of the ball position, the acoustic wave would be incident at the edge of the ball $8.3 \mu\text{s}$ before reaching the centre.

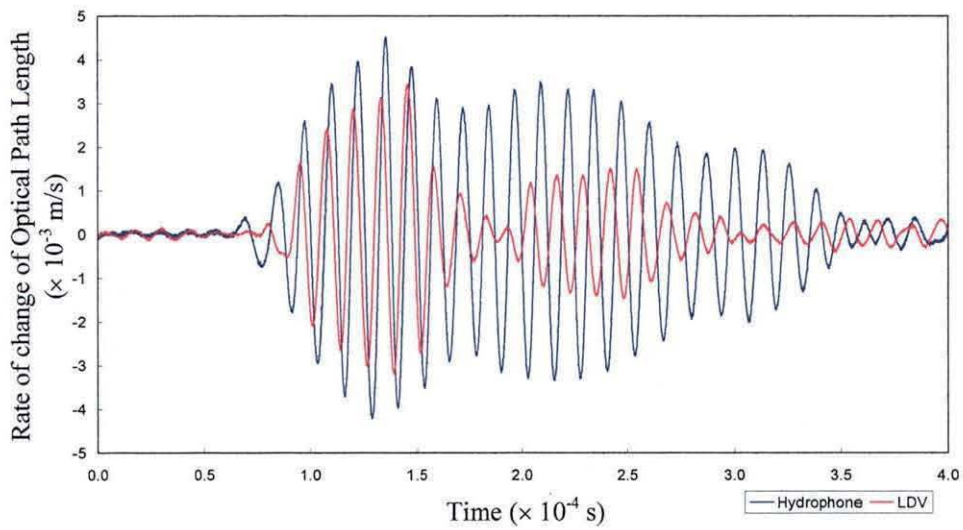


Figure 4.3.13 (a): Entire acoustic signal

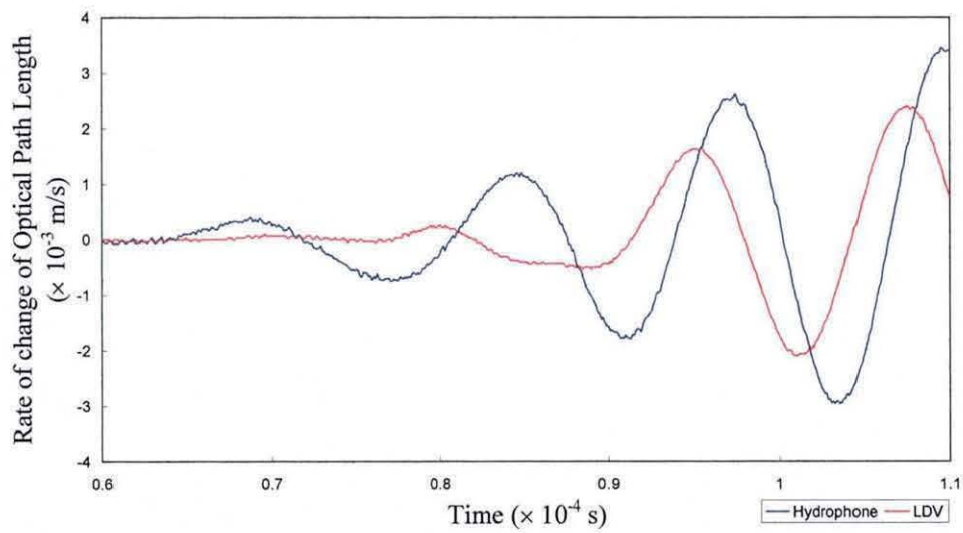


Figure 4.3.13 (b): Initial detection of acoustic signal

Figure 4.3.13: Time resolved rate of change of Optical Path Length for a 5-cycle, 80 kHz tone-burst derived from hydrophone measurements and measured by the LDV

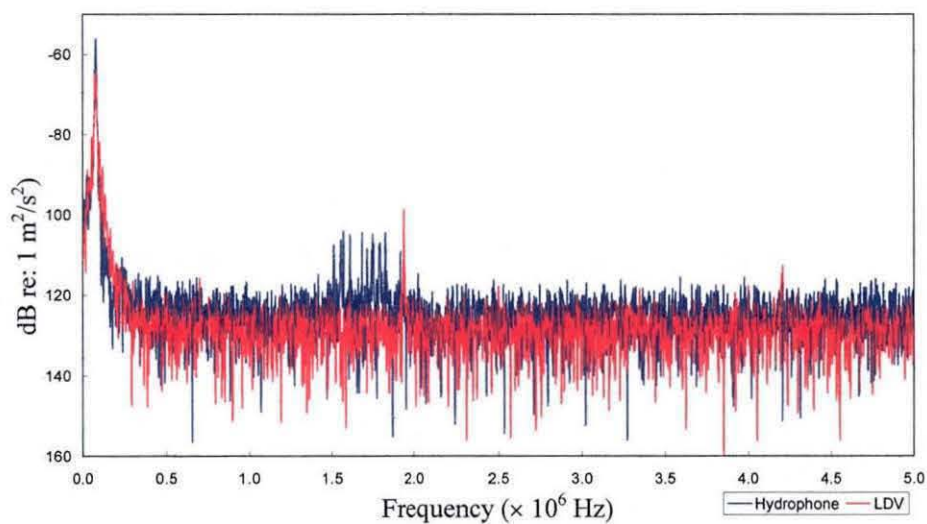


Figure 4.3.14 (a): Entire power spectrum

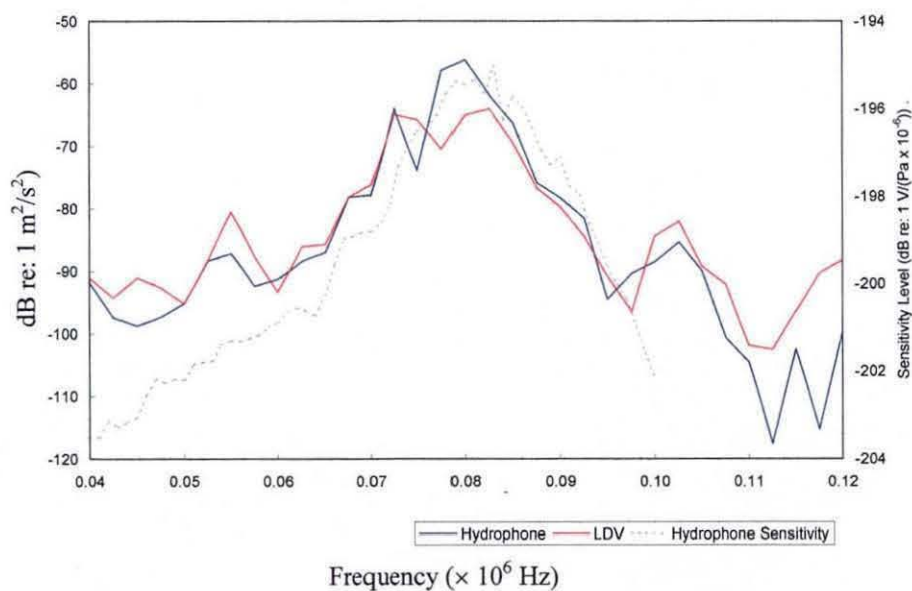


Figure 4.3.14 (b): 80 kHz region of power spectrum

Figure 4.3.14: Rate of change of Optical Path Length for a 5-cycle, 80 kHz acoustic tone-burst derived from hydrophone measurements and measured by the LDV

The discrepancy between this theoretical value and the measured time delay may be explained by considering the likely inaccuracies with the hydrophone positioning and LDV alignment, together with the theory that the apparent centre of the hydrophone approaches the perimeter when the acoustic wavelength is short in comparison to the dimensions of the hydrophone, as explained in Section 4.3.2.1. Another related effect, which may also contribute to the observation, is the shift in phase-response experienced by the hydrophone at frequencies close to resonance.

In the frequency spectra of Figure 4.3.14 (a), both measurement transducers provide similar responses, with the fundamental spike consistent with the drive frequency to the transducer at approximately 80 kHz. A closer inspection of the region around 80 kHz in the power spectrum, given in Figure 4.3.14 (b), shows minor discrepancies between the shape of the two signals. This is not unexpected, however, since the measured signal represents a convolution of the frequency responses of each of the transducers. Since the LDV is consistently responsive across its frequency range, as described in Section 3.6.1.3, the frequency content of the signal measured by the LDV is likely to represent that of the acoustic signal generated by the source. In contrast, the frequency response of the ball hydrophone, given in Section 3.4.1.1, demonstrates increased sensitivity centred around the resonance frequency. This introduces a bias in the frequency content of the signal measured by the hydrophone, as observed in Figure 4.3.14.

After discarding the start and finish transients, 4 complete cycles were identified within centre of the tone-burst. From the magnitude spectrum of a DFT of the 4 cycles, the respective amplitudes of the hydrophone and LDV signals at 80 kHz are found to be 3.66 mm/s and 2.85 mm/s. Hence the agreement in amplitude during the tone-burst is within 5 dB ($\approx 20 \log (3.66/2.85)$).

4.3.2.3 Calibration of a line-section through a 500 kHz Acoustic Tone-Burst

Due to the limited response of the OFV-302 and OFV-3000 LDV at frequencies greater than 150 kHz, described in Section 3.6.1.1, a Polytec Laser Scanning Vibrometer, consisting of an OFV-056 Scan Head and an OFV-3001-S LDV controller with an upper frequency limit of 1.5 MHz was used. Despite the LDV's capability to scan the beam through an angular range, the unit was set-up with the beam in a fixed position to enable 500 kHz acoustic signals to be observed without interference from reflected components of the field. In addition, an ITC 6128 hydrophone, calibrated in Section 3.4.1.2, was used to record pressure measurements from within the field. Experiments similar to those described in Section 4.3.2.1 were undertaken for tone-burst durations of 10-cycles from the Panametrics 500 kHz focused transducer. This was used primarily since its operational frequency range, centred around 500 kHz, was sufficiently high to fully isolate reflected signal components. An added benefit of the focused transducer was to concentrate the acoustic energy within the principal beam and not be distributed in secondary side lobes as with the plane-piston transducer.

The higher acoustic frequency enabled more cycles to be contained within a given duration of tone-burst. This ensured that steady state acoustic conditions to be reached between the start and finish transients. The scaled hydrophone measurements were then integrated with distance through the field, and a measure of rate of change of optical path length obtained. This was compared with the rate of change of optical path length measured by the LDV.

As can be seen from these signals represented in Figure 4.3.15, both the hydrophone and the LDV are successful in recording the tone-burst without the interference of any reflected components of the acoustic tone-burst. It can also be seen, from Figure 4.3.16, that the general shape of the power spectrum of each measurement signal is consistent. The LDV shows a slight peak at 1 MHz, which is likely to represent the second harmonic component ($= 2f$) of the acoustic frequency. This is not replicated in the hydrophone signal, primarily since the sensitivity of the hydrophone is known to be very poor at this frequency.

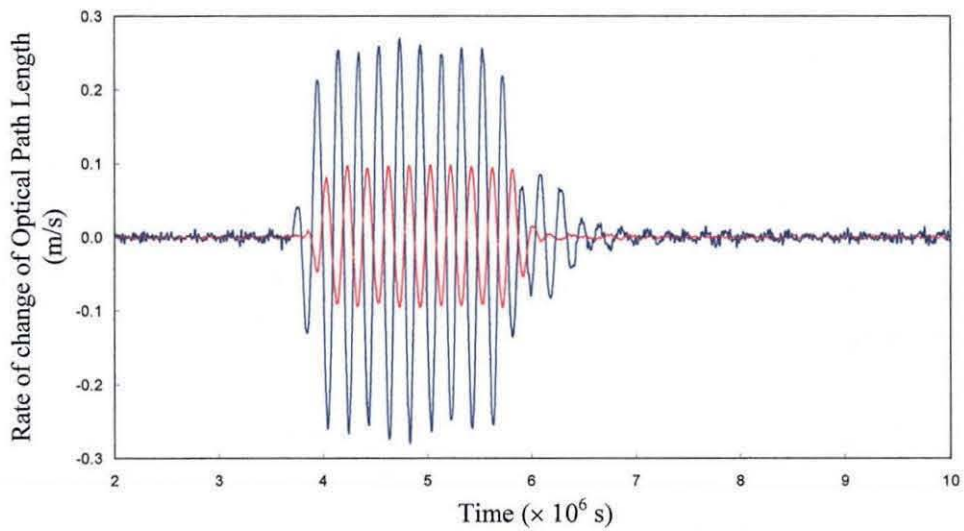


Figure 4.3.15: Time Domain Spectrum of Rate of change of Optical Path Length for a 10-cycle, 500 kHz acoustic tone-burst derived from hydrophone measurements and measured by the LDV

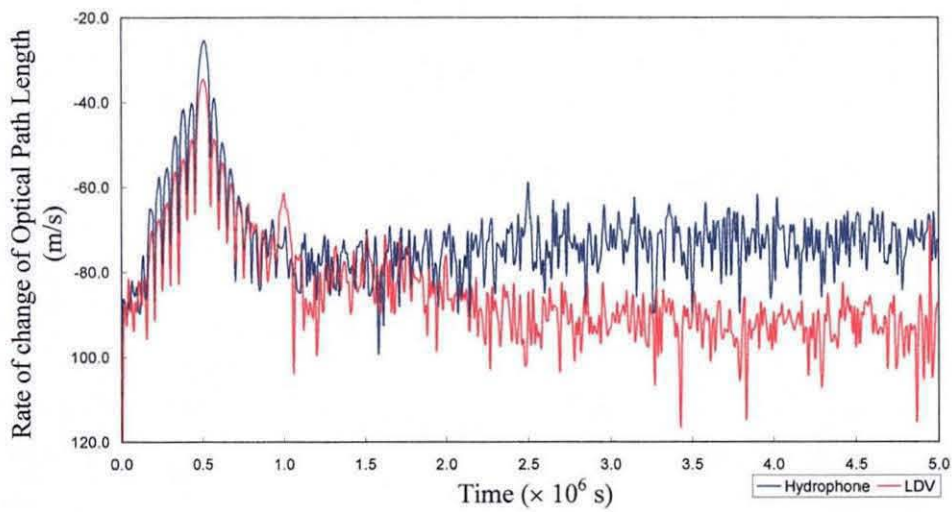


Figure 4.3.16: Magnitude Spectrum of Rate of change of Optical Path Length for a 10-cycle, 500 kHz acoustic tone-burst derived from hydrophone measurements and measured by the LDV

Similar to the comparison made in Figure 4.3.13, the phase of the derived hydrophone measurement leads that of the LDV signal, in this case by approximately π (0.8 μ s), which corresponds to a distance travelled by the acoustic tone-burst of 1.2 mm. The ITC 6128 hydrophone has a diameter of 7.9 mm, with the laser beam from the LDV directed at a point at its centre. Hence it can be concluded that the apparent centre of the ITC 6128 hydrophone for measurements of a 500 kHz acoustic tone-burst lies midway between its front surface and its geometric centre.

The major inconsistency between the two rate of change of optical path length signals is the amplitude of the steady state acoustic tone-burst. The 500 kHz components of the magnitude from a DFT of 8 complete cycles, identified between the start and finish transients of the steady state hydrophone and LDV signals, were found to be 256 mm/s and 94 mm/s respectively. This represents an agreement within 20.0 dB ($\approx 20 \log (256/94)$)

The primary cause of this discrepancy was identified to be the spacing increment used in the mathematical integration of the hydrophone data. The design of the focused transducer used is such that it concentrates the acoustic energy at a focal region, nominally 25.4 mm from front face. The pressure amplitude of signals measured away from the focus is known to deteriorate very rapidly with distance from the focal region. The 500 kHz component of the power spectrum of each discrete hydrophone measurement is plotted against the measured spacing increment used in the integration in Figure 4.3.17.

In order to account for the inaccuracies in the position and potential movement of the apparent centre of the hydrophone, the spacing increment used in the integral was adjusted in order to equate the amplitudes of the hydrophone and LDV signals during the steady state of the measurement. The broken line on the same axes represents an example of the adjustment of the spacing increment required to equate the amplitudes of the two signals, where the width of the focus is approximately half that derived from the original measurements.

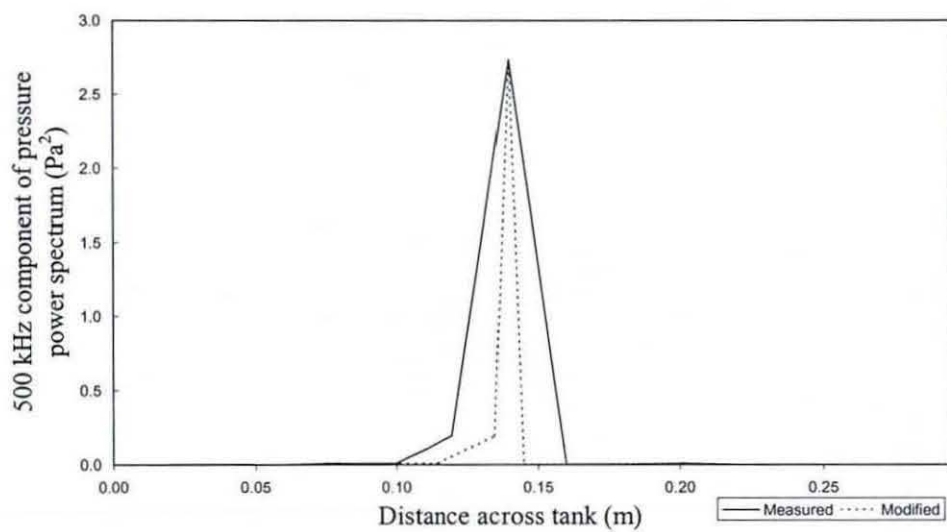


Figure 4.3.17: Measured and modified spacing increment used in hydrophone integration

Another attribute of the derived hydrophone measurement trace is that, in total, it depicts at least 13 cycles, whilst the drive signal to the acoustic source contained only 10. These additional cycles are caused predominantly by the 'ringing' of the element once the tone-burst has passed, since the frequency of the acoustic tone-burst is close to the principal resonance of the hydrophone. This is illustrated in Figure 4.3.18, where the peak value in the hydrophone spectrum for the entire trace is found at 510 kHz, as opposed to the 500 kHz maximum found for the DFT of an integer number of cycles within the tone-burst. The sensitivity of the hydrophone with frequency is plotted with a broken line on the same axes and exhibits a resonance at 550 kHz. From this it is evident that the peak frequency in the hydrophone measurement is influenced by this resonance. In contrast, the LDV signal depicts 10 cycles and visibly bears a closer resemblance to the input voltage to the acoustic source. The maximum component of the power spectrum from both an integer number of cycles and the entire trace is found at 500 kHz, the drive frequency to the acoustic source.

Mathematical theory suggests that the spectrum of a single frequency tone-burst will consist of a rounded peak at the fundamental frequency, f , followed by a series of smaller peaks as shown in Figure 4.3.19. For a tone-burst duration of t seconds, the first and second zero points separating the peaks are given by $f_0 \pm \frac{1}{t}$ and $f_0 \pm \frac{2}{t}$, respectively.

For the 10 cycle, 500 kHz acoustic tone-burst used in the experimentation, the first zero-points are calculated by theory to occur at 450 kHz and 550 kHz and the second zero-points at 400 kHz and 600 kHz. This is in agreement with the experimentally measured values for both measurement transducers given in Figure 4.3.18

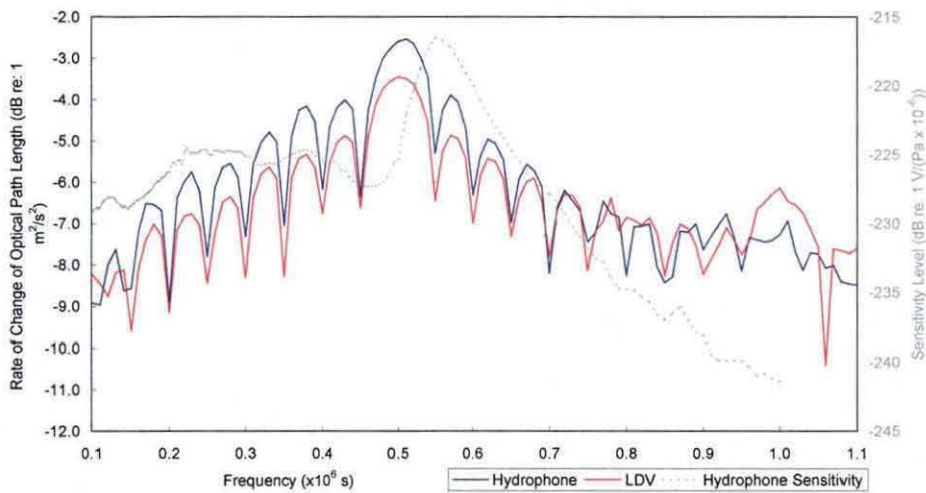


Figure 4.3.18: Power Spectrum of hydrophone and LDV measurements of 10-cycle 500 kHz acoustic tone-burst sensitivity level for ITC 6128 hydrophone

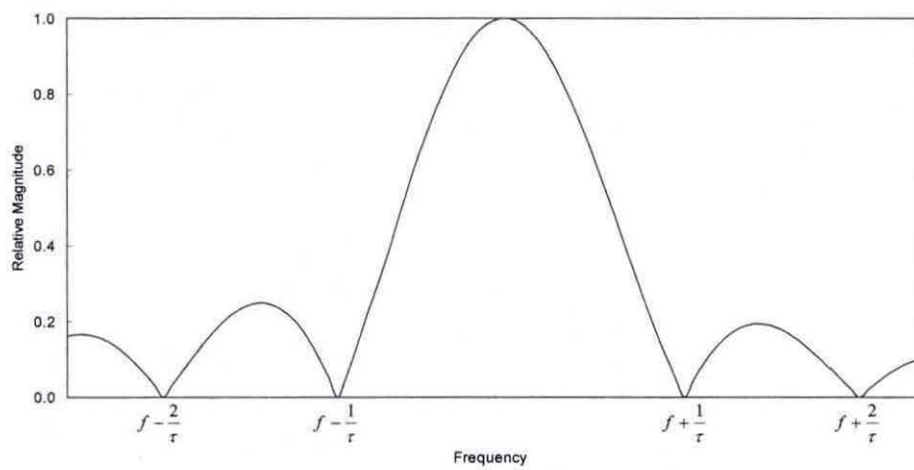


Figure 4.3.19: Theoretical Magnitude Spectrum of a tone-burst signal

The rise time of each measured signal was observed to be shorter than that encountered during the 80 kHz acoustic tone-burst measurements in Section 4.3.2.2. A measure of this was obtained from a plot of the peak at each local maxima within the Root Mean Square (RMS) of the measured signal, taken to represent the 'amplitude' against time, given in Figure 4.3.20 for both measurement transducers. The gradient of the line represents the ability of the transducer to respond to the signal, with a vertical line depicting a negligible rise time. It should be noted, however, that this does not represent purely the rise time of the transducer, since it is also dependent on the response of the acoustic source.

As has been previously mentioned in Section 1.3.1.1, the Quality Factor Q of a transducer is an important descriptive measure, which is determined by the ratio of the mass reactance to resistance [40]. An approximation of the Q of a transducer can be calculated from the theory that its signal will reach 95% of the steady state amplitude after Q cycles [41]. When an acoustic field generated by a source with $Q = Q_1$, is measured by a transducer with $Q = Q_2$, the overall measurement will exhibit a $Q = Q_3$, which is a function of Q_1 and Q_2 .

It can be seen from Figure 4.3.20 that the rate of change of optical path length derived from the hydrophone measurements reaches 95% of steady state amplitude within approximately $2.9 \mu\text{s}$ ($40.8 \mu\text{s} - 38.4 \mu\text{s}$) and the LDV measurement within $2.4 \mu\text{s}$ ($40.0 \mu\text{s} - 37.1 \mu\text{s}$). These measurements correspond to Q factors of 1.45 and 1.2 for the derived hydrophone and LDV measurements respectively.

Since it is known that the LDV has an excellent responsive bandwidth, it can be concluded that the comparatively lengthy rise-times observed during the 80 kHz measurements, where constant amplitude was not reached during 5 cycles, was due to the high Q of the acoustic source rather than the LDV.

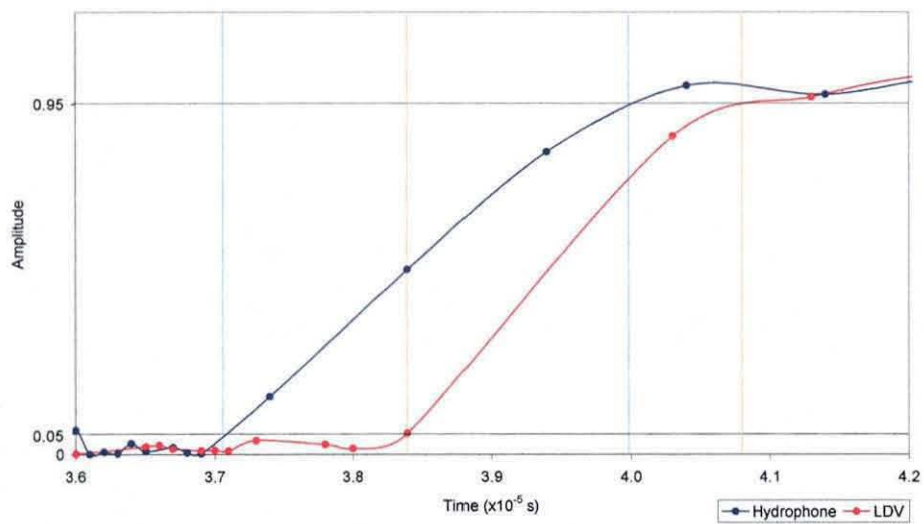


Figure 4.3.20: Amplitude versus Time for measurements from a 10-cycle 500 kHz Acoustic Tone-Burst

4.3.3 Calculation of Minimum Sensitivity

In characterising the use of an LDV system to record pressure variations within an acoustic field, it is important that a measure of the minimum detectable pressure level is established. In any measurement the minimum resolvable signal level must be sufficiently larger than the noise content of the signal in order for reasonable measurements to be made.

4.3.3.1 Noise Floor

The noise content of a signal is understood by calculating the noise floor. This is given as the mean of the Power Spectral Density (PSD) across a defined frequency band and is usually calculated for a signal recorded in the absence of the parameter to be measured, e.g. from a stationary target recorded by an LDV. The PSD represents the quotient of the Fourier Power Spectrum divided by the spectral bandwidth (frequency resolution) and takes the units of $Units^2/Hz$.

Whilst it is possible for an LDV manufacturer to quote a very low noise floor in their literature, it should be appreciated that the true noise floor of an instrument is in part a function of the speckle pattern behaviour caused by the diffuse target in the particular application [132]. For this reason an in-situ noise floor should be calculated for each application of an instrument. In a given measured PSD, the level will vary across the range of the frequency band. The variation present in the PSD of a signal recorded from a stationary target by a rigidly mounted LDV incorporating appropriate anti-vibration measures would be very small, perhaps less than ± 1 dB. This variation is likely to be increased by several of the factors involved in recording measurements from underwater acoustic fields such as the absence of anti-vibration measures and uncertainties introduced by the propagation of the light through the water. If more than one instrument is used in conjunction to record a measurement, the noise floor of the system would represent a combination of the individual noise floors of each instrument in addition to any systematic noise introduced by the measurement environment.

4.3.3.2 Minimum Resolvable Signal

The minimum resolvable signal is very simply defined as the minimum signal magnitude that can be distinguished from the background noise. It is commonly established by taking a nominal value, typically 3 dB or 10 dB, greater than noise floor. However, this procedure is only appropriate in those cases where the variation in PSD from the mean across the frequency band is smaller than the chosen value.

Where the range in PSD across the frequency band is large (> 20 dB), the addition of a nominal value to a mean is unlikely to provide a signal clearly distinguishable from any noise spikes. For this reason it was necessary in this work to define the minimum resolvable signal using a function of the signal variation. The standard deviation, σ , of a population of discrete sample points is determined from the number and value of items in the sample, given in Equation (4.3.6), where μ is the population mean, N is the number of sample points and x_n is the value of the n^{th} term.

$$\sigma = \sqrt{\left(\frac{\sum_{n=1}^N (x_n - \mu)^2}{N} \right)} \quad (4.3.6)$$

For a normally distributed sample, the probability, p , of a value, x , lying within certain limits defined by the mean, μ , and standard deviation, σ , is given by Equation (4.3.7) [145].

$$p = \int e^{-\psi^2/2} d\psi \quad (4.3.7)$$

where

$$\psi = \frac{x - \mu}{\sigma}$$

Probabilities for the first 4 integer multiples of the standard deviation, σ , around the mean, μ , are given in Table 4.3.1.

	Limits	Probability, p
Mean $\pm \sigma$	$[\mu - \sigma, \mu + \sigma]$	68.27%
Mean $\pm 2\sigma$	$[\mu - 2\sigma, \mu + 2\sigma]$	95.50%
Mean $\pm 3\sigma$	$[\mu - 3\sigma, \mu + 3\sigma]$	99.73%
Mean $\pm 4\sigma$	$[\mu - 4\sigma, \mu + 4\sigma]$	99.99%

Table 4.3.1: Statistics of a normally distributed sample

To establish beyond reasonable doubt, with a confidence of 99.99%, that a detected peak is that of a measured signal as opposed to a noise component, a value of 4 times the standard deviation greater than the spectral mean was chosen to represent the minimum resolvable signal level.

4.3.3.3 Comparison of Minimum Resolvable signal from Ball Hydrophone and OFV-302 / OFV-3000 LDV

An average of 1000 sweeps of the voltage signal was recorded from the Ball Hydrophone, calibrated in Section 3.4.1.1, and the Polytec OFV-302 / OFV-3000 LDV without the presence of an acoustic field.

The mean, peak and standard deviation of the PSD of the signal are computed in the frequency band from 20 kHz to 400 kHz, and are presented in Table 4.3.2. The minimum resolvable signal level ($\mu + 4\sigma$) is calculated along with the less appropriate levels of 3 dB and 10 dB greater than the peak within the range for the purposes of a comparison. The PSD of each recorded voltage signal, where the spectral bandwidth is 20 kHz, is given in Figure 4.3.21. The minimum sensitivity levels are also given.

	Hydrophone	LDV	Units
Peak	-146.39	-133.04	dB (re: 1 V ² /Hz)
Mean	-164.68	-152.32	dB (re: 1 V ² /Hz)
Standard Deviation, σ	6.65	6.68	dB (re: 1 V ² /Hz)
Mean + 4σ	-138.07	-125.61	dB (re: 1 V ² /Hz)
Peak + 3 dB	-143.39	-130.04	dB (re: 1 V ² /Hz)
Peak + 10 dB	-136.39	-123.04	dB (re: 1 V ² /Hz)

Table 4.3.2: Noise floor PSD levels for Ball Hydrophone and LDV

For both the hydrophone and LDV, these measurements can easily be resolved into minimum detectable voltage amplitudes, and, using the sensitivity at a given frequency, the hydrophone voltage can be related to a minimum detectable pressure amplitude. A depiction of the minimum resolvable voltage amplitude for the hydrophone and LDV at 80 kHz are superimposed onto the respective measured noise signals in Figure 4.3.22 (a) and (b) respectively.

For the LDV, it is impossible to relate the amplitude of the measured rate of change of optical path length to an absolute pressure amplitude without knowledge of the distribution of amplitude and phase along the line of the integrating laser beam. Instead, an approximation is obtained using a scaling factor, κ , derived from measurements taken in Section 4.3.2.2. The amplitude of the LDV voltage signal from a line section through the acoustic field, A_{LDV} , was compared with the amplitude of the hydrophone voltage signal at the centre of the line section, A_{MAX} , to obtain κ . The central hydrophone measurement, recorded 140 mm from the side wall of the tank, was assumed to represent the peak pressure amplitude within the field.

$$\kappa = \frac{A_{LDV}}{A_{MAX}} \tag{4.3.8}$$

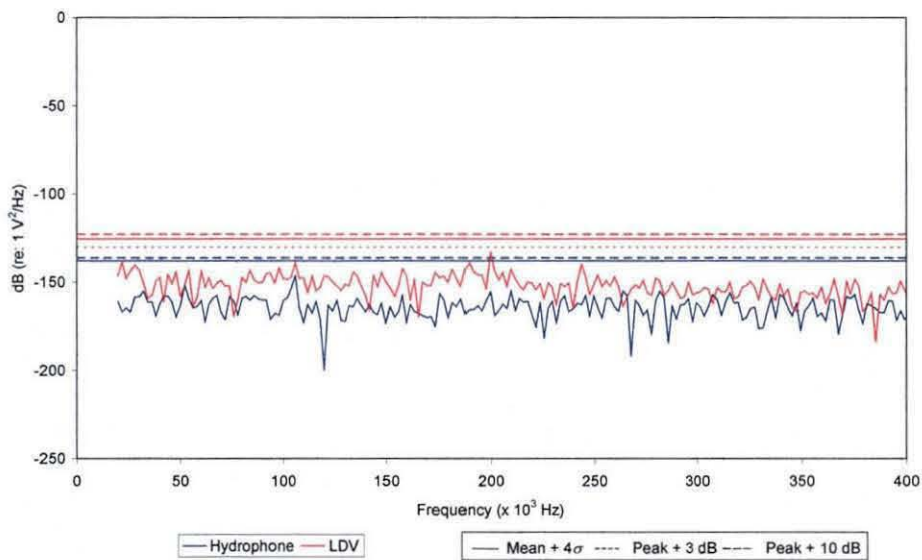


Figure 4.3.21: Noise Floor for Ball Hydrophone and Polytec OFV-302 / OFV-3000
LDV passing through a volume

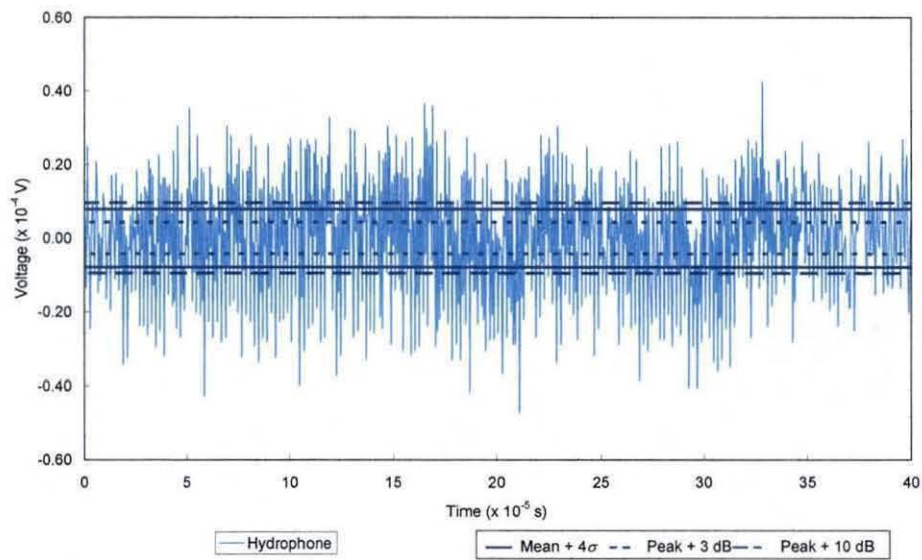


Figure 4.3.22 (a): Ball Hydrophone

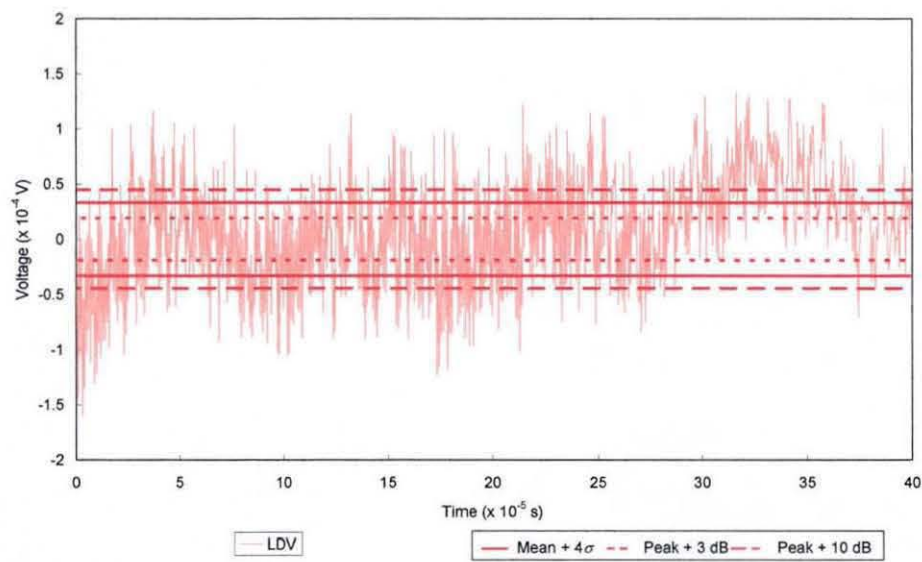


Figure 4.3.22 (b): OFV-302 / OFV-3000 LDV

Figure 4.3.22: Minimum resolvable amplitude from Hydrophone and LDV at 80 kHz

This scaling factor provides a crude method of converting a measured LDV voltage signal amplitude into an equivalent hydrophone voltage signal amplitude at the centre of the interrogated line section, which can then be scaled to obtain a pressure amplitude using the sensitivity coefficient of the hydrophone. The technique assumes that the distance travelled by the laser beam through the water and the shape of the acoustic phase and amplitude distribution remain constant at a given frequency.

From the measurements recorded at 80 kHz, κ , was calculated to be 10.52. The signal amplitudes were taken from the 80 kHz components in each of the magnitude spectra obtained from a DFT of 4 of the 6 cycles within the tone-burst. The process by which an estimate of the pressure was derived is tabulated in Table 4.3.3

		Hydrophone	LDV	Units
Minimum Resolvable Signal Amplitude at 80 kHz	Mean + 4σ	7.89×10^{-6}	33.1×10^{-6}	V
	Peak + 3 dB	4.28×10^{-6}	19.1×10^{-6}	V
	Peak + 10 dB	9.57×10^{-6}	44.5×10^{-6}	V
Scaling Factor, κ			$\frac{0.906}{0.086} = 10.52$	
Equivalent Hydrophone Voltage	Mean + 4σ		3.14×10^{-6}	V
	Peak + 3 dB		1.81×10^{-6}	V
	Peak + 10 dB		4.23×10^{-6}	V
Sensitivity @ 80 kHz		168.7×10^{-6}	168.7×10^{-6}	V/Pa
Minimum Resolvable Pressure Amplitude at 80 kHz	Mean + 4σ	46.8×10^{-3}	18.7×10^{-3}	Pa
	Peak + 3 dB	25.4×10^{-3}	10.8×10^{-3}	Pa
	Peak + 10 dB	56.8×10^{-3}	25.1×10^{-3}	Pa

Table 4.3.3: Minimum Resolvable Signal Amplitudes at 80 kHz

The approximate minimum resolvable pressure amplitudes derived at 80 kHz provide an indication of the comparative sensitivities of each measurement transducer. Regardless of the method of establishing a minimum resolvable signal, the LDV is shown to have greater than at least twice the sensitivity of the hydrophone for a double pass through a plane wave acoustic field. For the level defined by 4σ , the LDV is able to detect a signal approximately 2.5 times smaller than the hydrophone.

4.3.3.4 Comparison of Minimum Resolvable signal from the ITC 6128 Hydrophone and OFV-056 / OFV-3001-S LDV

A similar procedure was followed to enable the minimum sensitivity of the ITC 6128 hydrophone and OFV-056 / OFV-3001-S LDV to be established. The PSD of a section of the signal recorded from each device representing the response without the presence of an acoustic field is given in Figure 4.3.23. This enables the same three potential minimum sensitivity levels calculated previously to be determined for a spectral bandwidth of 20 kHz, as shown in Table 4.3.4.

	Hydrophone	LDV	Units
Peak	-136.35	-151.51	dB (re: 1 V ² /Hz)
Mean	-151.66	-163.82	dB (re: 1 V ² /Hz)
Standard Deviation, σ	6.24	7.31	dB (re: 1 V ² /Hz)
Mean + 4σ	-126.72	-134.58	dB (re: 1 V ² /Hz)
Peak + 3 dB	-133.35	-148.51	dB (re: 1 V ² /Hz)
Peak + 10 dB	-126.35	-141.51	dB (re: 1 V ² /Hz)

Table 4.3.4: Noise Floor PSD levels for ITC 6128 Hydrophone and OFV-056 / OFV-3001-S LDV

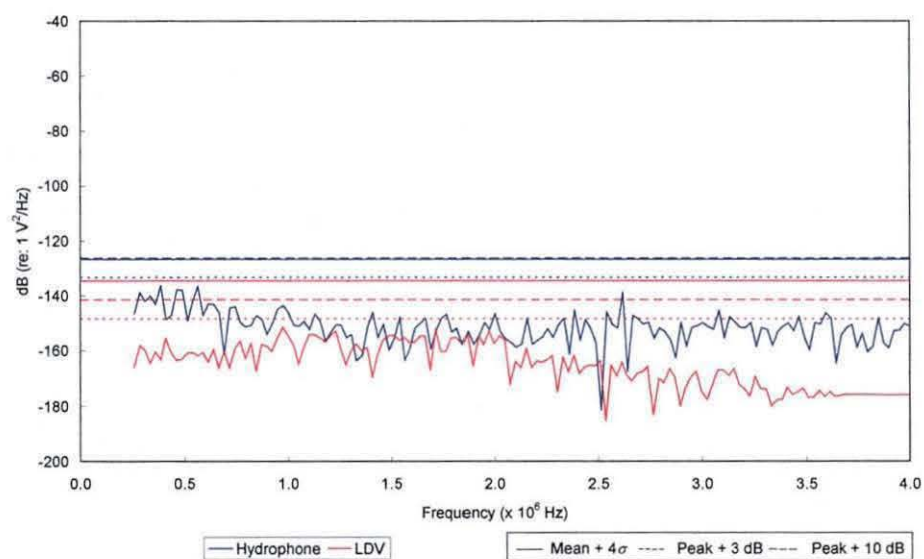


Figure 4.3.23: Noise Floor for ITC 6128 Hydrophone and Polytec OFV-056 / OFV-3001 LDV passing through a volume

A similar scaling factor, κ , was calculated from the ratio of the LDV and the peak hydrophone amplitudes taken from a DFT of 8 of the 10 cycles measured in Section 4.3.2.3. At 500 kHz, κ , was calculated to be 1.569. Calculations were then undertaken to establish firstly the minimum resolvable voltage signal from each measurement transducer, and the corresponding pressure amplitude. Minimum detectable voltage amplitudes for the Hydrophone and LDV are superimposed onto the noise signals in Figure 4.3.24 (a) and (b) respectively.

		Hydrophone	LDV	Units
Minimum Resolvable Signal Amplitude at 80 kHz	Mean + 4σ	1.04×10^{-4}	4.22×10^{-5}	V
	Peak + 3 dB	4.87×10^{-5}	8.50×10^{-6}	V
	Peak + 10 dB	1.09×10^{-4}	1.90×10^{-5}	V
Scaling Factor, κ			$\frac{0.094}{0.060} = 1.569$	
Equivalent Hydrophone Voltage	Mean + 4σ		2.69×10^{-5}	V
	Peak + 3 dB		5.41×10^{-6}	V
	Peak + 10 dB		1.21×10^{-5}	V
Sensitivity @ 500 kHz		5.37×10^{-6}	5.37×10^{-6}	V/Pa
Minimum Resolvable Pressure Amplitude at 80 kHz	Mean + 4σ	19.46	5.01	Pa
	Peak + 3 dB	9.06	1.01	Pa
	Peak + 10 dB	20.29	2.26	Pa

Table 4.3.5: Minimum resolvable signal amplitudes at 500 kHz

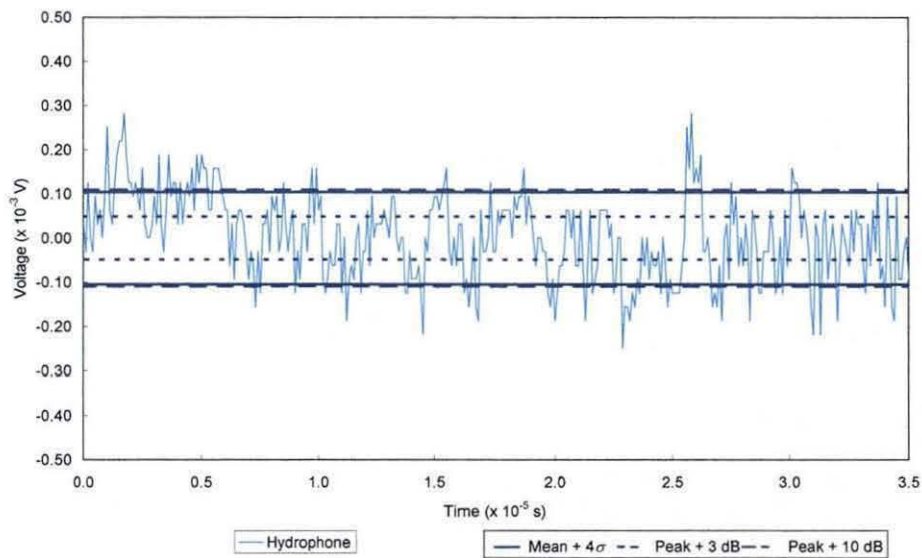


Figure 4.3.24 (a): ITC 6128 Hydrophone

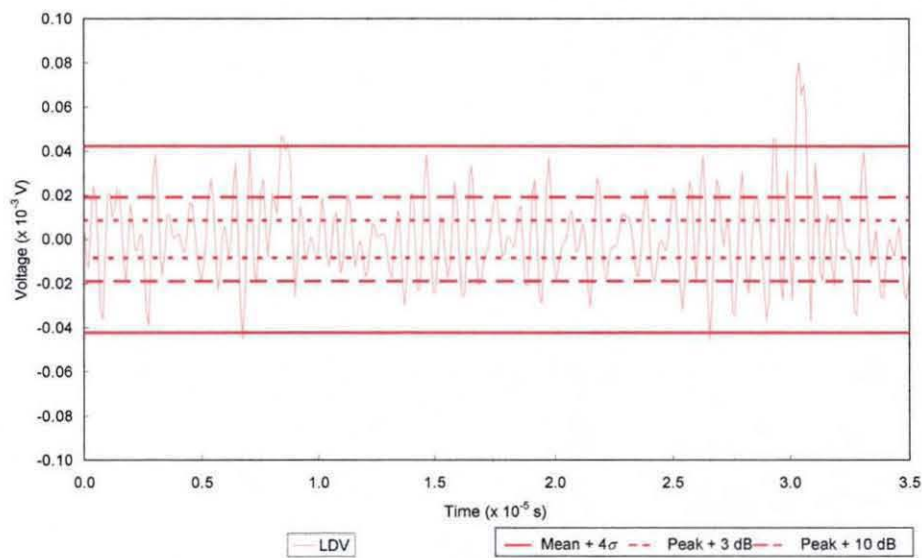


Figure 4.3.24 (b): OFV-056 / OFV-3001-S LDV

Figure 4.3.24: Minimum resolvable amplitude from Hydrophone and LDV at 500 kHz

As was the case with the 80 kHz measurement, the minimum resolvable amplitude of the LDV compares extremely favourably with that of the hydrophone at 500 kHz. For both the 3 and 10 dB levels, the LDV is shown to have ≈ 9 times the sensitivity of the hydrophone. For the 4σ level, the sensitivity of the LDV is shown to be ≈ 3.9 that of the hydrophone. It should be noted that since the scaling factor, κ , was calculated using measurements from a focused acoustic transducer, the approximation of minimum sensitivity is valid only for use with a similar transducer at the specified frequency.

Various methods can be employed to further reduce the noise content in a measured signal from the hydrophone or LDV. Examples of two simple approaches would be to increase the number sweeps used in the signal averaging and another would be to reduce the interference caused by the antenna effect of the connecting BNC cables, either by shortening their lengths or increasing the level of insulation. Other measures specific to the LDV, designed to maximise the quality of the reflected light from the mirror and reduce potential vibrations of the optical head or reflecting mirror would also reduce the minimum signal amplitude resolvable using the LDV.

4.4 CLOSURE

The work described in this chapter has successfully demonstrated the ability of Laser Doppler velocimetry to record measurements from underwater acoustic pressure fields. The rate of change of optical path length signal measured by the LDV passing through the acoustic field has been shown to recreate the major features of the measurement of pellicle motion recorded from the same field. Indeed the presence of noise and other spurious artefacts is shown to be reduced in the measurement directly from the field, predominantly due to the absence of reflected components within the time window. By extending the measurement duration the technique has proved effective in identifying the reflected components of the signal in time.

The results of additional comparisons of acoustic standing wave conditions measured through direct interrogation of the field using the LDV and conventionally using a hydrophone have also demonstrated the LDV to be effective in monitoring the acoustic pressure distribution.

Closer investigations of tone-burst acoustic fields using the non-perturbing LDV technique have enabled the successful measurement of parameters such as the distance of separation between the source and the laser beam, in addition to the frequency of the wave. The high Q of the hydrophone has been proven to restrict the fidelity of the measurements. The LDV, however, has an excellent bandwidth, which enables measurements to be made from tone-bursts of fewer cycles than required by the hydrophone. It is noted that the Q of the source transducer means that the signal recorded by the LDV will always exhibit a finite rise time. The combination of the Q s of the source and hydrophone have been demonstrated to be of significance in a small water tank, since the reflected components arrive before sufficient steady state cycles have passed the measurement position.

Discrete hydrophone measurements along an individual line section through the field have enabled an evaluation of the theory to be undertaken. In general, the LDV showed good similarity with the integrated hydrophone data at 80 kHz (within 5 dB), both in its time resolved signal and spectrum. The highly non-linear spatial

distribution of the field generated at 500 kHz caused a discrepancy between the two measurements and agreement is reduced to 20 dB.

An assessment of the minimum resolvable pressure amplitude of the LDV and hydrophone was undertaken. This required the development of a novel calculation procedure due to the high variation observed in the power spectral density noise floors. The technique involved utilising the standard deviation of the noise floor across its bandwidth to establish the minimum detectable signal level. These were converted into values of pressure for both the hydrophone and LDV. The results demonstrate the LDV to have a minimum resolvable pressure amplitude of 18.7 mPa at 80 kHz, compared to 46.8 mPa for the hydrophone. Similar calculations undertaken at 500 kHz demonstrate the minimum pressure amplitude of the LDV to be calculated as 5.01 Pa, compared to 19.46 Pa for the hydrophone.

Chapter 5

LDV Measurements of Spatially Distributed Underwater Acoustic Fields in Two-Dimensions

5.1 INTRODUCTION

This chapter further develops the theory and practical investigation detailed in Chapter 4. Previous discussion is centred on characterising an acoustic signal by the change in its instantaneous pressure magnitude with time at a single line position. However, when assessing the signal generated by an acoustic source, it is important to consider the temporally resolved pressure amplitude throughout the field. By establishing the spatial distribution of an acoustic field generated by an acoustic source, a description of the nature and magnitude of the principal beam generated by the source can be determined. A quick, robust and effective means of characterising this spatial distribution is proposed, which it is anticipated would be of significant benefit to users and source manufacturers in both the medical and marine communities.

A theoretical explanation of the interaction of the beam from a scanning LDV system is presented which caters initially for the case where the beam intersects the acoustic axis and subsequently for the general case where incidence of the laser beam is arbitrary. A detailed description of the capabilities of the scanning LDV system is given, including an assessment of the accompanying PSV-200 software and the manner in which data is stored.

A series of data presentation methods for distributed field parameters is proposed and an assessment of the relative merits of each is presented. These include images depicting magnitude, power, phase and temporally resolved rate of change of optical path length.

5.2 THEORETICAL METHODOLOGY

Laser Doppler Velocimetry (LDV) has been proven to be effective in recording the temporal distribution of an underwater pressure wave as it passes over the single line section of the laser beam directed through the acoustic volume. With the LDV measurement triggered in time by the input voltage to the transducer, the perpendicular distance from the laser beam position to the front face of the acoustic source determines the time delay prior to the arrival of the acoustic tone-burst. It follows, therefore, that by comparing the rate of change of optical path length measured at a range of laser beam positions with respect to the acoustic source, information can be obtained regarding the spatial distribution of the acoustic field.

5.2.1 Application of a Polytec Scanning LDV

A Polytec scanning LDV enables the rate of change of optical path length of a laser beam to be measured for a range of discrete beam positions through an underwater acoustic volume. The output from each measurement recorded in such a manner is likely to vary both in phase, predominantly due to the time-of-flight delay prior to the arrival of the acoustic tone-burst, and in magnitude, dependent on the position of the measurement, as described in Section 4.2.3. However, unlike the theoretical and experimental examples presented in Chapter 4 and depicted in Figure 5.2.1, the laser beam from the LDV is not necessarily directed so as to intersect the acoustic axis with normal incidence.

Due to the nature of the scanning mirror arrangement within the optical head, the angles of incidence cannot be perpendicular to the acoustic axis for more than one measurement from the same scan. Therefore, additional mathematical explanation must be provided to accommodate for this angular discrepancy.

It is appreciated that a lens can be included to correct the direction of the beam, so the incidence with the acoustic axis can be perpendicular for all measurements within a scan. However, such a lens would need to be impractically large, and consequently expensive, in order to facilitate the scanning of an area of the same size as the lens.

Once an array of discrete positions has been established on the target, and the time range, sensitivity and frequency limits defined, the laser beam is directed at each position in turn and an average of a predetermined number of sweeps is saved to disk. Certain features of the measured data can be highlighted and investigated in the PSV 200 software. A variety of quantities can be presented as 2 or 3-dimensional, colour scaled images, where the colour scaled image is either superimposed onto an image of the target or in 3-dimensions where the third axis represents the measured velocity or displacement. Two examples of such depictions are power distribution and reconstructed amplitude and phase.

A measure of the acoustic distribution at a specific frequency can be obtained by plotting the value of the power spectrum of each discrete measurement within a scan at its respective position in 2-dimensions. When applied to the measurement of underwater acoustic fields, the frequency at which the power is calculated is typically the frequency of the acoustic excitation. Throughout this work, such images are referred to as 'power' distribution images.

From the recorded FFT data, both the amplitude and phase of a vibration can be calculated for each position. Reconstructing this information at each discrete measurement position enables a set of images representing one cycle of oscillation at the chosen frequency to be generated. When displayed sequentially as an animation, it is possible to visualise the phase relationships of oscillations within the measurement scan.

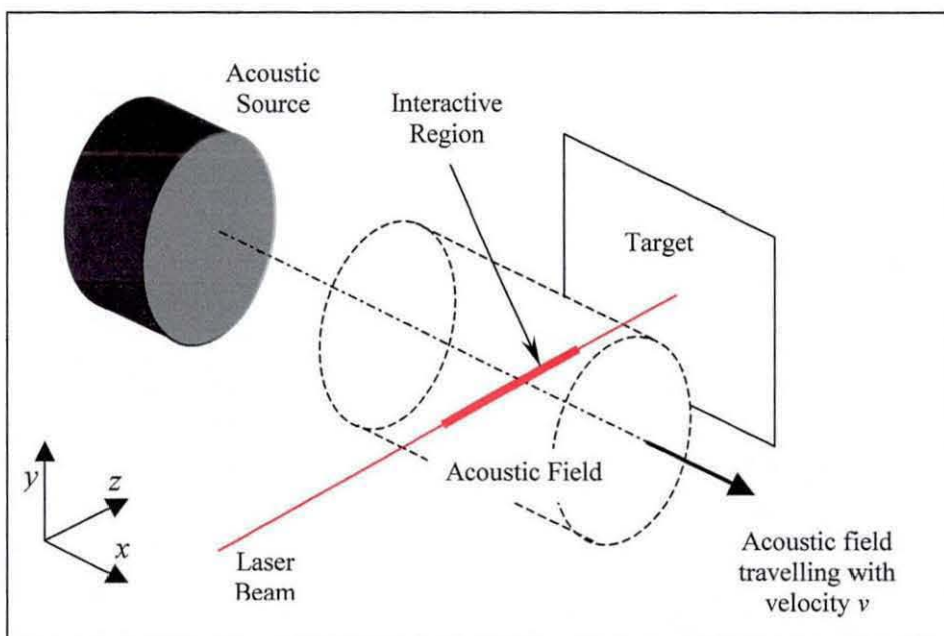


Figure 5.2.1: LDV laser beam passing through acoustic axis with normal incidence

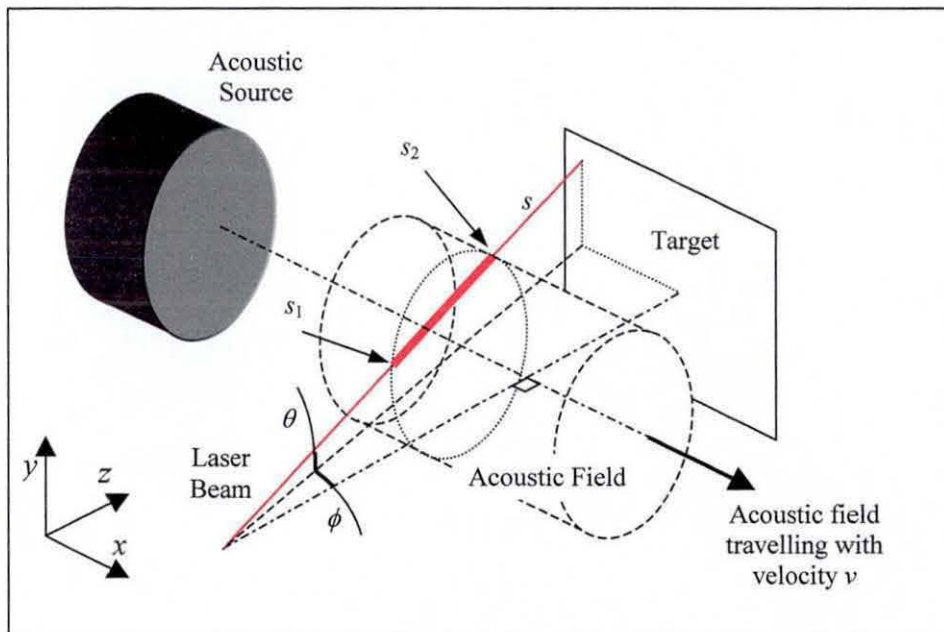


Figure 5.2.2: LDV laser beam passing through acoustic axis with incidence defined by angles ϕ and θ

5.2.2 Theoretical Analysis of Scanning LDV laser beam passage through an underwater acoustic field

In considering the passage of the laser beam from a scanning LDV through an acoustic volume, provision must be made for the case where the laser beam is not orthogonal to the acoustic axis. Given that the beam is directed by two scanning mirrors, each manipulating the horizontal and vertical position of the beam respectively, it follows that the position of the beam should be defined by angles in two planes; the x - z plane, represented by ϕ , and y - z plane represented by θ . A typical arrangement is shown in Figure 5.2.2. The z -axis is defined as the line passing from the laser source through the acoustic axis with normal incidence. The y -axis remains orthogonal to both the acoustic axis and the z -axis.

When applied to non-perturbing underwater acoustic measurements, the voltage output from an LDV, proportional to the rate of change of optical path length experienced by the laser beam is described in Section 4.2.3. For interrogation of a plane-wave acoustic field, the voltage is shown to be dependent on the acoustic frequency, f , the sensitivity scalar of the LDV electronics, K , the limits of the integral, z_1 and z_2 , the piezo-optic coefficient, $\left(\frac{\partial n}{\partial p}\right)$, and the amplitude and phase, A and Φ , of the acoustic pressure variation, as given in Equation (5.2.1).

$$V(t) = 4\pi f K (z_2 - z_1) \left(\frac{\partial n}{\partial p} \right) A \cos(2\pi f t - \Phi) \quad (5.2.1)$$

The integral of refractive index with distance along a laser beam line that does not pass through the acoustic axis is considerably more complicated to describe. It is necessary to define a path, s , representing the laser beam. The distance from the laser source to a point along the laser beam line (x_0, y_0, z_0) is given in Equation (5.2.2).

$$s_0 = \sqrt{x_0^2 + y_0^2 + z_0^2} \quad (5.2.2)$$

From the notation defined in Figure 5.2.2, the magnitudes of the unit vectors i, j and k , in directions x, y and z , respectively, can be described in terms of θ , and ϕ .

$$\begin{aligned}
i &= \cos \theta \sin \phi \\
j &= \sin \theta \\
k &= \cos \theta \cos \phi
\end{aligned}
\tag{5.2.3}$$

For a continuous plane wave of circular cross-section, the amplitude, A , will remain constant as in Equation (4.2.3). However, the phase of the pressure sinusoid, $\Phi_{(x,y,z)}$ will be dependant on the position of the point within the field.

$$\Phi_{(x,y,z)} = \Phi_0 + \frac{cx_0}{2\pi f} + \frac{sci}{2\pi f} = \Phi_0 + \frac{c(x_0 + si)}{2\pi f}
\tag{5.2.4}$$

where x_0 is the distance of the laser source from the acoustic source in the x -direction, $x_0 + si$ is the distance of the point, (x,y,z) , from the acoustic source $(0,0,0)$

Similarly, Equation (4.2.6) can now be rewritten to accommodate the incidence angles θ and ϕ .

$$\begin{aligned}
l(t) &= l_0 + \int_{s_1}^{s_2} n_{(x,y,z)}(t) ds \\
&= l_0 + A_0 \left(\frac{\partial n}{\partial p} \right) \int_{s_1}^{s_2} \sin \left(2\pi ft - \frac{c(x_0 + si)}{2\pi f} \right) ds \\
&= l_0 + A_0 \left(\frac{\partial n}{\partial p} \right) 2\pi f \left[\frac{\cos \left(\frac{c(x_0 + si)}{2\pi f} - 2\pi ft \right)}{ci} \right]_{s_1}^{s_2} \\
&= l_0 + \frac{A_0 2\pi f}{ci} \left(\frac{\partial n}{\partial p} \right) \left[\cos \left(\frac{c(x_0 + s_2 i)}{2\pi f} - 2\pi ft \right) - \cos \left(\frac{c(x_0 + s_1 i)}{2\pi f} - 2\pi ft \right) \right]
\end{aligned}
\tag{5.2.5}$$

where the limits s_1 and s_2 represent the position of the beginning and the end, respectively, of the interactive region along s . These positions can be described in terms of x , y , and z ;

$$\begin{aligned}
x_1 &= \tan \phi \cos \theta \left(d_a \cos \theta - \sqrt{r^2 - (d_a \sin \theta)^2} \right) \\
y_1 &= \sin \theta \left(d_a \cos \theta - \sqrt{r^2 - (d_a \sin \theta)^2} \right) \\
z_1 &= \cos \theta \left(d_a \cos \theta - \sqrt{r^2 - (d_a \sin \theta)^2} \right) \\
x_2 &= \tan \phi \cos \theta \left(d_a \cos \theta + \sqrt{r^2 - (d_a \sin \theta)^2} \right) \\
y_2 &= \sin \theta \left(d_a \cos \theta + \sqrt{r^2 - (d_a \sin \theta)^2} \right) \\
z_2 &= \cos \theta \left(d_a \cos \theta + \sqrt{r^2 - (d_a \sin \theta)^2} \right)
\end{aligned} \tag{5.2.6}$$

such that by substitution into Equation (5.2.2), s_1 and s_2 can be given in a simplified form.

$$\begin{aligned}
s_1 &= \sqrt{-\frac{\left(-d_a \cos \theta + \sqrt{r^2 - d_a^2 + d_a^2 \cos^2 \theta} \right)^2 \left(-\cos^2 \theta + \cos^2 \theta \cos^2 \phi - \cos^2 \phi \right)}{\cos^2 \phi}} \\
s_2 &= \sqrt{-\frac{\left(d_a \cos \theta + \sqrt{r^2 - d_a^2 + d_a^2 \cos^2 \theta} \right)^2 \left(-\cos^2 \theta + \cos^2 \theta \cos^2 \phi - \cos^2 \phi \right)}{\cos^2 \phi}}
\end{aligned} \tag{5.2.7}$$

Differentiating twice the optical path length, $2l$, with respect to time to calculate the rate of change of optical path length as measured by the LDV, gives the following:

$$\frac{dl(t)}{dt} = -\frac{8A_0 \pi^2 f^2}{ci} \left(\frac{\partial n}{\partial p} \right) \left(\sin \left(2\pi f t - \frac{c(s_2 \mathbf{i} + x_0)}{2\pi f} \right) - \sin \left(2\pi f t - \frac{c(s_1 \mathbf{i} + x_0)}{2\pi f} \right) \right) \tag{5.2.8}$$

From Equation (5.2.8) it can be seen that the sensitivity of an LDV laser beam is dependent on its angular position with relation to the acoustic axes, θ and ϕ and the frequency, f , of the acoustic wave. Due to the presence and relative positions of these

variables within Equation (5.2.8), it follows that at certain angular positions, the pressure distribution will be such that the integral of refractive index with distance along the laser beam through the interactive region is equal to zero. This will result in the optical path length of the laser beam remaining constant with time. Hence the LDV, which provides a measure of the rate of change of optical path length, will be totally insensitive to the acoustic wave.

The theoretical rate of change of optical path length described in Equation (5.2.8) is valid only for LDV interrogations of continuous wave acoustic signals. These are not generally used in laboratory based underwater acoustic studies due to the need to eliminate interference effects between the signal and other portions of the signal reflected from the tank walls, surfaces or other impeding obstacles. For this reason, tone-burst acoustic signals are used. These consist of typically between 5 and 50 cycles of a single frequency separated by a delay sufficient for the reflected components of the wave to die away.

Whilst the mathematical description of rate of change of optical path length given in Equation (5.2.8) holds true for the scenario shown in part (b) of Figure 5.2.3 where the interactive region of the laser beam extends from the near to the far side of the acoustic field, it does not describe the measured effect depicted in parts (a) and (c). In both these scenarios, the interactive region is reduced from that of the mathematical description.

To account for the period before and after interaction with the steady-state region of the acoustic wave, one of two approaches can be taken. The first is to consider the tone-burst to be a continuous wave but relate the limits of the integral, s_1 and s_2 , to the position of the tone-burst in time and space, such that the distance over which the integral is taken, $(s_2 - s_1)$, is equal to zero before and after the acoustic tone-burst has passed. The second approach, is to modify the description of pressure given in Equation (4.2.3) from a continuous wave into a tone-burst by multiplying the signal by a rectangular window of an appropriate duration in the time-domain.

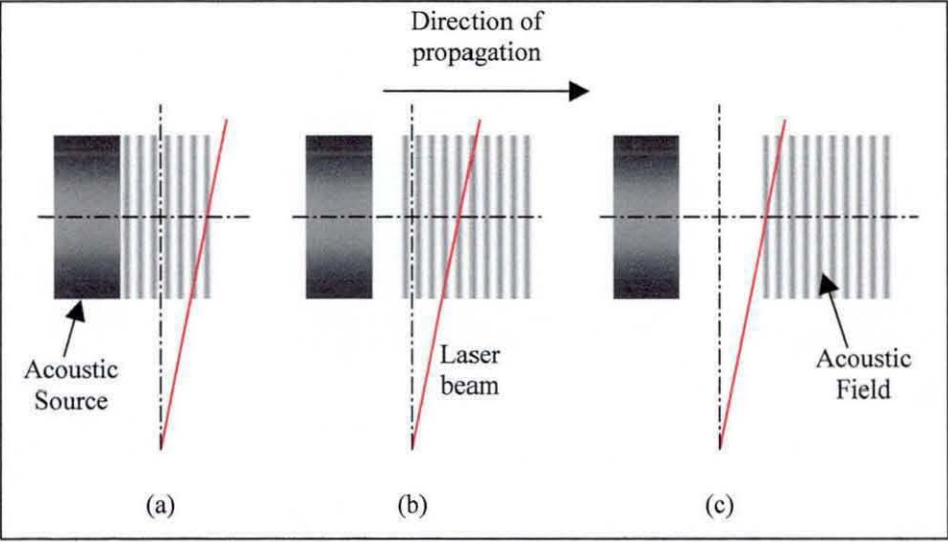


Figure 5.2.3: LDV laser beam traversing a propagating acoustic tone-burst

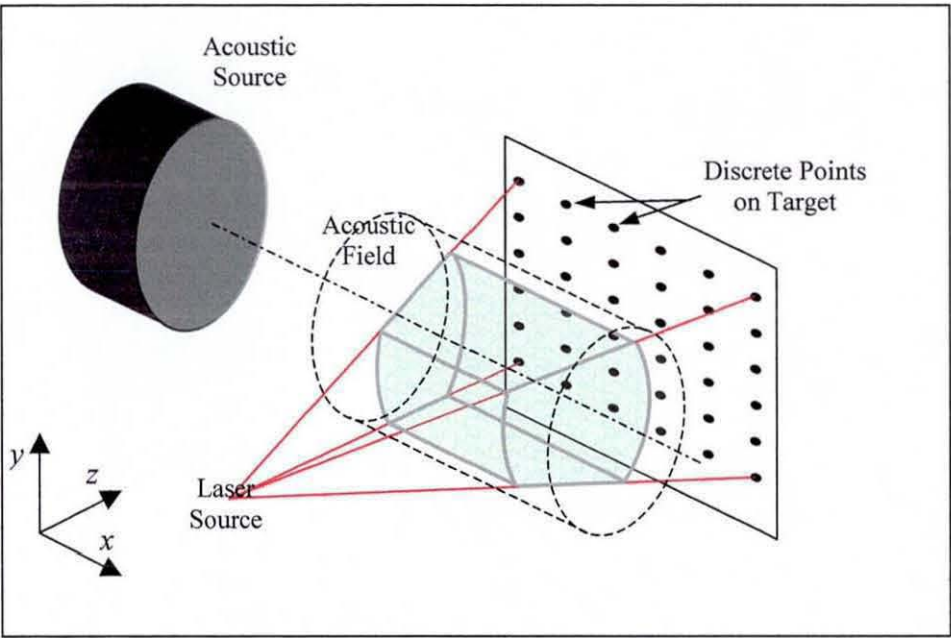


Figure 5.2.4: The interactive region defined by the LDV laser beam at its angular extremities

In practice, it is extremely unlikely that the wave front from a plane-piston acoustic source will exhibit entirely plane wave characteristics. Instead, the amplitude, phase, shape and divergence of the acoustic field will mean that the description of pressure variation with time at a point will be significantly more complex than that used for the mathematical description presented so far. In addition, there are many other designs of acoustic transducer in industrial use, each of which enables the generated field to exhibit certain characteristics.

One such design in widespread use in the medical community is the focused transducer. Here, a concave transducer face generates a spherical wave front, which reduces to a minimum cross-section at a focal distance away from the transducer. The relationship between the amplitude and phase of the pressure variation with spatial position in three dimensions in a focused field would require the mathematical description of the rate of change of optical path length LDV given in Equation (5.2.8) to take a more generic form as given in Equation (5.2.9).

$$\frac{dl(t)}{dt} = 4\pi f \left(\frac{\partial n}{\partial p} \right) \int_{s_1}^{s_2} A(s) \cos(2\pi f t - \Phi(s)) ds \quad (5.2.9)$$

where $A(s)$ is the amplitude as an unknown function of distance, s and $\Phi(s)$ is the phase, also as an unknown function of distance, s .

When considering the interaction of a Polytec Scanning LDV system with an acoustic field, the range of the scan is determined by the angular position of the laser beam in terms of ϕ and θ in their minimum and maximum positions as depicted in Figure 5.2.4. A measurement of time-resolved velocity is recorded at each of the predetermined discrete target positions.

One measure which can be taken to minimise the influence of the angular position of the beam is to ensure that the stand-off distance between the scanning head and the acoustic field is sufficiently greater than the range of the scan to enable a small angle approximation to be used.

5.3 EXPERIMENTATION METHODOLOGY

5.3.1 *Experimental Arrangement*

A Polytec scanning LDV system was set-up as shown in Figure 5.3.1, with the LDV positioned approximately 1 m from the acoustic axis. The image captured by the CCD camera within the LDV scanning head was then brought into focus on the PC monitor using the remote zoom lens. Since the position of the focused image plane was not constant with each magnification setting, calibration of the intersection of the laser beam with the image plane was required for each experimental set-up. This was done simply by aligning the screen cursor with the position of the laser spot at a minimum of three positions in x and y on the target.

A network of scanning positions is then established using a range or combination of grid patterns with specified linear spacing increments. This is done visually on screen, and each position is related to a pair of angular positions required to direct the laser beam appropriately. For each scan, the frequency cut-off filter, sensitivity scalar and time window duration are specified, along with the appropriate quantities ensuring the signals are triggered correctly from the input signal to the transducer.

5.3.2 *PSV 200 Software*

The FFT of the rate of change of optical path length is sampled at 40 MHz by the OFV-3001-S LDV controller and recorded by the PSV 200 software with a maximum resolution of 6400 lines, for each measurement position. Speckle effects which restrict the quality and quantity of the light returning from the target [146] are required to be considered since they can lead to erroneous measurements, often of a magnitude greater than the measured signals. Consequently an indication of the 'quality' of each measurement is provided by the data validation label given to each position once a measurement has been made. If the level falls below a threshold, an appropriate label is attached to the point and it is re-measured once the remainder of the scan has completed. If, however, the point is defective due to laser speckle effects, its quality will not be improved by re-measurement, unless the position of the target is altered.

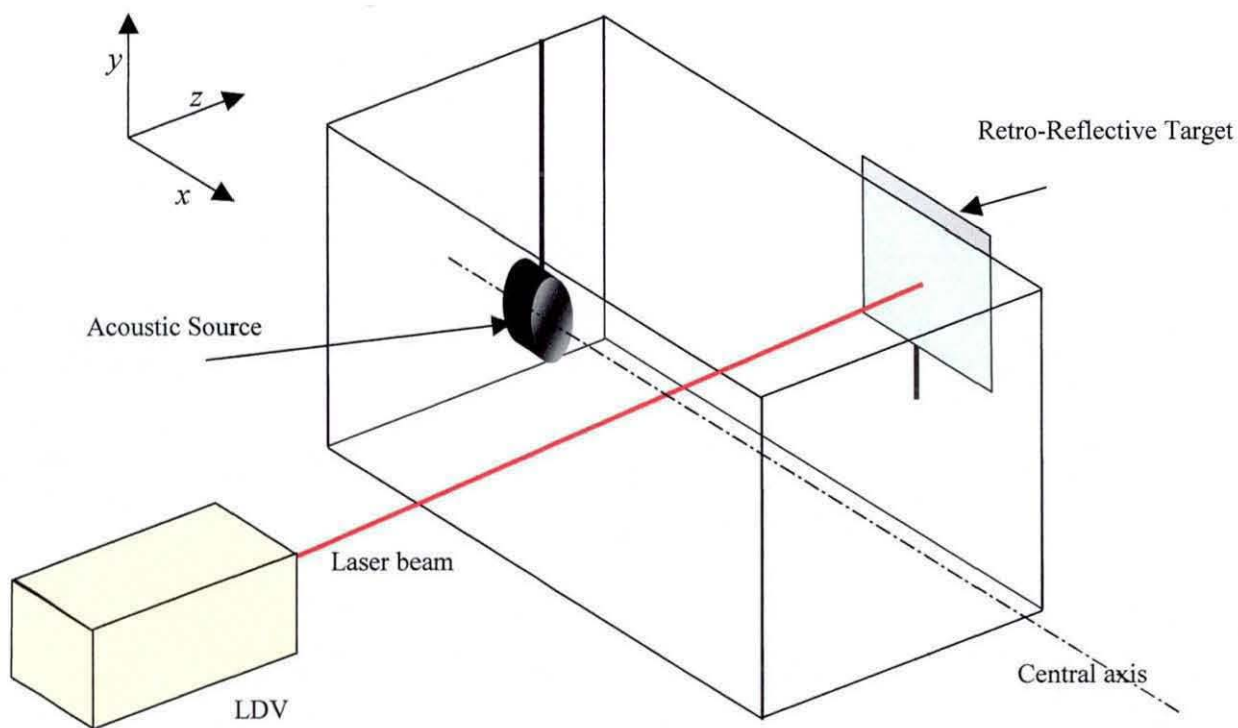


Figure 5.3.1: Experimental set-up for recording 2-dimensional scans from an underwater acoustic field

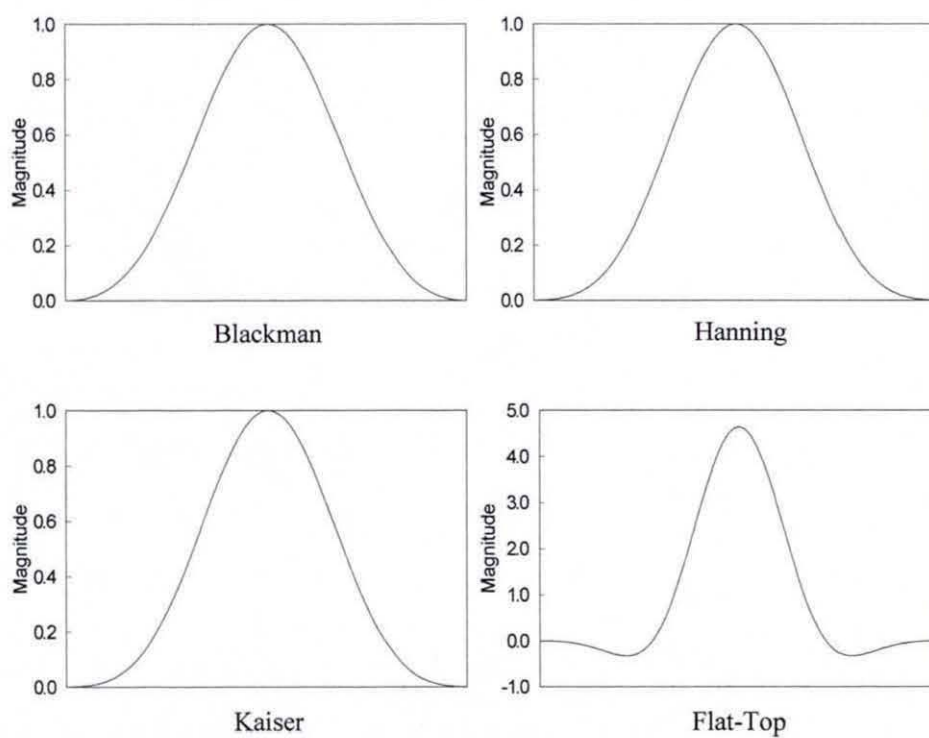


Figure 5.3.2: Examples of Window Functions

The visual interface of the PSV software can be accessed in either the acquisition or display mode. The acquisition mode is the mode in which the laser beam is positioned and the measurement points are defined before the procedure of data acquisition and recording is completed.

In display mode, specified quantities from the measured data such as magnitude, power or phase distribution or reconstructed modal analysis type 'frequency response' plots are displayed as colour or grey-scaled images in 2 or 3-dimensions. Here, erroneous points can be discarded and replaced by values derived by interpolation from surrounding points. A low pass filter can also be applied to remove much of the higher frequency noise within the image.

The magnitude or power distribution images consist of a colour scaled pixel for each measurement position. The values used are the components at the specified frequency of the magnitude or power spectra respectively.

The 'frequency response' plots are intended to provide information regarding the mode shapes of the target surface at certain frequencies of excitation. They consist of a sequence of images each constructed at a different angular interval, α , through one complete cycle of the oscillation at the specified frequency. The value of each point is calculated from the component of the real and imaginary FFT spectra at the frequency of interest. If the magnitude is calculated to be M , and the phase β , the instantaneous value, Q , is given as:

$$Q = M \cos(\alpha - \beta) \quad (5.3.1)$$

When these images are displayed in sequence, the phase and amplitude of one point with respect to another can be visualised. It is important that such an animation is not confused with a reconstruction of the time resolved rate of change of optical path length for the scan. This becomes evident when used to represent an underwater acoustic tone-burst measurement. Here, in the majority of experimental cases, the physical length of the burst is less than the width of the scan, meaning both the near and far extremities of the scan area with respect to the acoustic source can not oscillate simultaneously, as they do in a 'frequency response' plot.

5.3.2.1 Cosine Compensation for Laser Scanning Angle

Under normal circumstances, an LDV is intended to measure the velocity of the surface of a target. Since it is sensitive only to the component of the motion in the direction of the laser beam, the signal will change as the scan angle varies. If it can be assumed that the vibration is entirely in the z -axis and has no component of its motion in x or y , this change can be eliminated by a simple cosine correction. For this reason the PSV 200 software includes an optional cosine correction function, which can be used to compensate for the reduced amplitude of measured vibration velocity.

Throughout the experimentation described here, the cosine compensation was not used due to the fact that the measurements were made from changes in properties of the transmitting media (water) and were not representative of 'out-of-plane' motion. Instead the signals were obtained from a complex integral of phase and amplitude along the lengths of the beams and would not have benefited from a simple scaling factor.

5.3.2.2 Windowing

Since the basis of operation of the PSV software is that of FFT analysis, it is important to consider the role of windowing. Multiplying the measured time-resolved signal by one of a number of potential windows can reduce some of the unwanted effects brought about by the FFT process.

Since the FFT operates by assuming that the sampled signal is repeated, if an incomplete number of cycles are included within the time window, the end of one signal segment does not connect smoothly with the beginning of the next. This can be encountered if the sample length is short and sits within a period of steady state oscillation, or if the duration of the steady state vibration is considered continuous with respect to the sample length. If this is the case, misleading broadening of the anticipated peak is included in the spectrum as a result of the FFT.

Most window functions, (such as Blackman, Hanning and Kaiser, each depicted in Figure 5.3.2) have the property that their value and all their derivatives are zero at both of their ends. This has the effect of maintaining the small bandwidth anticipated in the spectrum. However, it is unlikely that the frequency content of the signal will lie entirely within the boundaries of a particular FFT line and will instead be distributed between 2 or more lines. Consequently, another window (Flat-top, also shown in Figure 5.3.2) attempts to broaden the bandwidth of the peaks in the frequency domain, and in doing so, guarantee that the height of a peak is within 2% of the value of the peak at the specific fundamental frequency.

To reconstruct the time-resolved signal from the FFT, an inverse FFT is performed and the resultant time signal divided by the original window function. This is subject to certain anomalies since the division of any value by zero or a value close to zero leads to unfeasibly large or even infinite values in the time-domain. In practice, for the majority of windows, this means that the first and last few data points are discarded, since these correspond to the very small values of the window. However, in the case of the flat-top, zero points are also included at two positions within the window. Hence reconstructions of time-resolved signals from flat-top windowed spectra are subject to more uncertainty than other windows. The PSV 200 software offers the user the opportunity to apply a window function from a range including each of those mentioned here.

For transient signals, which arrive and fully die away within the sample length, such as the acoustic tone-bursts measured in the majority of this work, a specific windowing function is generally unnecessary. Unless stated otherwise, the FFTs and DFTs calculated from measurement of acoustic signals have not been multiplied by a window.

5.3.2.3 Universal File Format

Whilst the PSV 200 software provides a range of different data presentation options itself, the data can be saved in an export format, facilitating transfer to other software packages for further manipulation and presentation. The file format used is the Universal File Format (UFF, suffix: .unv). This format is readily accepted

throughout commercial and industrial modal analysis software packages and enables a range of variables and formats to be recorded and subsequently reconstructed.

The UFF consists of a series of datasets each separated by an identifying code. Within each dataset, a header details the precise nature of the data that follows. Various sections follow, each of which contains specific information about the stored data. For example, typical data recorded by the PSV 200 software from a Polytec OFV-302 / OFV-3000 LDV controller, will take the format given in Table 5.3.1:

Description	Code	Precision
Header	151	
Units	164	double
Geometry	15	single
Elements	82	integer
F Bands	55	single
Full Spectra	58	single

Table 5.3.1: Datasets used in PSV-UFF Converter

- **Header (151)** provides basic information as to the origin of the data, including the time and date of its creation and the software used to record the measurement.
- **Units (164)** simply states the nature of the quantities recorded within the dataset, typically SI units for the measurements recorded using the PSV 200 software.
- **Geometry (15)** describes the three dimensional Cartesian co-ordinates of each of the laser beam positions within the scan area. This is calculated from a measurement of the respective angular positions of both mirrors and a user inputted stand off distance. For each of the measurements recorded in this work, the position in the z -axis is taken to be 0 throughout the scanning range.

- **Elements (82)** describes the connections between the nodal positions within a scan. This is of significance when recording measurements from complex 3-dimensional surfaces, but since the laser beam is reflected from a flat plane throughout the measurements reported in this work, this dataset is not required.
- **Frequency Bands (55)** is used for certain types of measurement scans. The PSV 200 software offers a 'fast-scan' option where a predetermined frequency is identified and only the response of the LDV measurement at that frequency is recorded. This enables a faster scan to be completed since the duration of each measured signal at each point can be reduced to the minimum required to identify the response at the given frequency. This option was not used for the measurements recorded in this work, and hence this particular dataset is not required.
- **Full Spectra (58)** is where the measured data from each measurement position is recorded. The dataset begins with a sub-heading where logistical information is given such as the time and date of the measurement, as well as the identifying number of the measurement position. Information is provided as to the specific units used, typically Frequency (Hz) and Velocity (m/s) throughout the work described here, and the direction of the measured quantity with respect to the Cartesian co-ordinate reference frame.

In addition, a description of the format of the measured data is given, which throughout the work described here states that the data is complex, single precision with regular abscissa spacing. Since regular abscissa spacing is specified, the abscissa increment is not provided, if this were not the case, an additional string of values would be required.

The measured data contained in dataset (58) is arranged in six columns. The odd columns represent the real components of the data and the even represent the imaginary components with successive columns being paired together. For example the first row provides the first three data points of the spectrum as shown in Figure 5.3.3.

-1.04e-05	-2.49e-05	2.19E-05	1.01e-5	-1.87e-05	1.53e-06
...	...	...	...	...	...
Real	Imag.	Real	Imag.	Real	Imag.
					
Value #1		Value #2		Value #3	
Row 1 data =					
$-1.04 \times 10^{-5} - 2.49 \times 10^{-5} j$					
$2.19 \times 10^{-5} + 1.01 \times 10^{-5} j$					
$-1.87 \times 10^{-5} + 1.53 \times 10^{-6} j$					

Figure 5.3.3: Example of data storage within dataset 58

When saved as ASCII text, the Universal Files recorded in this work from the PSV 200 software ranged in size from approximately 1 to 60 MB, depending on the number of data points and FFT lines stored.

Mathematical computer code was written enabling processing of UFF data to take place using *Matlab*. The primary function of the code was to convert each of the respective FFTs stored in dataset 58 into time resolved signals. Before an Inverse Fourier Transform (IFT) was performed, the FFT was padded with zeros, representing the first (DC) value and the upper $\approx 20\%$ of the spectrum. This data is not stored within the Universal File to conserve the memory required to store the file. For example if 400 FFT lines are selected during the measurement, 1024 time samples are recorded by the PSV-200 software, 512 FFT lines are calculated, of which 400 are saved and 112 discarded. Since it is known that the FFT was recorded from a real signal, the conjugate of this data is then ‘unfolded’ to form the right hand side of the spectrum. An IFT will then recreate an approximation of the original measured signal, although, due to the fact that the higher frequency components of the FFT were discarded, it will never be a true replica.

For each converted signal, the number of the measurement position was extracted from the header of dataset 58. This was of significant importance in the cases where the LDV signal quality was not sufficient for a measurement to be made, resulting in the measurement position being omitted from the saved data. The Cartesian coordinates in x and y were extracted for each measurement position and stored in an array of 3 columns (point number, x -coordinate, y -coordinate) and as many rows as there were measurement positions. For each scan undertaken, approximately 2000 – 7000 data points were recorded, each containing between 100, 200 or 400 complex FFT values.

5.3.3 Generation of Colour Scaled Images

One of the most straightforward means of representing the spatial distribution of any given quantity is through the use of colour scaled images. As mentioned in Section 5.3.2, a specific value representative of the quantity under scrutiny is calculated for each measurement position and presented as a coloured pixel. When each pixel is positioned relative to the neighbouring measurements, the array of individual elements combines to form the image. The graduated colour scale is calibrated from the lowest to the highest pixel value contained within the image. On occasions where erroneous data points are contained within the measurement, the colour scale is adjusted to only include values within the specified range.

An example of an image representative of the rate of change of optical path length at an instant in time for each measurement position from a scan of a 180 kHz planar acoustic wavefront is given in Figure 5.3.4, the derivation of which is described in Section 5.3.4.4.

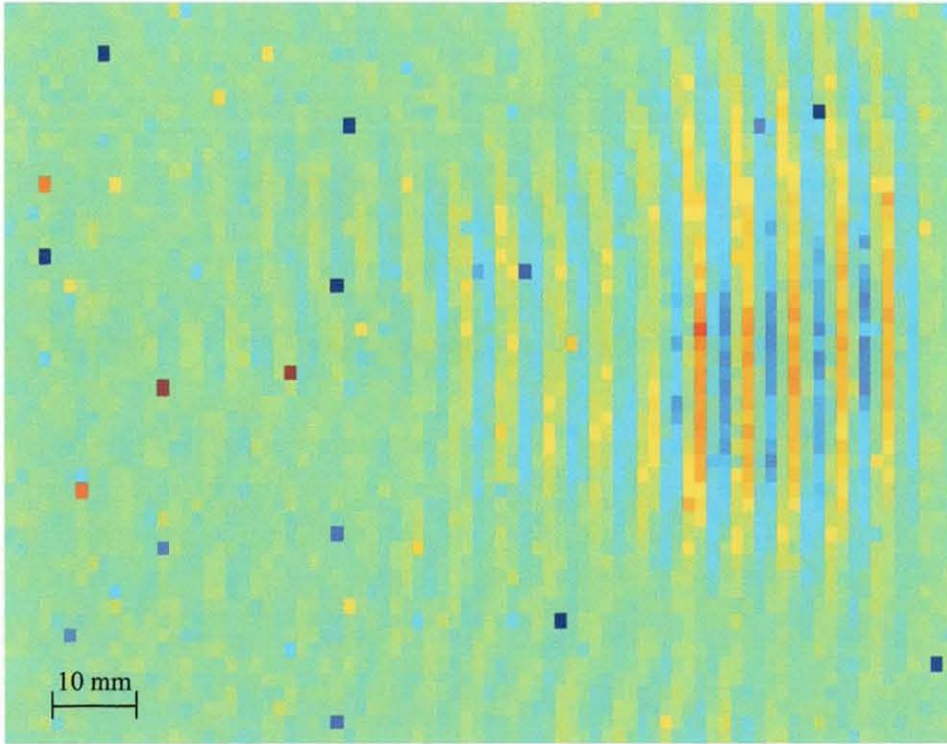


Figure 5.3.4: Image representing the time resolved change of optical path length for a 180 MHz planar acoustic tone-burst

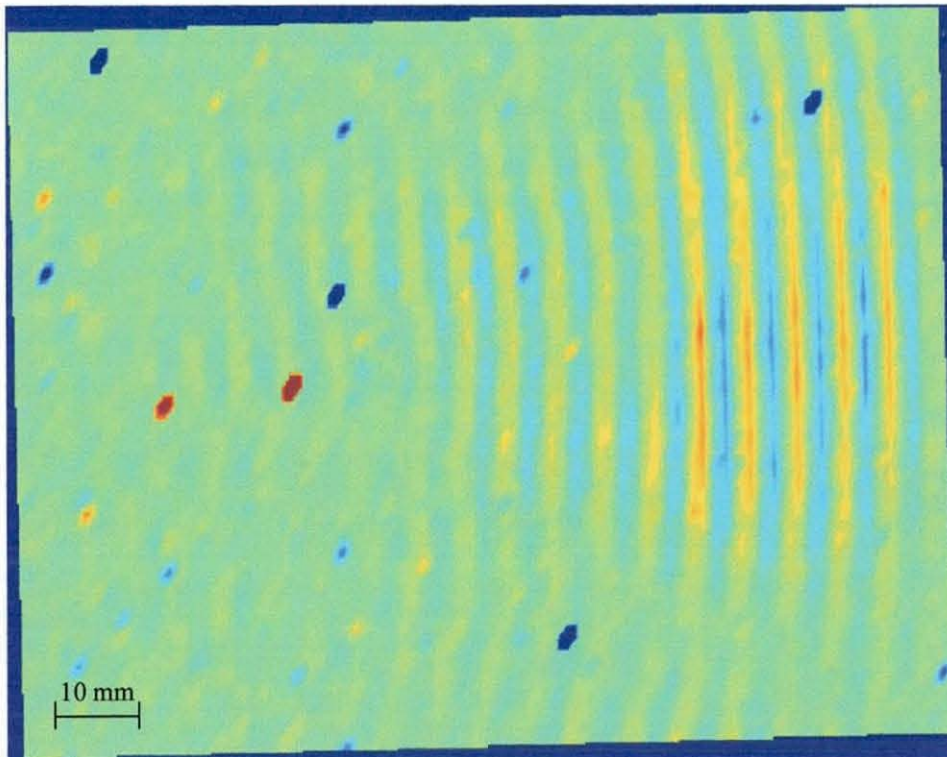


Figure 5.3.5: Interpolated image representing time resolved rate of change of optical path length

5.3.3.1 Image Interpolation

Whilst each pixel within the image given in Figure 5.3.4 is a faithful representation of the rate of change of optical path length at the point, the visual quality of the image is low due to the 'pixelated' appearance. In addition, each pixel is plotted on a rectangular grid of even spacing, where non-uniformed measurement positions cannot be catered for. Since the coordinates of the data positions are stored, it is possible to position each pixel within the image with reference to its measurement position. An interpolated image can then be created which passes through each of the discretely positioned pixels. Figure 5.3.5 shows an interpolated version of the data given in Figure 5.3.4, and the visual quality of the image can be seen to have improved. This image measures 501×302 pixels as opposed to 81×51 in the original.

One point to note from Figure 5.3.5 is that the entire image appears to have been rotated counter-clockwise by approximately 2° . This demonstrates that the scanning mirrors, which were fixed in their respective orientations, were not accurately aligned with the camera within the scanning head. This was the case throughout the measurements recorded in this work.

5.3.4 Formation of Images from Rate of Change of Optical Path Length Data

In order to provide an example of the range of information contained within each LDV scan result, an experimental scan was completed of the field generated by a 1 MHz focused acoustic source, shown in section in Figure 5.3.6. The transducer is defined by the outer radius, r_{cas} , the focal length, d_{foc} and the lip thickness, d_{lip} . An image recorded by the digital camera in the scanning head of the experimental arrangement is given in Figure 5.3.7. At the extreme left of the image is the acoustic source in side profile, and along the lower edge is a ruler, graduated in centimetres.

An isometric scanning grid was defined, consisting of 7543 discrete laser target points – 71 columns each of 53 points and 70 columns each of 54 points. An average of 15 successively triggered time-swept signals of 200 μ s duration were recorded at a sampling frequency of 5.12 MHz, and 400 FFT lines stored in the Universal File.

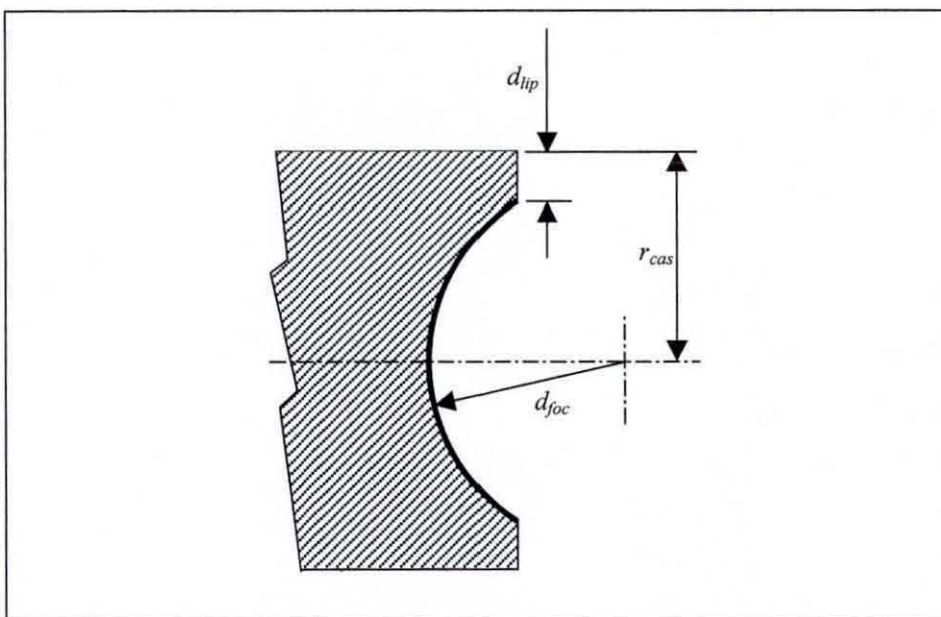


Figure 5.3.6: Cross-section of focused acoustic transducer

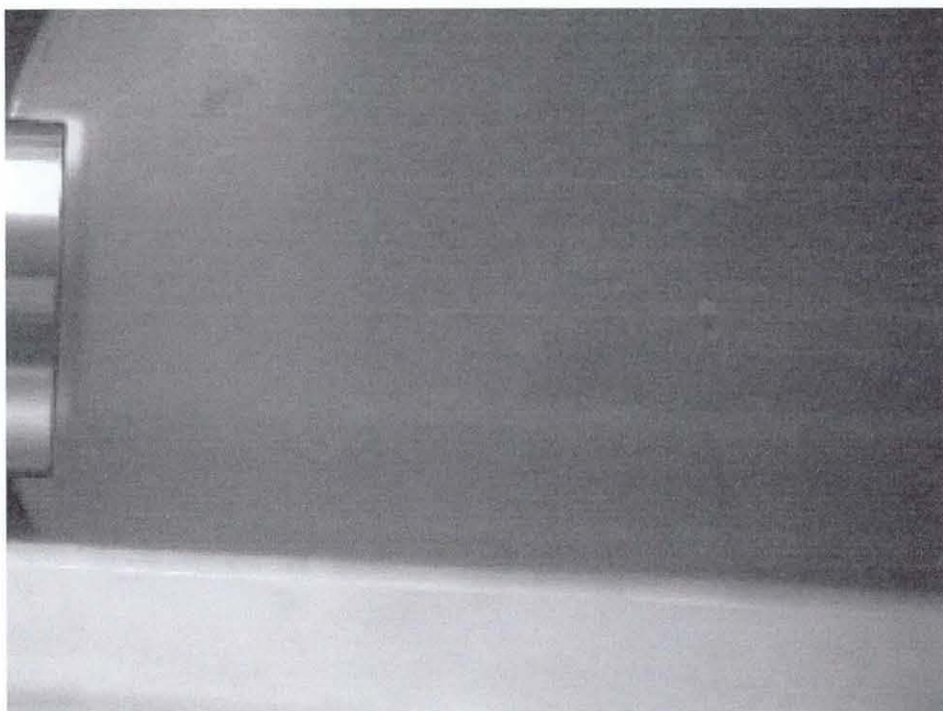


Figure 5.3.7: Experimental Arrangement of Focused Transducer

5.3.4.1 Magnitude and Power Images

A measure of the magnitude or power of a certain frequency within a signal can be established from the respective FFT component of the magnitude or power spectrum at the frequency concerned. Each complex FFT extracted from the Universal File was converted into the power spectrum and the component at the acoustic frequency was taken to represent the power of the signal. The magnitude was calculated as the square root of the calculated power value. As was explained in Section 5.3.2.2, the deployment of a flat-top window would improve the accuracy of the fundamental frequency component in the power spectrum.

Two approaches can be taken when calculating these values. Firstly, the power spectrum can be derived from the FFT of the complete signal, as is the case for the results presented by the PSV-200 software. Given the wide range of power values throughout the scan, it is often useful to present the image on a logarithmic scale. For the worked example the power distribution of the rate of change of optical path length is plotted on a linear scale in Figure 5.3.8, and on a logarithmic scale in Figure 5.3.9. This data is referred to as 'FFT power distribution'

However, when making measurements of acoustic tone-bursts, since the signal duration was required to be sufficient to record the entire tone-burst both immediately once it had left the source and after it had traversed the field, the actual signal occupies only a small percentage of the entire signal. For this reason a Discrete Fourier Transform (DFT) of a finite number of cycles within the tone-burst was calculated for each signal. This data is referred to as 'DFT power distribution' and is given for the worked example on a linear scale in Figure 5.3.10 and on a logarithmic scale in Figure 5.3.11.

From both the DFT and FFT power distribution images, it can be seen that the logarithmic scaled images are more effective in representing the distribution of power throughout the scanning area. Consequently, all power images are plotted on a logarithmic scale. For convenience, the data values within the image have been normalised between 0 and 1.

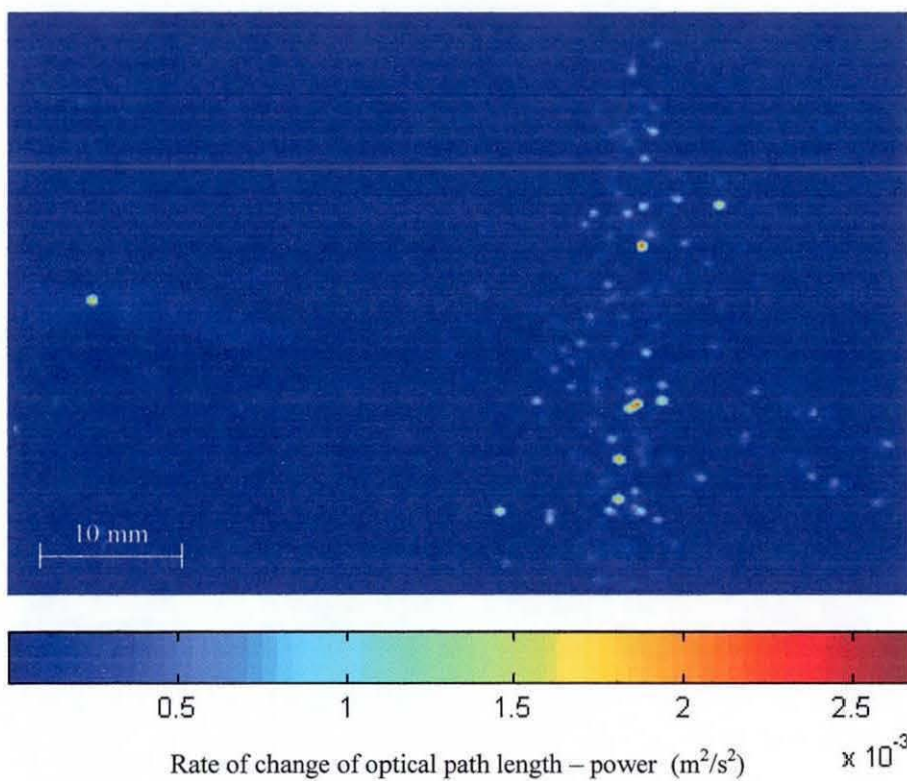


Figure 5.3.8: FFT power distribution of the rate of change of optical path length on a linear colour scale

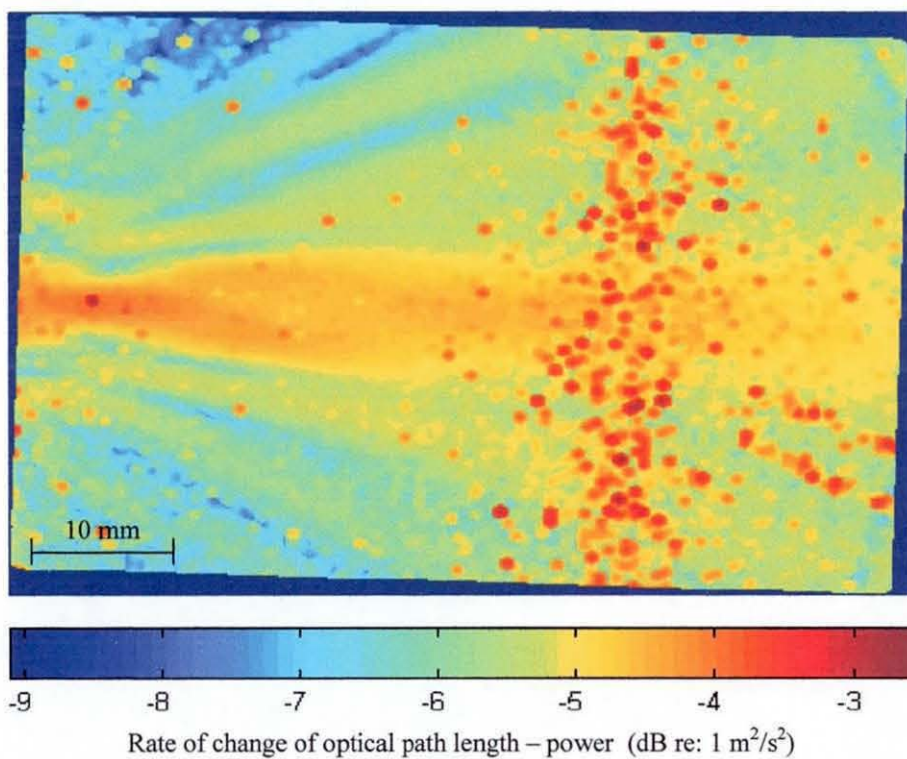


Figure 5.3.9: FFT power distribution of the rate of change of optical path length on a logarithmic colour scale

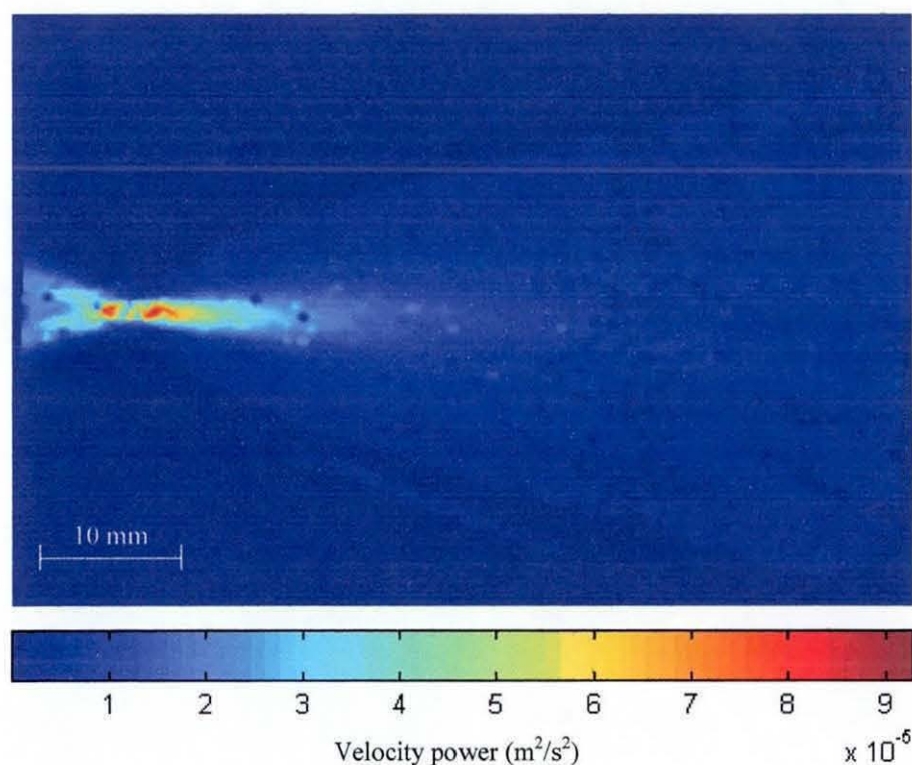


Figure 5.3.10: DFT power distribution of the rate of change of optical path length on a linear colour scale

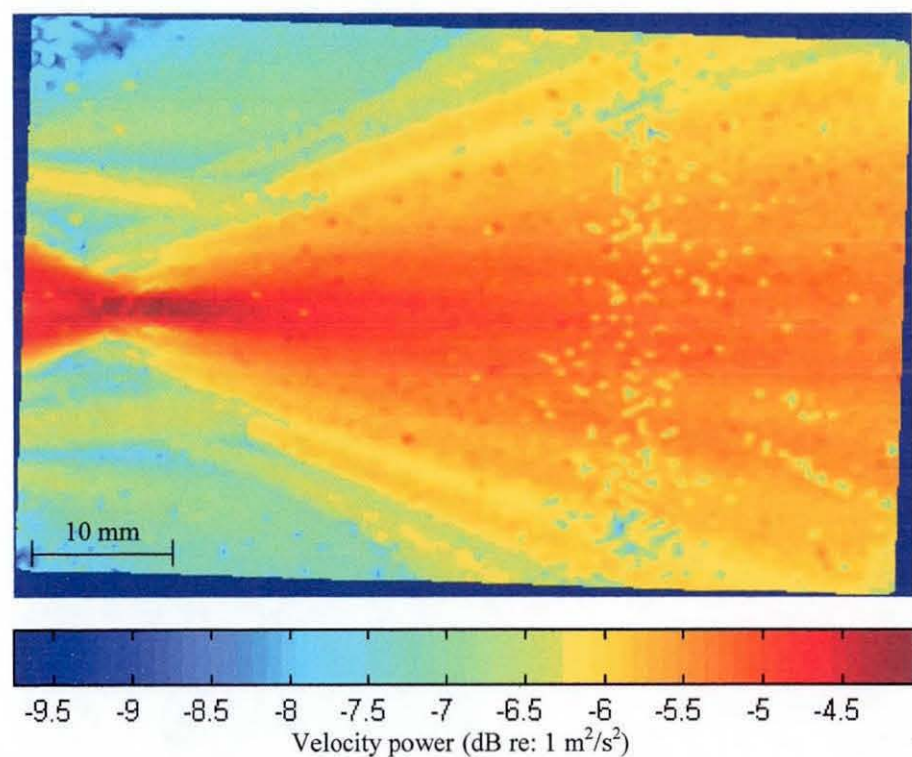


Figure 5.3.11: DFT power distribution of the rate of change of optical path length on a logarithmic colour scale

In this particular worked example, the reflecting target contained a scratch running from the top to the bottom of the scan approximately one quarter of the image width from the right hand side. When assessing the differences between the FFT and DFT images, it is interesting to observe the influence this scratch has on the LDV measurements. In general, the quality and/or quantity of the light reflected from this region is not as high as that from the remainder of the target, resulting in a noisier measured LDV signal. This is highlighted in the FFT images, but is reduced in the DFT plots. The FFT suggests that aside from the focal region, the distribution of the field takes the form of a thin central section in which the majority of the power is contained, alongside several discrete side lobes. In contrast the DFT power distribution image has a more even distribution throughout the diverging region past the focus. A fewer number of side lobes are present although each is not separated from the next as clearly as in the FFT image. This suggests that the DFT power distribution image is more representative of the acoustic tone-burst than the FFT image, which is influenced by signal artefacts outside of the tone-burst.

Another feature of the DFT image is the observed power emanating from the aluminium 'lip' at the perimeter of the concave surface of the acoustic source, as depicted in Figure 5.3.6. Although the source is designed to maximise the acoustic energy generated by the concave surface, the lip will also oscillate and consequently produce an acoustic wave. The lip of the transducer used in the worked example is approximately 2 mm wide and according to acoustic theory will act in a similar fashion to a plane piston source, with the flat surface generating a plane wave and the edges generating radiating waves.

This region can be clearly identified between the face of the acoustic source and the principal acoustic field both for the top and bottom perimeter. Clearly this effect will be present around the entire perimeter of the source, but is only evident in an LDV scan where the interaction length between the laser beam and the acoustic wave is sufficiently long for the integral of the refractive index change across the length to be detected by the LDV system.

The presence of these and other spurious or reflected acoustic wave components is likely to contribute towards the side lobes observed in the power images. However, given the fact that these acoustic waves are likely to arrive some time later than the principal wave, it follows that their presence will have greater influence on the FFT than the DFT. This is confirmed by the reduction of the presence of clearly defined side lobes observed in the DFT images.

5.3.4.2 Phase Distribution Images

The images described in 5.3.4.1 are effective in detailing the spatial distribution of the amplitude of the measured rate of change of optical path length magnitude or power. It is, however, important to consider the phase of this amplitude in order to gain a complete understanding of the nature of the acoustic field distribution.

The absolute phase of each measurement can be calculated directly from the saved complex FFT spectrum in the Universal File by taking the arctangent of the imaginary component divided by the real component. For the worked example, this approach yields the image shown in Figure 5.3.12. The image is plotted on a red-green colour gradient to improve visual resolution. This type of image is referred to as a 'FFT phase distribution'.

Another approach, designed to reduce the influence of spurious signal components on the phase data was to compare the respective position in time of a similar point within the tone-burst for each measurement. For the worked example, the reference position was taken to be the first peak of the tone-burst signal. This time duration was converted into a phase using the known time period of the signal. A plot of this comparative phase is given in Figure 5.3.13. This data is referred to as 'DFT phase distribution', since despite not being derived from a DFT, it is taken only from the tone-burst section, and is comparable with the DFT power data.

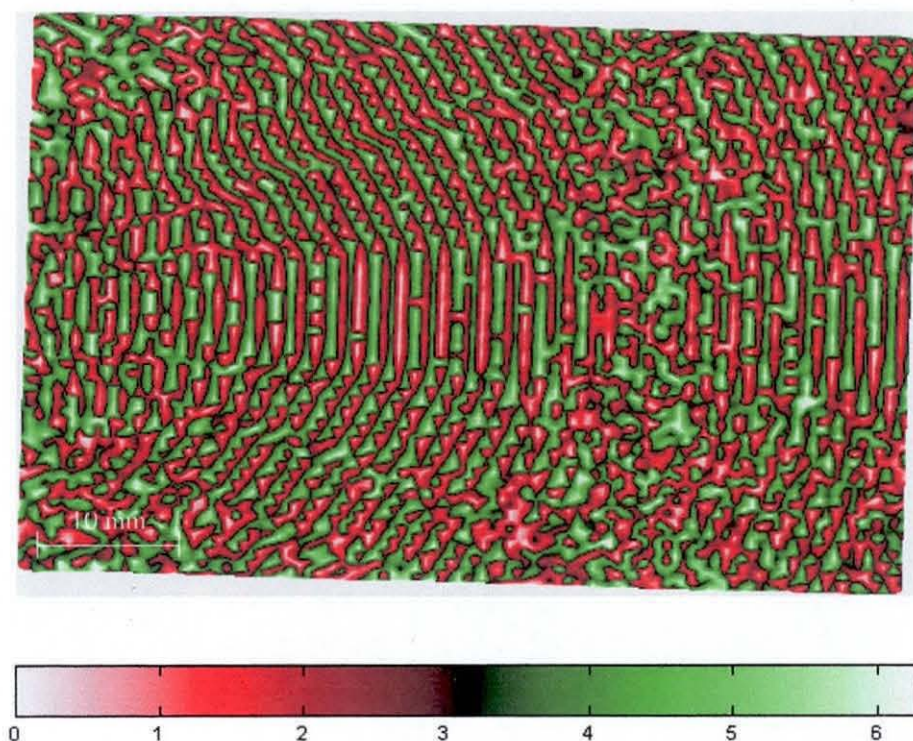


Figure 5.3.12: FFT phase distribution of rate of change of optical path length

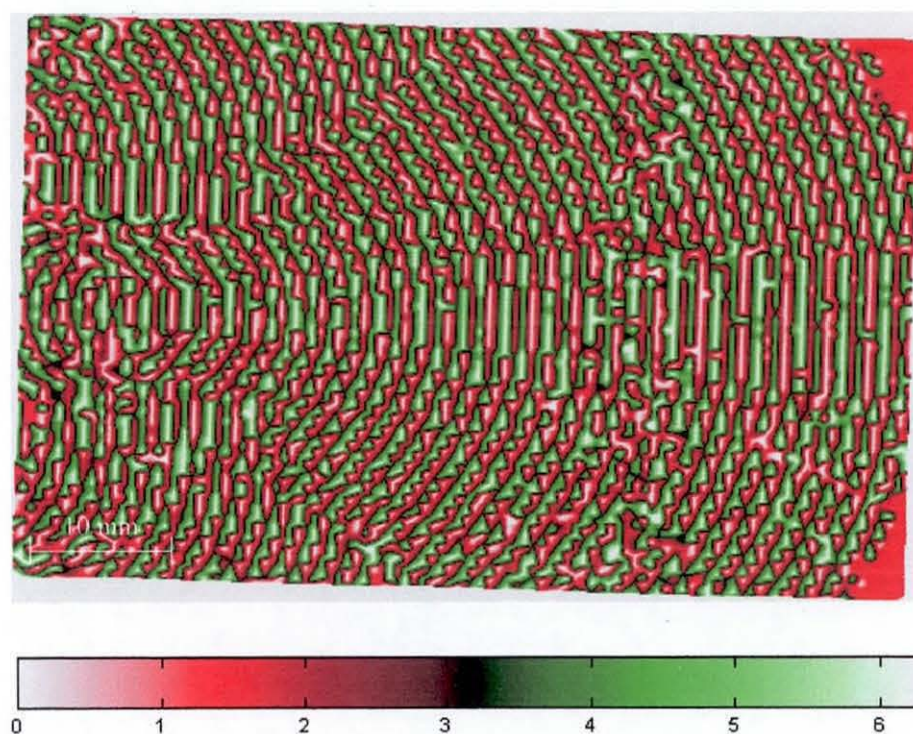


Figure 5.3.13: DFT Phase of the rate of change of optical path length

Again, the noise introduced by the scratched reflective target is observed to have been reduced in the DFT phase image from the FFT equivalent, and in general provides a more clearly defined image, particularly in the region closest to the front face of the acoustic source. However, the most significant observation to be made is the effect of the spatial sampling resolution. Digital sampling theory suggests that 10 sampling points per wavelength are required at the maximum resolvable frequency to accurately record the shape of a signal. As an absolute minimum, Nyquist's theory states that at least 2 sampling points per wavelength are required [147].

Given that the LDV interrogation grid contained 81 discrete columns (in the principal direction of the acoustic beam), by Nyquist's theory, a maximum of 40 complete cycles can be accurately recorded. From the image, 42 complete cycles can be counted running horizontally across the image, meaning that the replication of the spatial distribution of phase will be subject to errors. The images shown have each been interpolated, but the quality of the phase reconstruction remains low. It can be concluded that in addition to the restrictions imposed by the LDV and its associated electronics in the time domain, the maximum resolvable frequency for a spatially distributed scanning measurement is governed by the minimum resolvable separation of the laser beam spot positions, in accordance with Nyquist's theory.

The precision resolution of the scanning mirrors is quoted in the Polytec literature as 0.002° . Therefore a simple trigonometric calculation can be undertaken to calculate the minimum resolvable acoustic wavelength for a given stand-off distance. At a stand off distance of 1 m, the minimum resolvable acoustic wavelength is ≈ 0.7 mm when the laser beam is at normal incidence. Clearly, the scanning range would need to be reduced to maintain a reasonable scan time and file size for such a fine resolution.

5.3.4.3 Combined Magnitude and Phase Images

From the magnitude and phase quantities derived in Sections 5.3.4.1 and 5.3.4.2, it follows that an image can be created representative of a continuous wave acoustic wave passing through the field at a nominal time. Such an image would demonstrate the relationship between the magnitude and phase throughout the scan region. By creating a sequence of these images, the PSV-200 software generates cyclic animations that mimic the motion of a continuous wave acoustic wave through the field.

Two combined magnitude and phase images are presented, calculated from the FFT data in Figure 5.3.14 and from the DFT data in Figure 5.3.15. In both images, the value at each discrete point within the image has been calculated by multiplying the respective magnitude value with the sine of the phase value.

The improved quality of the respective DFT phase and magnitude images enables a dramatic difference to be observed between the DFT combined magnitude and phase image and that generated from the FFT data. In the DFT image, the spatial distribution of phase and amplitude is clearly evident, whereas in the FFT image, the noise caused by the scratch in the reflective target dominates the colour scaling.

The colour scaling has been normalised between + 1 and – 1 for both the FFT and DFT data to enable a direct comparison between the images to be made.

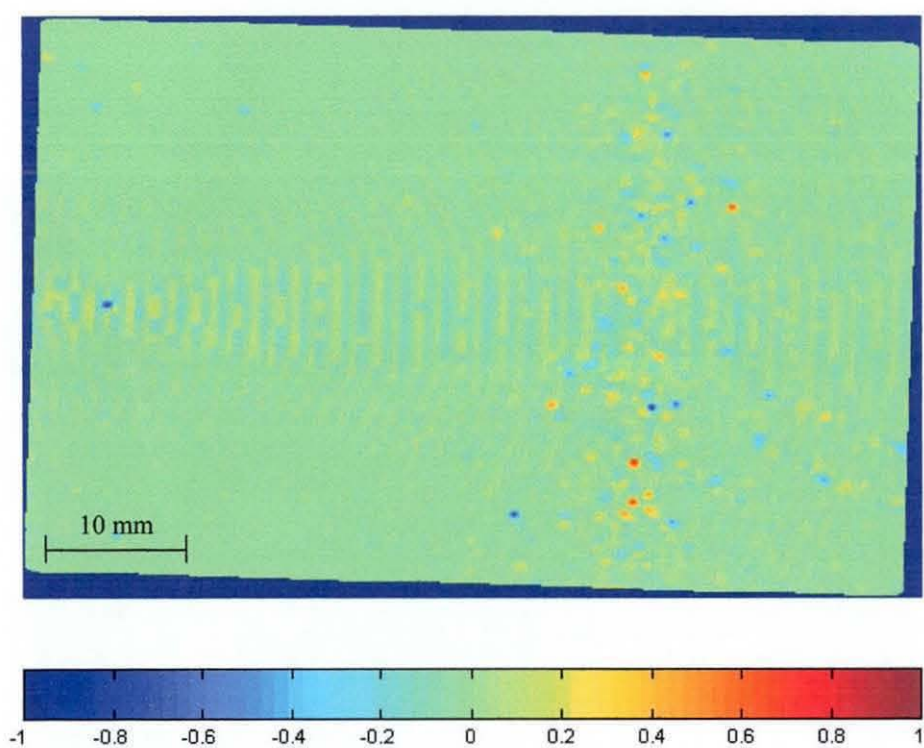


Figure 5.3.14: Combined magnitude and phase image from FFT data

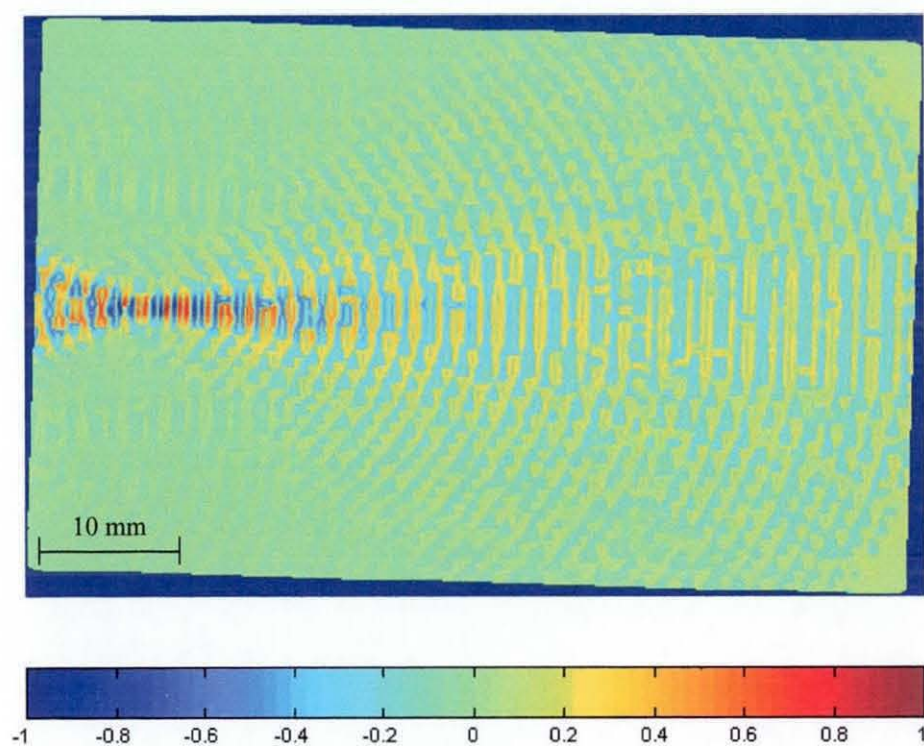


Figure 5.3.15: Combined magnitude and phase image from DFT data

5.3.4.4 Time Resolved Images

From the time resolved signal calculated from the Universal File, a 3-dimensional array of data representing the rate of change of optical path length in x , y , and time, t , can be created. By extracting a plane of data in x and y at a given time, t_n , a depiction of the position and amplitude of the acoustic tone-burst can be obtained at that instant. For the worked example, four images representing the acoustic tone-burst at different instants in time are presented.

Figure 5.3.16 (a) depicts an instant in time, $t_1 = 1.5 \mu\text{s}$, after the beginning of the input signal to the acoustic source (from which the measurement is triggered). At this time, the principal signal has not encroached into the scanning area, although upon very close inspection, the first 3 or 4 cycles of the secondary acoustic tone-burst generated by the perimeter lip of the acoustic source as described in Section 5.3.4.1 can be observed. Since this originates from a position in space ahead of the principal acoustic field, it travels ahead of the principal tone-burst. However, the amplitude of this signal is sufficiently small in comparison to the principal signal (by whose amplitude the colour scaling is calibrated) for identification to be difficult.

The subsequent images shown in Figure 5.3.16 (b), (c) and (d) depict the acoustic field at times $t_2 = 50 \mu\text{s}$, $t_3 = 130 \mu\text{s}$, $t_4 = 200 \mu\text{s}$, respectively. In each image, the 5-cycle acoustic tone-burst can be clearly identified by its shape, amplitude (given by the colour) and position in space. Each time instant was chosen arbitrarily to demonstrate the various features of this type of image.

The previously mentioned scratch on the reflecting pellicle causes a 'noisy' vertical region, although this does not hinder identification of the acoustic tone-burst in the images shown. The principal beam can be shown to reduce in amplitude with distance away from the focus, through which it passes in Figure 5.3.16 (b), and the shape of the field, represented in cross-section in the images is consistent with that expected from a focused field. The secondary acoustic field generated by the lip of the acoustic source can also be seen to traverse the scan region, with each half converging such that in Figure 5.3.16 (d) its appearance merges into a single plane wave.

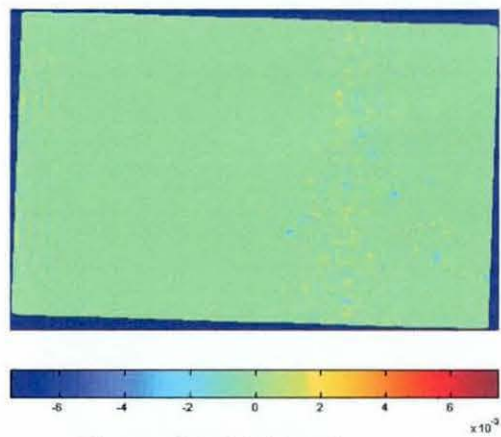


Figure 5.3.16 (a): Time = t_1

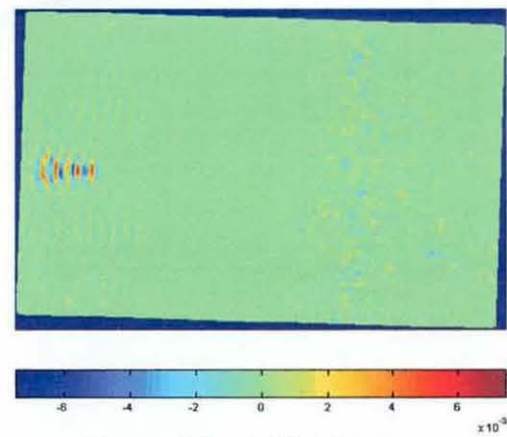


Figure 5.3.16 (b): Time = t_2

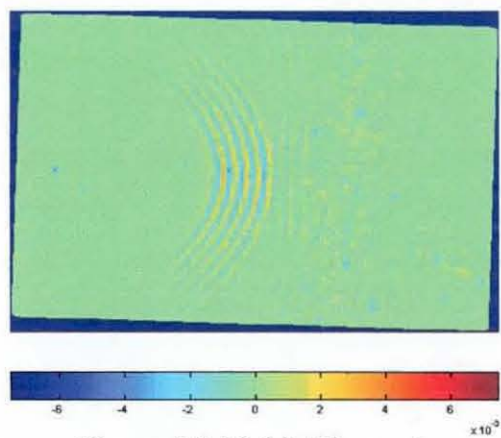


Figure 5.3.16 (c): Time = t_3

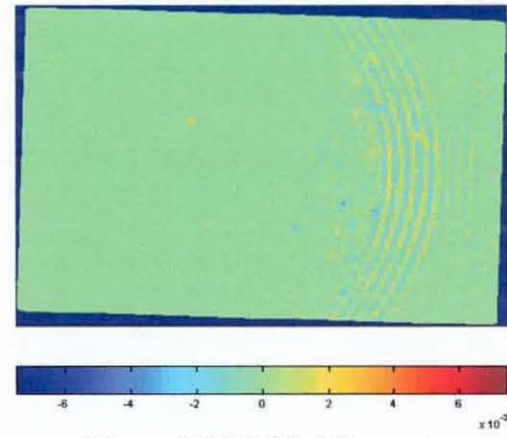


Figure 5.3.16 (d): Time = t_4

Figure 5.3.16: Rate of change of optical path length for acoustic tone-burst

Given the ability of post processed scanning LDV measurements to enable reconstructions of images at instants in time to be created, it follows that a series of sequential images can be created, which form the individual frames of an animated picture. Consequently, for each LDV scan, an animation can be produced, recreating the passage of an acoustic tone-burst through the scanning region. Without interpolation in the time domain, the maximum number of frames constituting the animation is equal to the number of time samples of the recorded signal.

Animations are especially useful when examining low amplitude signal features within the image, such as the field emitted from the lip of the acoustic source, since it is recognised that the human eye is more sensitive to a moving feature than the same feature depicted within a static image.

A study of the features of the time resolved images created in this way can assist in the understanding of some of the characteristics of the rate of change of optical path length measured at certain positions within the field. In the worked example, three positions, A, B and C are identified within the field as depicted in Figure 5.3.17. Each position was chosen to enable a variety of attributes within the measured signal to be identified. It is anticipated that in addition to the principal tone-burst, each signal will contain additional signal components. Any spurious components are likely to be caused by reflected signals or signals generated by areas of the acoustic source other than the focused face, which oscillate with reduced amplitude. Additionally, depending on the Q of the acoustic transducer, the emitting face may continue to oscillate for a number of cycles once the exciting electrical tone-burst is complete.

The time-resolved signal recorded at position 'A', in close proximity to the focus of the acoustic field, is given in Figure 5.3.18. Here, the peak magnitude is approximately 9 mm/s and the principal 5-cycle acoustic tone-burst can be clearly identified. The remainder of the signal is observed to be free from artefacts of a comparable magnitude, although some very much smaller amplitude signals can be identified, delayed in time from the principal tone-burst. Suggestions as to the origins of these signals are included in Figure 5.3.18.

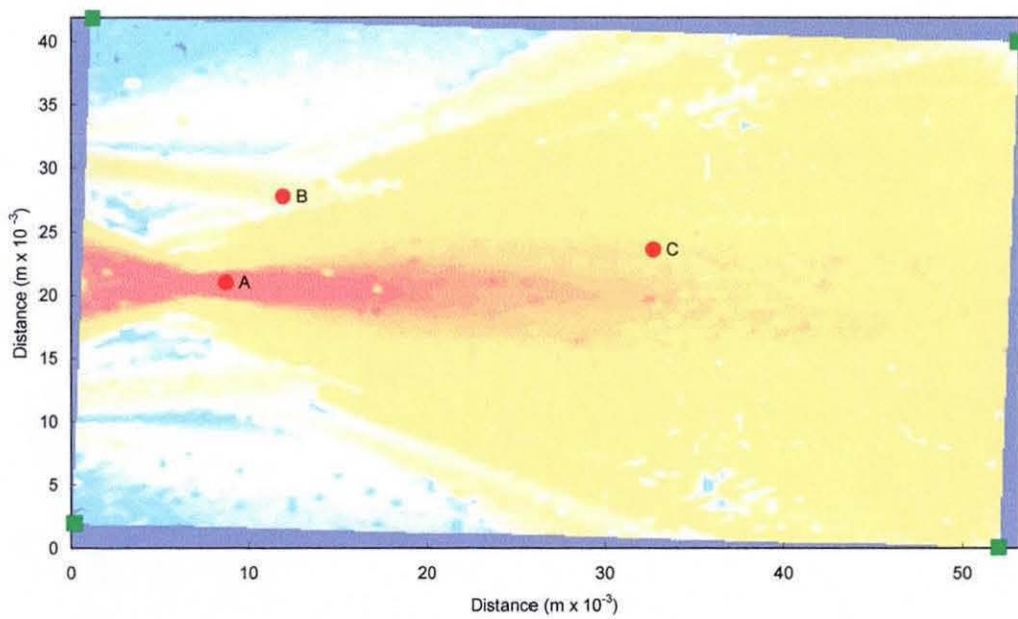


Figure 5.3.17: Three measurements positions identified within the acoustic field of the worked example

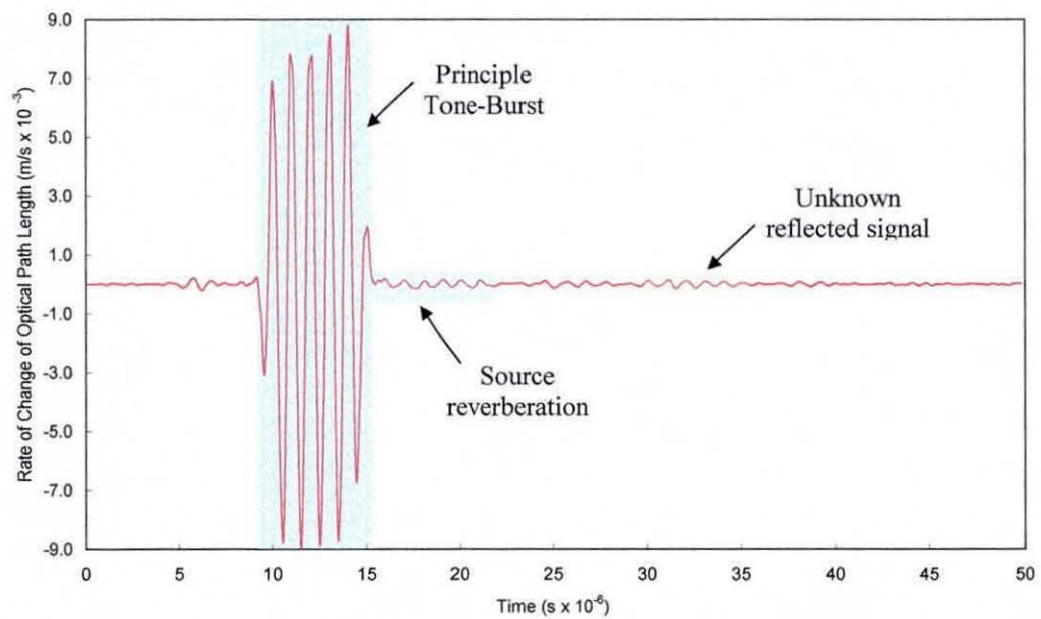


Figure 5.3.18: Signal recorded at position 'A'

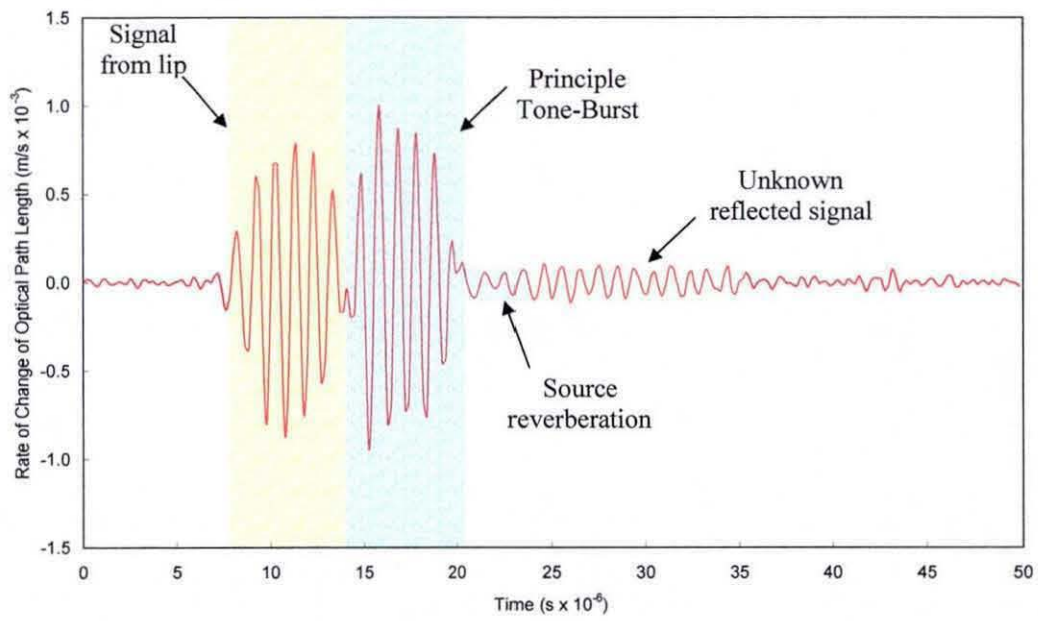


Figure 5.3.19: Signal recorded at position 'B'

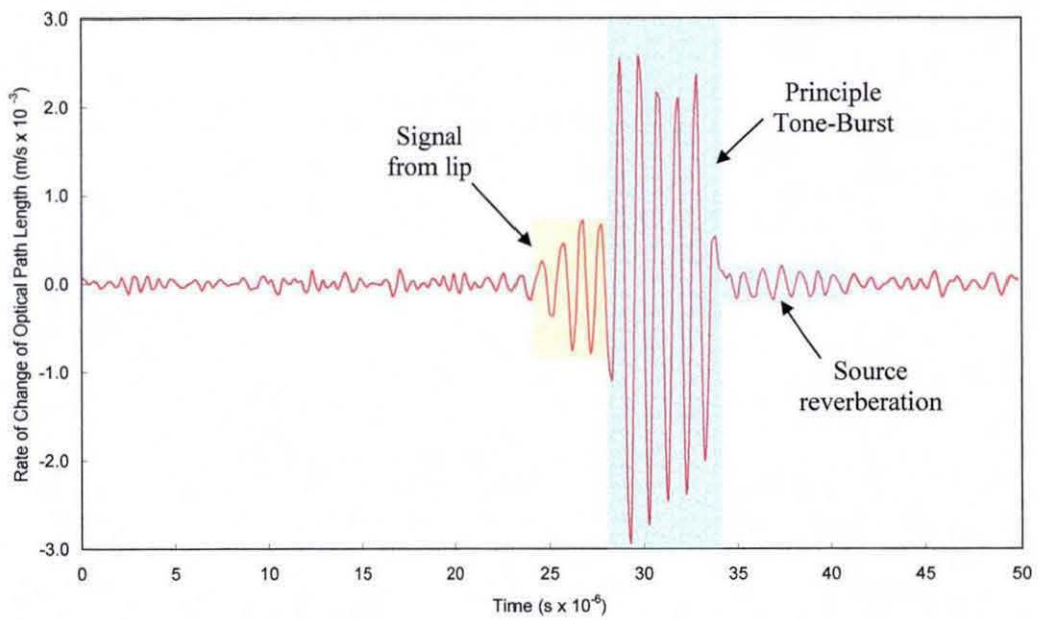


Figure 5.3.20: Signal recorded at position 'C'

The time resolved images of spatial distribution, such as the one depicted in Figure 5.3.16 (b), confirm the observed signal to indeed originate from the principal tone-burst, since the region around the focus is seen not to be affected by other components of the signal.

Position 'B' was chosen at a point that coincides with the principal acoustic tone-burst and the secondary signal generated from the lip of the source, as can be observed in Figure 5.3.17. The measured time-resolved signal is given in Figure 5.3.19. Without the aid of a time resolved image, the presence of two similar amplitude tone-bursts within the signal is likely to cause confusion and identifying the principal tone-burst would be very difficult.

By referring to the time resolved image, it can be observed that the signal originating from the lip of the acoustic source precedes the principal tone-burst signal in this region of the field. Consequently, the two major signal components can be positively identified. Labels are included in Figure 5.3.19.

For position 'C', the measured time-resolved signal is given in Figure 5.3.20. Here the major feature of the signal is a series of approximately 9 cycles, with the first 4 of significantly reduced amplitude compared with the following 5 cycles. Identification of the principal tone-burst within this signal is therefore subject to uncertainty. However, by reference to the time resolved images, it can be seen that the signal originating from the lip of the source again precedes the principal signal in this region of the field. Hence the likely origins of the constituent sections of the signal can be identified. These are included in Figure 5.3.20.

5.4 CLOSURE

The work described in this chapter has successfully developed the theory of acousto-optic interaction along a single line section presented in Chapter 4 to include scans in 2-dimensions. A comprehensive model of the mathematics required to fully describe this interaction has been developed. This enables the rate of change of optical path length to be calculated for a line interrogation in an arbitrary position defined by two angles θ and ϕ . The pressure field is defined in terms of the amplitude and phase of the acoustic pressure, each as functions of x , y , z and t .

Analysis of the PSV-200 software into which the scanning LDV system recorded data has been completed. This has identified a number of assumptions made in the design of the software that limit its successful application to those circumstances where the refractive index of the media through which the laser beam travels can be assumed to remain constant. Since this was not the case in the experimentation described here, the raw data was required to be extracted and processed independently. This has enabled the development of precise methods by which different attributes of the measured data can be analysed.

A range of images representing different quantities of the measured data was proposed. Each enabled the visualisation of particular field parameters. Interpolation was successfully introduced to improve the visual quality of the images. The first of these images was formed from the fundamental components of the magnitude or power spectra and was given the name magnitude or phase distribution respectively. These were demonstrated to be effective in enabling the field distribution to be visualised, including regions outside of the principal tone-burst envelope. Normalised logarithmic scales are used to present the data.

The second images proposed were formed from the phase angles calculated between the real and imaginary components of the magnitude spectrum at each position and were given the name phase distribution images. These were also demonstrated to be effective in registering the distribution of phase throughout the field.

Two methods of data analysis were proposed for each of the image types described, fast Fourier transform (FFT) and discrete Fourier transform (DFT). These differed in that the FFT represented the frequency content of the entire time history including any rise and fall transients and reflected signal components, whereas the DFT was calculated from a finite number of complete cycles within the principal tone-burst.

The FFT images were demonstrated to offer the potential to visualise the influence of all components of the acoustic signal in addition the principal beam. This was of particular interest in the example presented since it enabled the presence of an additional tone-burst generated by the lip of the transducer to be identified and monitored. The DFT images were found to enable visualisation of just the principal component of the tone-burst. These images were shown to be less influenced by source of noise, such as that caused by the scratch on the surface of the reflective target.

Images representing the instantaneous rate of change of optical path length were proposed as a means of monitoring the progression of an acoustic tone-burst through a volume. These proved to be highly effective in this aim, such that at all time instants, the position of the principal 5 cycle tone-burst could be identified in space. This also enabled the positions of any spurious acoustic signals to be related to that of the principal tone-burst.

A combination of these images enabled understanding of temporally resolved signals from within the field to be advanced. This was of particular interest in the example presented, since the presence of spurious signals and reflected components was highly ambiguous at certain positions within the field. The images presented enabled the correct identification of each signal component.

Chapter 6

Experimental Results

6.1 INTRODUCTION

This chapter details an in depth investigation into measurements made from spatially distributed acoustic fields. Two fields are analysed, each consisting of a tone-burst signal. The first is a 15 cycle tone-burst from the Panametrics V3438 focused transducer at a frequency of 1 MHz, and the second a 5 cycle tone-burst from the Met-Optic plane piston transducer at a frequency of 180 kHz.

The chapter begins with the development of a mathematical simulation by which the interrogation of each field with a scanning LDV beam can be modelled. Twelve independent parameters are identified and used to define the nature of the simulated acoustic field. Results of the simulation are presented in the same manner as that described for experimentally recorded data described in Section 5.3.4.

The results of measurement scans recorded by the scanning LDV system from fields generated by the respective transducers are presented. The images generated from this experimental data are then compared with those from the simulation.

6.2 MATHEMATICAL SIMULATION OF LDV INTERROGATION OF AN ACOUSTIC FIELD

A mathematical model was developed to represent the theoretical interaction of the beam from an LDV with an acoustic field in two-dimensions (x and y). The model was based on the theoretical description of opto-acoustic interaction given in Section 5.2.2, and enabled a direct comparison with data recorded by the LDV to be made. The basis of the simulation involved intersecting a line representing the laser beam with a volume representing the acoustic field. A finite number of points were defined in x , y and z , at equal spacing along the interactive region of the line. The refractive index variation at each point was defined in terms of the pressure variation with respect to time, t . A simple trapezoidal method was then used to approximate the integral of refractive index with distance along the line, and this was differentiated to provide a signal equivalent of the rate of change of optical path length. This was repeated for each discrete laser beam position and images representing the projection of each rate of change of optical path length measurement onto the target plane were created for each time increment.

The model was based on a range of parameters used to define the nature of the field and the position and direction of the LDV. The basic 12 parameters were as follows, although additional functionality was added to describe the shape of a focused field:

- a) Acoustic frequency, f
- b) Pressure amplitude at a point as a function of position, $A_{(x,y,z)}$
- c) Pressure phase at a point as a function of position, $\Phi_{(x,y,z)}$
- d) Radius of acoustic source, r
- e) Number of cycles, N
- f) Distance of laser source from target, d
- g) Distance of laser source from acoustic axis, d_a
- h) Perpendicular distance of source from laser beam, d_s
- i) Range of scan in x , X
- j) Range of scan in y , Y
- k) Spacing of laser beam position in x , δx
- l) Spacing of laser beam position in y , δy

The velocity of sound in water, c , was calculated using the equation derived by Coppens [4] at a temperature of 16° C and salinity of 0 parts per thousand. At an average depth of 0.2 m, the velocity was calculated to be approximately 1,469 m/s.

The major shortcoming of such a mathematical simulation is the process of integrating the refractive index with distance to obtain optical path length. In the experimental case, the laser beam, by its very nature, travels over the continuous analogue optical path length, whereas in the theoretical simulation the distance between the laser source and the target position is divided into a number of discrete sections, η , over which the integral is approximated. In the case of the focused acoustic field in particular, η , was of great significance since both the phase, amplitude and the length of the interactive region varied with angular position. Here the choice of η was based on compromise between two factors. The value of η had to be sufficiently small to enable the simulation to be calculated efficiently in terms of time and computing memory yet large enough to provide an acceptable number of discrete points within the interactive region. This is especially important near to the focus where the radius of the acoustic field becomes very small. Values chosen for η were 100 and 1000 for (a) and (b) respectively.

6.2.1 Field from a Focused Acoustic Source

The generic description of the interaction of the beam from an LDV with an acoustic field of unknown shape presented in Equation (5.2.9) defines amplitude and phase as a function of distance along the laser beam line, $A(s)$ and $\Phi(s)$ respectively.

An assumption is made that a focused acoustic field either side of its focus behaves in a similar manner to a spherical wave approaching and originating from a point source, where the amplitude decays inversely proportionally to the radial distance [38]. In reality this is not the absolute case since the focus occupies a finite volume, but it is small enough to approximate a point for the purposes of the work discussed here. Therefore the pressure amplitude, A , at a point (x,y,z) is defined by the amplitude at the focus, A_0 , and the physical distance of the point from the focus, d_f .

$$A_{(x,y,z)} = \frac{A_0}{|d_{f(x,y,z)}|} \quad (6.2.1)$$

The distance, d_f , describes the distance of the point (x,y,z) from the focus, (x_f,y_f,z_f) . It is expressed for two regions within the field

$$\begin{aligned} \text{for } x > x_f; \quad d_f &= -\sqrt{(x_f - x)^2 + (y_f - y)^2 + (z_f - z)^2} \\ \text{for } x < x_f; \quad d_f &= \sqrt{(x_f - x)^2 + (y_f - y)^2 + (z_f - z)^2} \end{aligned} \quad (6.2.2)$$

The phase, Φ , at a point (x,y,z) is defined by the distance of the point from the focus, d_f , the focal length of the source, F , the speed of sound in water, c , and the acoustic frequency, f .

$$\Phi = \frac{-2\pi f(d_f + F)}{c} \quad (6.2.3)$$

The parameters required to simulate the measurement of a field generated by a 1 MHz focused source are stated in Table 6.2.1. For simplicity, the amplitude at the focus was taken to be 1 Pa.

The simulated field interrogation was calculated for 270 discrete 0.2 μ s time intervals, from 0 to 56 μ s. The resultant time histories for each point were used to generate images, by the method described in Section 5.3.4.

An image representing the 'power' of the 1 MHz frequency component is given in Figure 6.2.1. The absence of reflections and other erroneous acoustic signals enables the frequency spectra to remain free from misleading artefacts, and the power distribution to be calculated directly from the FFT of the signal without the need for a DFT of just the acoustic signal to be calculated. Similarly, the simulated phase distribution within the field is given in Figure 6.2.2, calculated from the FFT of each respective measurement signal.

Parameter	Abbreviation	Value	Units
Radius	r	12.7×10^{-3}	m
Focal Length	F	25.4×10^{-3}	m
Number of Cycles	N	15	
Distance	d	0.9×10^{-3}	m
Distance	d_a	0.8×10^{-3}	m
Distance	d_s	-9.4×10^{-3}	m
Range in x	X	-9.3 to $+63.3 \times 10^{-3}$	m
Range in y	Y	-15 to $+15 \times 10^{-3}$	m
Acoustic Frequency	f	1×10^6	Hz
Amplitude	$A_{(x,y,z)}$	$= \frac{1}{ d_f }$	Pa
Phase	$\Phi_{(x,y,z)}$	$= \frac{-2\pi f(d_f + F)}{c}$	

Table 6.2.1: Controlling parameters for Simulation of Focused Acoustic field

Three images representing the 15-cycle acoustic tone-burst at discrete instants in time are given in Figure 6.2.3 (a), (b) and (c).

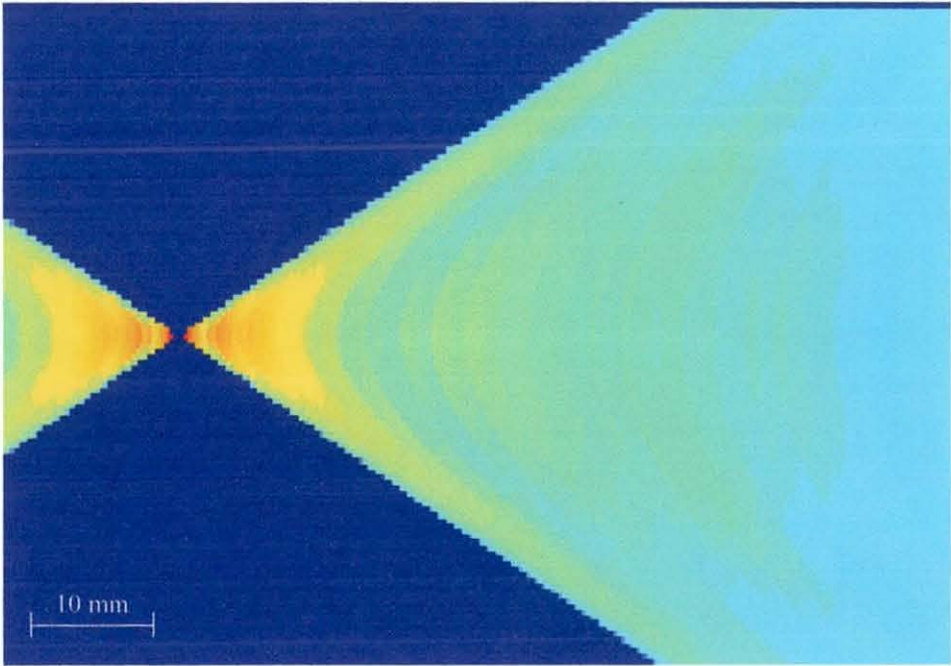


Figure 6.2.1: Simulated ‘power’ distribution for 1 MHz, 15-cycle Acoustic Tone-burst

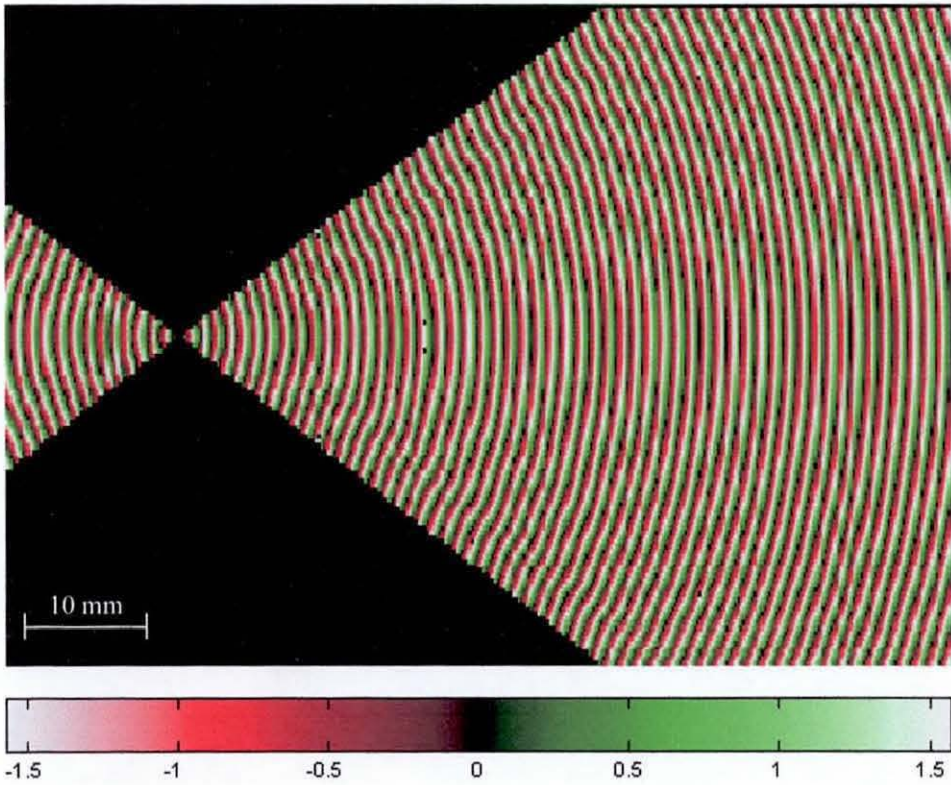


Figure 6.2.2: Simulated phase distribution for 1 MHz, 15-cycle Acoustic Tone-Burst



Figure 6.2.3 (a): Time = t_1

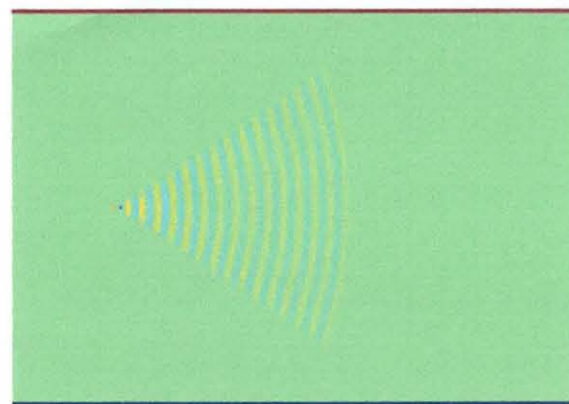


Figure 6.2.3 (b): Time = t_2

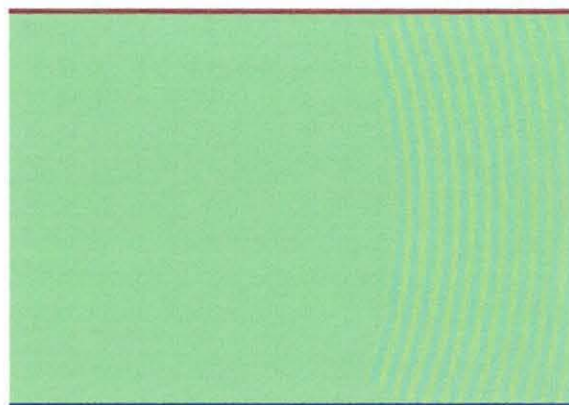


Figure 6.2.3 (c): Time = t_3

Figure 6.2.3: Rate of change of optical path length for simulated 1 MHz, 15-cycle acoustic tone-burst

The power distribution image is represented on a logarithmic scale and demonstrates the extremely high concentration of acoustic energy at the focus of the field. This concentration is also evident in the time resolved images, where the maximum amplitude is found as the tone-burst passes through the focus. The limits of the colour scaling are set by the maximum rate of change of optical path length amplitude within the series of tone-burst images. The magnitude of the colour scale required to cater for this amplitude extends far beyond that required for the simulated tone-burst at positions away from the focal region, and as such, the visual clarity of the tone-burst decreases with distance away from the focal region, as observed in Figure 6.2.3 (c).

6.2.2 Field from a Plane Piston Source

The mathematics required to simulate a planar acoustic wave are based around the description given in Section 5.2.2. Unlike the simulation of the focused wave, however, the distribution of the pressure amplitude and phase obey a simpler relationship with position within the field.

The amplitude, A , at a point (x,y,z) within the volume is taken to be irrespective of the position within the volume, where A_0 is some arbitrary pressure amplitude

$$A_{(x,y,z)} = A_0 \quad (6.2.4)$$

Similarly the phase distribution obeys a simple relationship, described as a function of distance from the acoustic source.

$$\Phi_{(x,y,z)} = \frac{-\omega x}{c} \quad (6.2.5)$$

The remaining parameters required to simulate the measurement of a field generated by a focused source are stated in Table 6.2.2. Again, for simplicity, the arbitrary pressure amplitude, A_0 , was taken to be 1 Pa.

Parameter	Abbreviation	Value	Units
Radius	R	30.0×10^{-3}	m
Number of Cycles	N	5	
Distance	d	1.28×10^{-3}	m
Distance	d_a	1.18×10^{-3}	m
Distance	d_s	-92×10^{-3}	m
Range in x	X	$-90 \text{ to } +90 \times 10^{-3}$	m
Range in y	Y	$-50 \text{ to } +50 \times 10^{-3}$	m
Acoustic Frequency	f	180×10^3	Hz
Amplitude	$A_{(x,y,z)}$	1	Pa
Phase	$\Phi_{(x,y,z)}$	$= \frac{-2\pi fx}{c}$	

Table 6.2.2: Controlling parameters for Simulation of Planar Acoustic Field

The simulated field was calculated for 370 discrete time instants, separated by $0.5 \mu\text{s}$ time intervals; from 0 to $186 \mu\text{s}$. This duration was sufficient for the simulated acoustic tone-burst to propagate through the scanning range. An image representing the 180 kHz component of the Fourier power spectrum is given on a logarithmic colour scale in Figure 6.2.4. It is known from the mathematical description that the pressure amplitude remains constant throughout the tone-burst. Since the interactive length of the laser beam represents a chord through the circular section of the field, it may be anticipated that the measured rate of change of optical path length would remain constant with distance in x , varying only with distance in y . However, the image depicted in Figure 6.2.4 illustrates the reduction in sensitivity of the LDV system as certain critical angles are approached. As the boundaries in x are expanded beyond those used in the simulation, the power can be shown to reduce to zero. This

corresponds to those positions where the phase and amplitude of the pressure along the laser line integrate to zero. It should be noted that whilst it is possible to absolutely define the angular range of the LDV used in the simulation, in practice it is extremely unlikely that the acoustic axis would be normal to the laser beam in its origin position for the experimental arrangements used.

The consideration of this phenomenon when interpreting acoustic ‘power’ images is of significant importance. Ideally, the measured power distribution should be deconvolved with the spatial sensitivity of the LDV system used. In practice, however, the idiosyncrasies of the shape and pressure amplitude and phase distribution within the field and the errors associated with the position of the LDV with respect to the acoustic field make it extremely difficult to calculate an accurate representation of the spatial sensitivity.

The phase plot depicted in Figure 6.2.5 displays a distribution as anticipated, where in general, the phase contours run parallel to the face of the acoustic source. Some curvature is observed towards the extremities. It is anticipated that this is an effect caused by the integration of refractive index with distance at the associated angles. As has been previously explained, the amplitude is significantly reduced at these angular positions.

Three time resolved images are given in Figure 6.2.6 (a), (b) and (c). In each image, the 5 cycles within the tone-burst can be clearly identified. It can be observed, however, that the physical length of the tone-burst is increased with the angle, ϕ . This is a function of the LDV interacting with a diagonal dimension of the acoustic tone-burst as alluded to in Figure 5.2.3. From careful inspection of Figure 6.2.6 (c), it can be seen that the amplitude on the extreme right hand side of the image is beginning to be reduced from that in the centre of the interrogation region for the same reasons given for the power image.

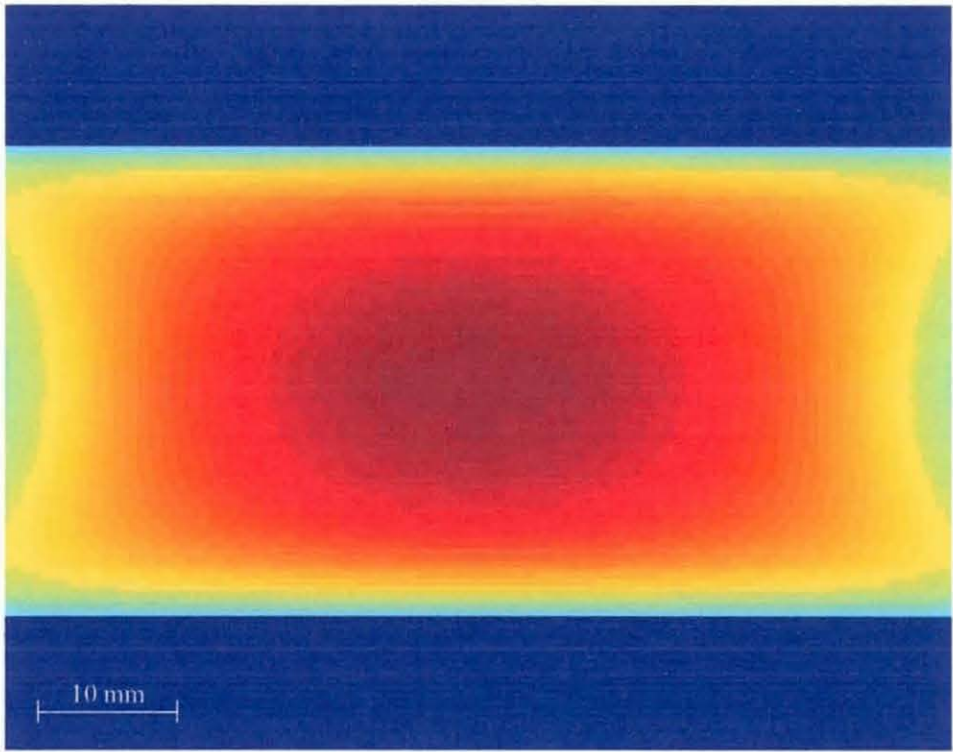


Figure 6.2.4: Simulated 'power' distribution for 180 kHz, 5-cycle Acoustic Tone-Burst

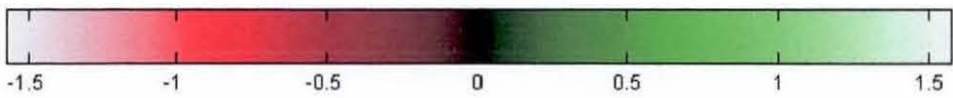
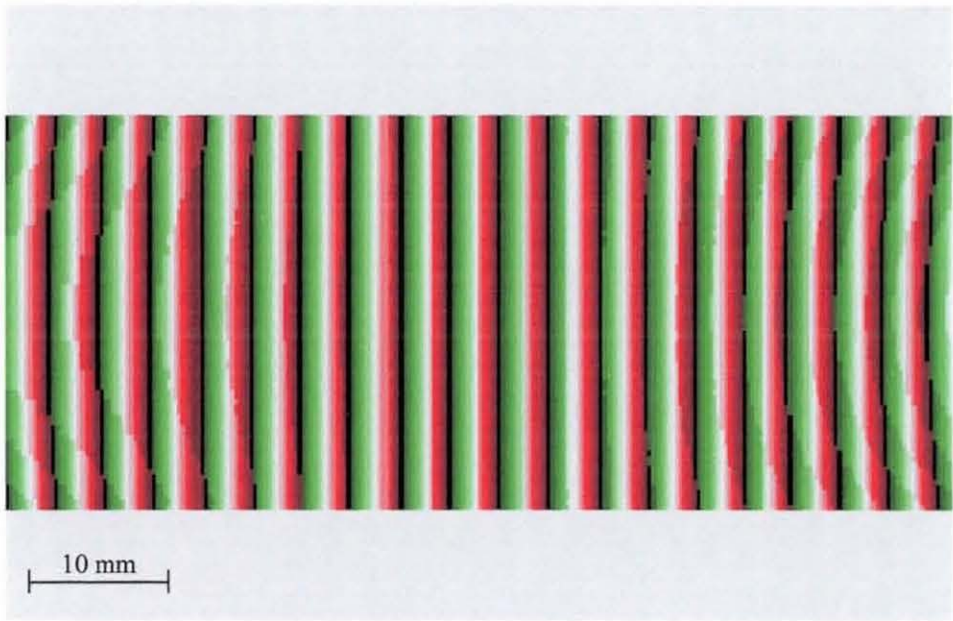


Figure 6.2.5: Simulated phase distribution for 180 kHz, 5-cycle Acoustic Tone-Burst

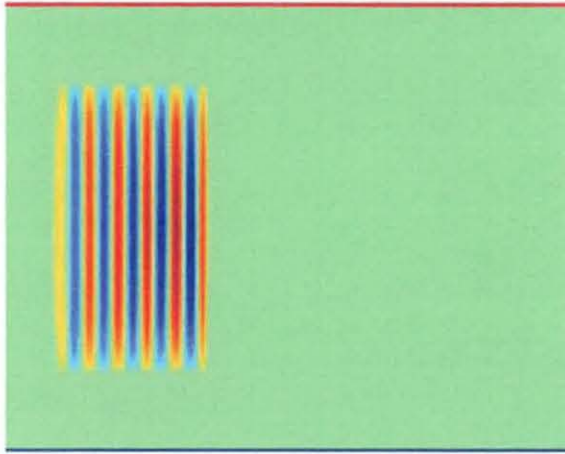


Figure 6.2.6 (a): Time = t_1

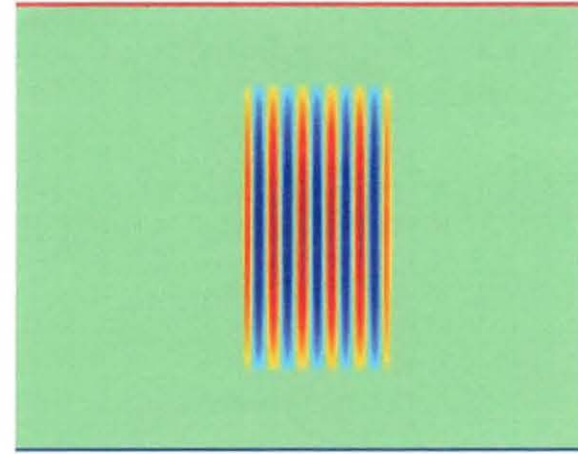


Figure 6.2.6 (b): Time = t_2

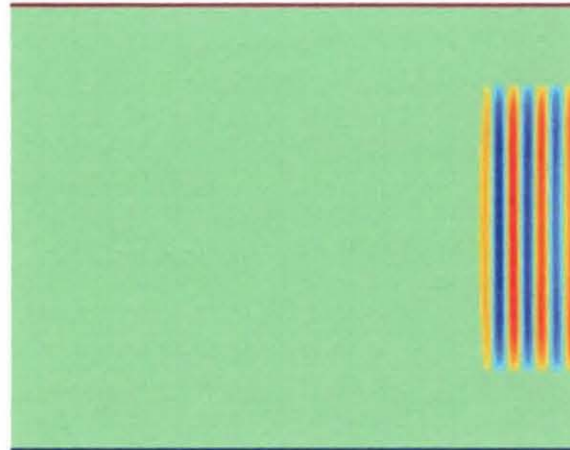


Figure 6.2.6 (c): Time = t_3

Figure 6.2.6: Rate of change of optical path length for simulated 180 kHz, 5-cycle acoustic tone-burst

6.3 LDV MEASUREMENT SCAN

Two experiments were undertaken to assess the integrity of the simulation models. In each experimental case, the characteristics of the acoustic field and position, range and spatial resolution of the LDV and scanning grid were chosen to replicate the simulation input parameters as closely as possible. For reasons previously stated, it was predicted that the positioning of the LDV scanning head with relation to the acoustic equipment would cause the most significant contribution to any discrepancy between the simulated and measured results. Whilst every attempt was made to ensure the careful positioning of the LDV system, it was likely that an angular uncertainty of $\pm 5^\circ$ was associated with the nominally perpendicular incidence of the laser beam in its origin position and the acoustic axis.

6.3.1 Field from a Focused Source

A 1 MHz focused acoustic source was used to generate a repeated 15-cycle tone-burst which was interrogated using the LDV system. A series of images are presented in the Figures that follow, each representing the equivalent quantities of measured experimental data to those given for the simulation model.

The power distribution depicted in Figure 6.3.1 shows similarities with the simulated equivalent given in Figure 6.2.1, in the general shape of the field and concentration of the power around the focus. Imperfections in the physical characteristics of the source result in acoustic energy being detected at positions outside of the field boundaries described in the simulation. Additionally, spurious signals generated by the source, such as those originating from the perimeter lip of the transducer, as described in Section 5.3.4.1, can also be observed. The various components within the acoustic field combine to cause diffractive interference patterns throughout the field, although these are more clearly evident at the field boundaries. It is suggested that the interference patterns are exaggerated for increased tone-burst lengths where the overlapping region of the principal signal with that originating from the source perimeter is large.

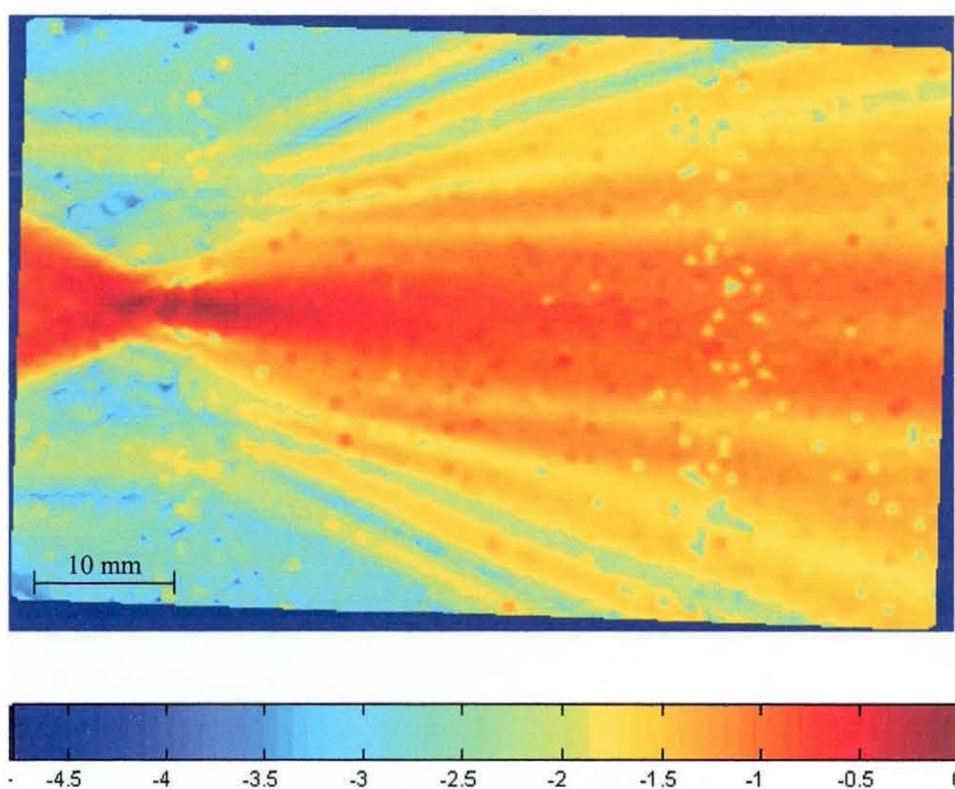


Figure 6.3.1: Experimentally Measured 'power' distribution for 1 MHz, 15-cycle Acoustic Tone-Burst (Log_{10} scale)

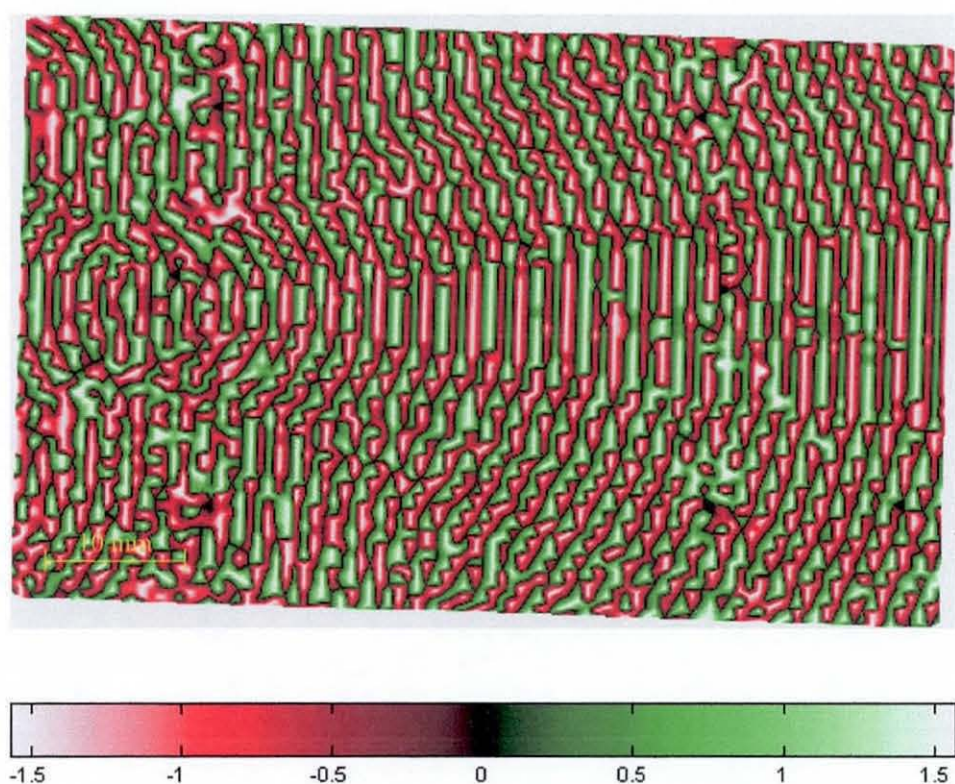


Figure 6.3.2: Experimentally Measured phase distribution for 1 MHz, 15-cycle Acoustic Tone-Burst

The phase distribution given in Figure 6.3.2 demonstrates good visual similarity with the simulated equivalent given in Figure 6.2.5. Attempts were made to assess this similarity by image subtraction methods, but this was found to be subject to significant uncertainties due to the combined influence of small errors in many of the input parameters used in the simulation. Spurious signals and background noise contribute to a non-uniform phase distribution outside of the field boundaries, although given the very small amplitude, indicated by the power distribution image, these apparent discrepancies in phase are immaterial.

The three time-resolved images depicted in Figure 6.3.3 (a), (b) and (c) represent the tone-burst at similar positions in time and space as in the simulated images given in Figure 6.2.3 (a), (b) and (c). In each image the tone-burst consisting of 15-cycles is clearly identifiable, and its propagation within the boundaries projected from the source perimeter through the acoustic focus is similar to the equivalent images generated from the simulation model.

The major observed differences between the simulated data and the experimentally measured data are that the focal region is larger in the experimental case than in the simulation and that spurious signal components are contained within the measured field. In the simulation, the focus of the acoustic field is described as an infinitely small point. Clearly in practice this is not possible, since the focus must occupy a finite volume. Additionally, any imperfections in the structure of the acoustic source are likely to result in the focus increasing in size. In a spherical wave, the model on which the simulation is based, the intensity, I , of the acoustic wave is proportional to the square of the pressure amplitude, p .

$$I = \frac{p^2}{2Z} \quad (6.3.1)$$

where Z is the acoustic impedance.

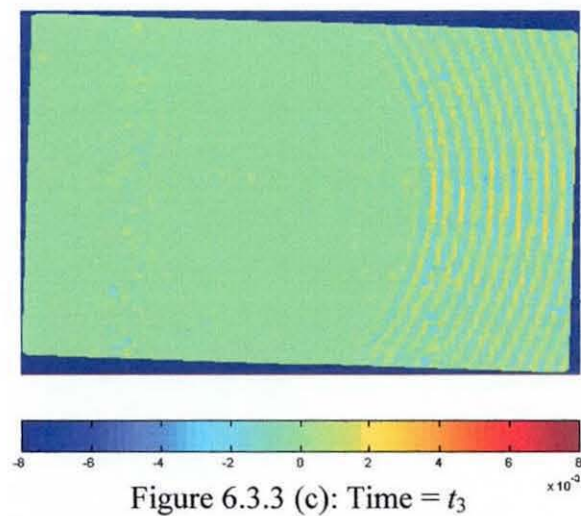
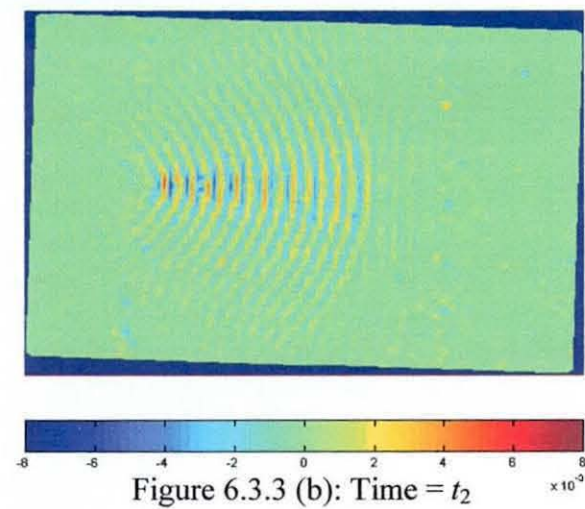
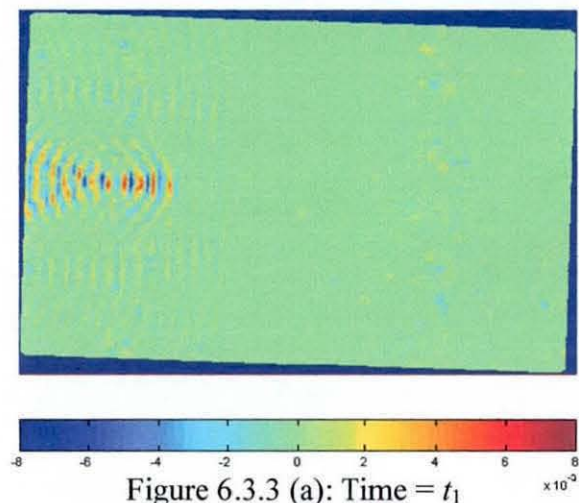


Figure 6.3.3: Experimentally measured rate of change of optical path length for 1 MHz, 15-cycle acoustic tone-burst
(m/s)

The product of the intensity and the spherical surface area of the propagating field yields the acoustic power. Since in theory the acoustic power is conserved, the amplitude of the acoustic pressure is required to be extremely large as the field approaches the focus in the simulation, where the area becomes extremely small. Consequently, the amplitude of the rate of change of optical path length at the focus is significantly greater than that observed elsewhere in the field. Since the focus within the experimental acoustic field does not occupy such a small volume, the pressure amplitude is not as comparatively large as that measured elsewhere in the field.

Within the field, spurious signals such as those originating from the perimeter of the acoustic source, as described in Section 5.3.4.1 can be observed, beginning ahead of the principal acoustic tone-burst but running alongside the principal tone-burst for the majority of their length. This is particularly evident in Figure 6.3.3 (a), where the positions of the respective acoustic components are isolated. In Figure 6.3.3 (b), the divergence of the principal acoustic field begins to overlap that of the spurious signal and its effect is more difficult to observe. However, reference to the power image given in Figure 6.3.1 enables its influence to be considered.

6.3.2 Field from a Plane Piston Source

An appropriate plane-piston acoustic source was used to generate a 5-cycle 180 kHz tone-burst, which was measured using the scanning LDV system. Again, the accuracy of the positioning of the LDV scanning head with respect to the acoustic axis is likely to be subject to an uncertainty of $\pm 5^\circ$.

The power distribution image depicted in Figure 6.3.4 demonstrates good similarities with the simulated power image given in Figure 6.2.4. In both images the peak power is found at a position along the central acoustic axis of the field. The reduction with radial distance is similarly consistent, although the overall shape of the field shows subtle differences, most notably that the measured field demonstrates a divergence of approximately 6° , which was not included in the mathematical simulation.

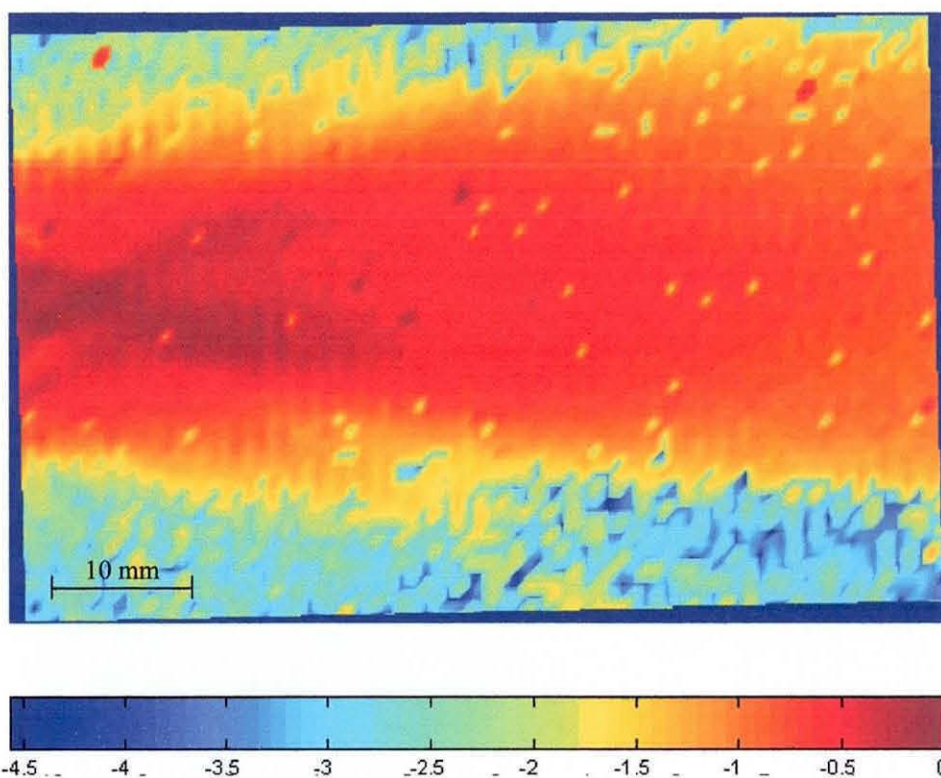


Figure 6.3.4: Experimentally Measured 'power' distribution for 180 kHz, 5-cycle Acoustic Tone-Burst

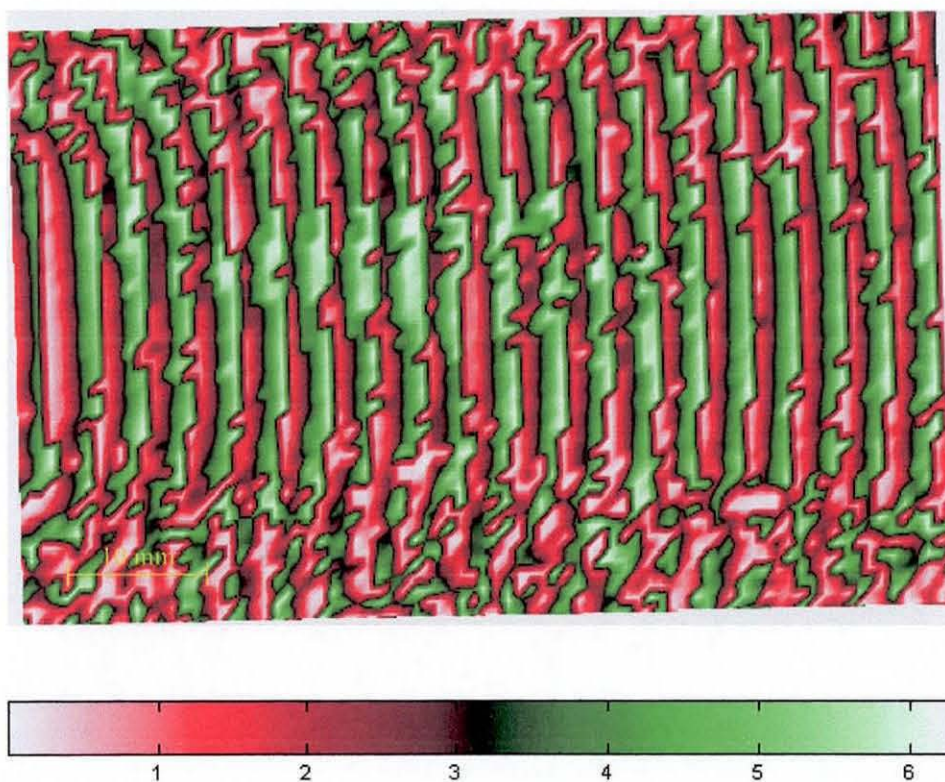


Figure 6.3.5: Experimentally Measured phase distribution for 180 kHz, 5-cycle Acoustic Tone-Burst

The amplitude of the measured field appears not to reduce to zero at any position within the field. This implies that the amplitude and phase distribution within the field are such that they do not combine to cancel the rate of change of optical path length, as was the case in the mathematical simulation.

The phase distribution image is depicted in Figure 6.3.5, and also shows close similarities with the simulated phase distribution given in Figure 6.2.5. Here the general phase relationship sees parallel plane waves through the centre of the field, as was the case in the simulated field. A certain amount of curvature is observed at the radial extremities of the field.

In each of the three time-resolved images depicted in Figure 6.3.6 (a), (b) and (c) the tone-burst can be observed passing through the field. However, the number of cycles contained within the tone-burst is not consistent with the 5-cycles observed in the equivalent images from the mathematical simulation. The measured acoustic field contains the original 5-cycle tone-burst followed by an additional 4 or 5 cycles caused by the reverberation of the high Q acoustic source. These additional cycles are reduced in amplitude from the principal tone-burst, but have similar shape and phase distribution.

The divergence of the field is also evident in the time resolved images, where the width of the tone-burst is increased with the distance of propagation through the field. Other phenomena can also be observed, such as the spherical waves most evident in Figure 6.3.6 (b), which appear to originate from the edges of the acoustic source.

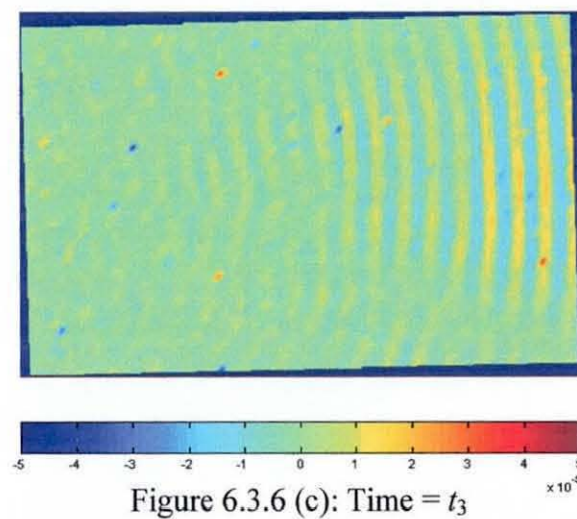
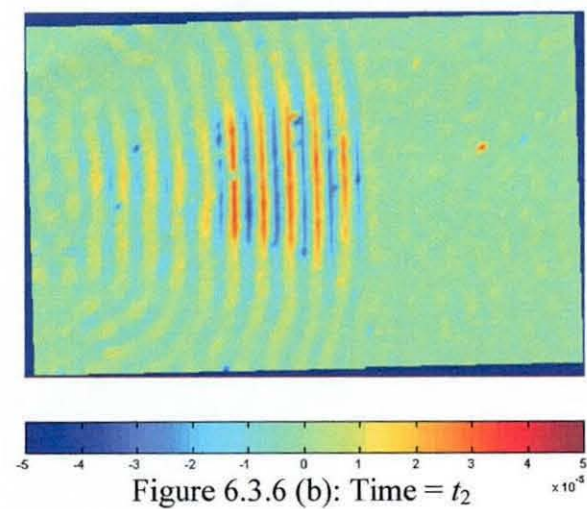
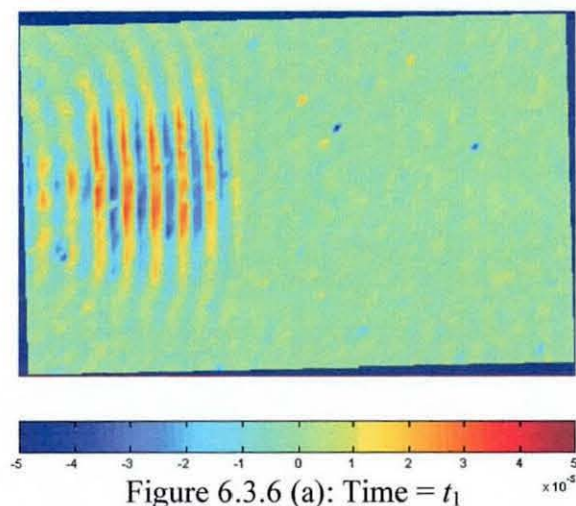


Figure 6.3.6: Experimentally measured rate of change of optical path length for 180 kHz, 5-cycle acoustic tone-burst (m/s)

6.4 CLOSURE

The theoretical and experimental results presented in this chapter have further confirmed the ability of the scanning LDV system to record measurements from spatially distributed acoustic fields. Images from equivalent simulated and experimentally measured wavefronts were observed to exhibit similar power and phase distributions, and the wavelengths and spatial positions of the tone-bursts in the temporally resolved images were also consistent. In general, the close similarities observed between the major features of the equivalent images served to validate the simulation.

However, subtle differences were observed between the images generated from the simulated data and those from the experimental data. These were shown to be caused predominantly by the noise and aberrations measured in the experimental data. The limitations of the simulation are manifest also, in that the experimental data contains many additional features caused by such things as wavefront divergence, curvatures and the presence of spurious side lobes and waves generated from parts of the transducer other than the front face. Potential for the inclusion of these features was not included within the simulation.

Chapter 7

Scattered Fields

7.1 INTRODUCTION

The potential of the scanning LDV system to accurately record measurements from spatially and temporally distributed acoustic fields is exploited in this chapter. Experimental scans are recorded from acoustic fields including potential obstructions such as a measurement hydrophone, a PVDF pellicle and other rigid metallic obstructions.

In the cases of the hydrophone and the pellicle, it is anticipated that the ability of the scanning LDV system to resolve small discrepancies caused by the presence of the obstruction will be challenged. In the measurements taken from fields including rigid metallic obstacles, it is anticipated that the ability of the system to identify and monitor field components scattered, diffracted and transmitted from and around the obstacle will be examined.

Images depicting the amplitude, phase and time resolved rate of change of optical path length of the scattering and diffractive influence of the obstructions are presented. These images are then analysed and the origins of various observed features are discussed.

7.2 INTERROGATION OF REFLECTIONS FROM INTERFACES

The sensitivity of the scanning LDV to spurious low amplitude components of the acoustic field enabled further interrogation to be made. This was of particular benefit when considering the reflected components of the acoustic field, particularly in the Loughborough University glass tank. Here, a 10-cycle 180 kHz plane wave tone-burst was generated and the scanning LDV used to interrogate a region 330 mm in width.

Figure 7.2.1 (a) depicts the principal tone-burst on a red-green colour scale to ease visual clarity. Figure 7.2.1 (b) depicts the field 55 μs later, by which time additional spurious and reflected signal components have begun to combine in the region behind the tone-burst inducing a complex phase and amplitude pattern. Figure 7.2.1 (c) represents the field a further 60 μs later, where a diagonal mesh formation can be observed in the central region of the image. This pattern is caused by the interference between the two components reflected from both the lower water-glass interface and the upper water-air interface. Both reflected signals can be clearly observed, each travelling at approximately 45° either side of the direction of propagation. From the image, it would appear that the reflected components from both interfaces are of a similar pressure amplitude.

Whilst it might have been anticipated that the acoustic signals outside of the principal tone-burst generated by the source were of insignificant magnitude, the images presented in Figure 7.2.1 demonstrate their influence to be appreciable. In the region of interference created in the wake of the principal tone-burst, the measured amplitudes of areas of constructive interference were observed to be reduced by a less than a factor of 2 from the principal acoustic beam. This further demonstrates the care that must be taken when identifying and measuring acoustic signals in confined volumes.

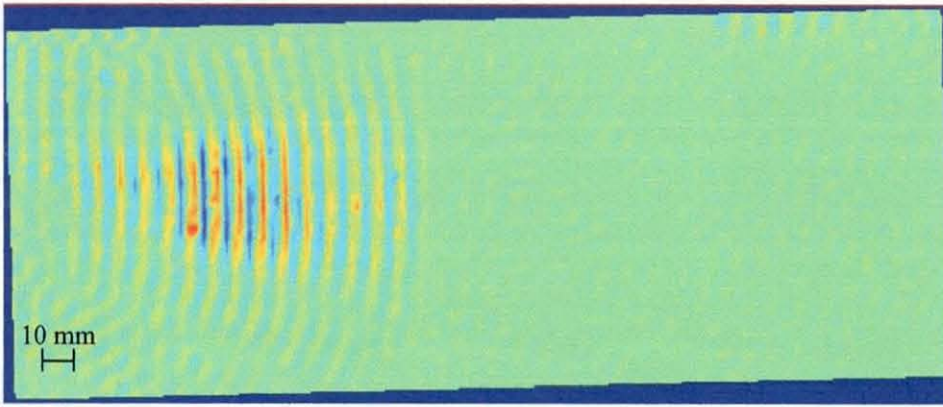


Figure 7.2.1 (a) Time = t

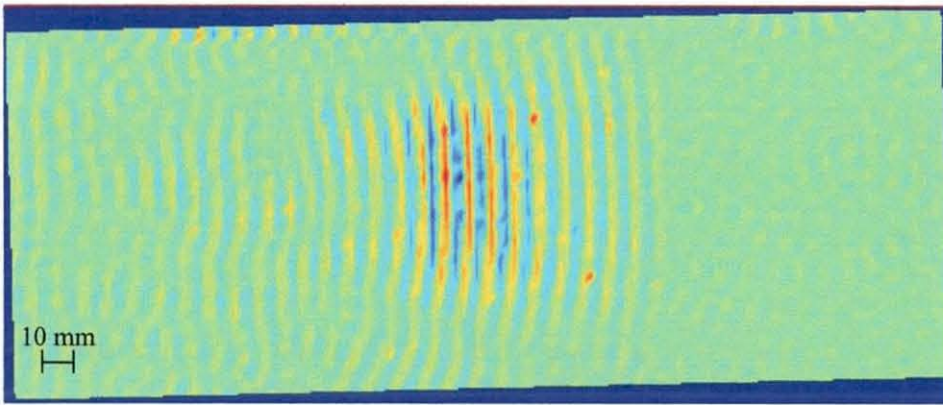


Figure 7.2.1 (b) Time = $t + 55 \mu\text{s}$

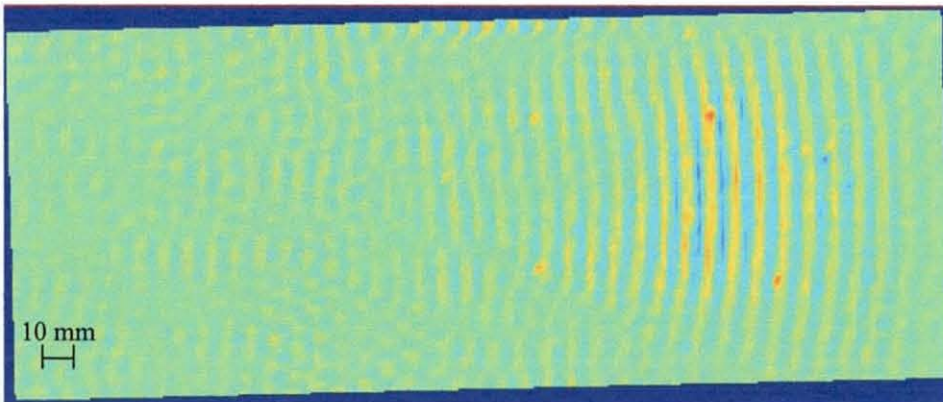


Figure 7.2.1 (c) Time = $t + 115 \mu\text{s}$

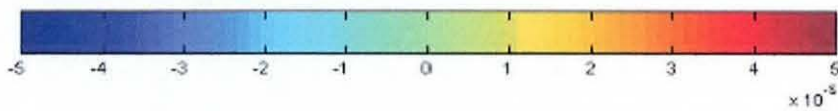


Figure 7.2.1: Reflected components of a 180 kHz plane wave acoustic field

7.3 ANALYSIS OF FIELDS IMPEDED BY OBSTACLES

The ability of the scanning LDV system to identify the amplitude and phase of the integrated refractive index with distance in time and space enables both the principal tone-burst and secondary acoustic patterns within a field to be interrogated and identified, as demonstrated in Section 7.2. Whereas for calibration purposes, reflections from tank walls and water-air interfaces are generally undesirable, in a host of medical imaging applications the detection of scattered and reflected components from impeding boundaries within a field are an essential part of the measurement process.

For this reason, acoustic fields were established where the tone-burst was directed at a strategically placed obstacle of known shape. The scanning LDV system was then used to enable the principal tone-burst and any scattered and reflected components to be identified. Such obstacles included those designed for submersion in underwater acoustic fields, such as a hydrophone or reflective pellicle used in conjunction with the NPL Laser Interferometer [73], and rigid metallic cylinders and spheres.

7.3.1 LDV Measurements from fields including a hydrophone

One of the aims of the National Measurement System Programme for Quantum Metrology [54] is to further the development and application of optical metrology techniques for the measurement of underwater acoustic quantities. The primary benefit of such optical interrogation is the elimination of any acoustic perturbation caused by the need to place a physical object within the field. Experiments were undertaken to observe the perturbing effect of a hydrophone, when suspended within an acoustic field. In accordance with the procedure undertaken by Faran [61], the scatterer, in this case an ITC 6128 hydrophone, was suspended within a volume and three measurements were made each recording the propagation of an acoustic tone-burst of a particular frequency.

The ITC 6128 hydrophone had a diameter of 7.9 mm and a principal resonance at 550 kHz, which corresponds to an acoustic wavelength in water of 2.7 mm. The acoustic frequencies used were 250 kHz, 500 kHz and 800 kHz, which correspond to

acoustic wavelengths of 5.9 mm, 2.9 mm and 1.8 mm respectively. These wavelengths were chosen as one greater than, one less than and one approximately equal to the hydrophone diameter. The transducer used generated a converging acoustic field, which focused within a cylindrical region of approximately 10 mm diameter by 20 mm long. The Panametrics V389 transducer was designed for use at 500 kHz, and hence provided a larger pressure amplitude for a given voltage input than at 250 kHz, which was in turn larger than that at 800 kHz.

An assessment of the impeding or scattering influence of the hydrophone within the acoustic field can firstly be made by monitoring the propagation of the acoustic tone-burst. Two images representing the tone-burst at different instants in time are depicted for each acoustic frequency. The dark region in each image represents the position of the hydrophone suspended within the focal region of the field.

The 250 kHz tone-burst observed in Figure 7.3.1 depicts the acoustic wave arriving at the hydrophone position in (a), and a further 16 μ s later having partially passed the hydrophone in (b). The shape, amplitude and phase of the tone-burst observed in Figure 7.3.1 (b) remain consistent with what might be expected by extrapolating the field measured in Figure 7.3.1 (a). Hence, from this measurement it can be concluded that the 250 kHz acoustic tone-burst experiences minimal obstruction caused by the presence of the hydrophone.

Figure 7.3.2 depicts the 500 kHz tone-burst at two time instants, also separated by 16 μ s. Here the shape and phase of the tone-burst measured in (b) remain consistent with that anticipated by extrapolation from that observed in (a). However, the amplitude of the measured rate of change of optical path length once the acoustic wave has passed the hydrophone is reduced to approximately half that of the tone-burst observed in Figure 7.3.2 (a) and within the tone-burst of Figure 7.3.2 (b) prior to arrival at the hydrophone position.

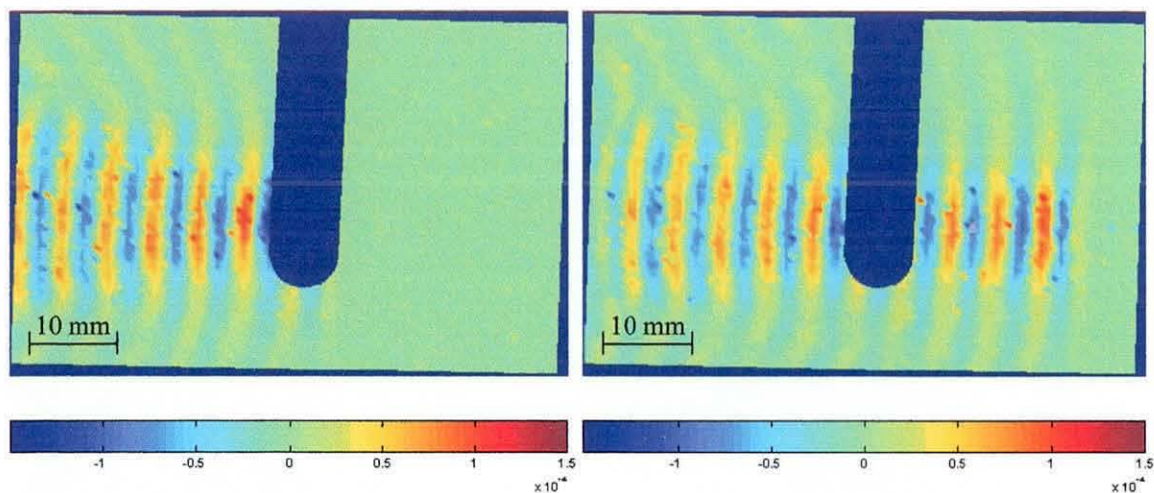


Figure 7.3.1: 10-cycle 250 kHz tone-burst incident on ITC 6128 hydrophone (m/s)

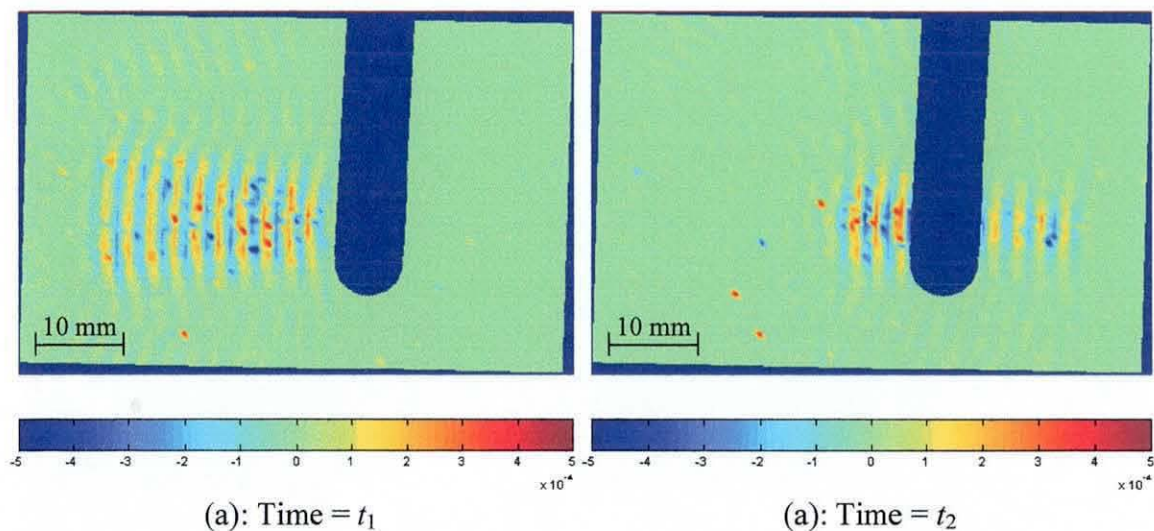


Figure 7.3.2: 10-cycle 500 kHz tone-burst incident on ITC 6128 hydrophone (m/s)

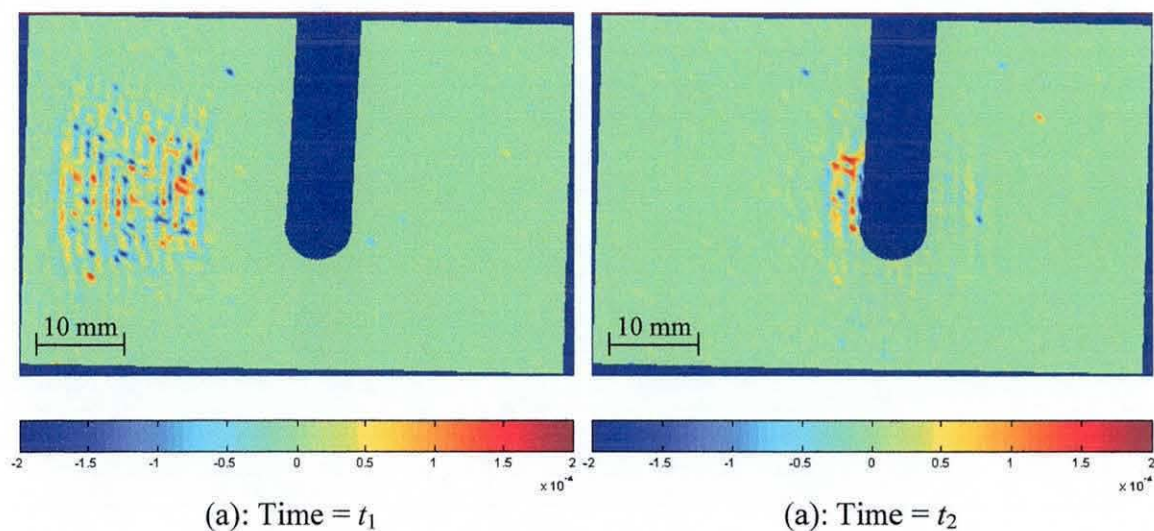


Figure 7.3.3: 10-cycle 800 kHz tone-burst incident on ITC 6128 hydrophone (m/s)

The passage of the 800 kHz tone-burst observed through the two images, again separated by 16 μ s in Figure 7.3.3, can clearly be seen to experience significant obstruction caused by the hydrophone. The tone-burst observed in Figure 7.3.3 (a) can be clearly identified, although a combination of poor spatial resolution and the low response of the source at 800 kHz result in a reduction in the visual clarity of the acoustic signal. However, the tone-burst depicted in Figure 7.3.3 (b) demonstrates the significant reduction in pressure amplitude caused by the presence of the hydrophone, since the identification of the tone-burst to the right hand side of the obstacle becomes very difficult. The increased complexity of the acoustic signal to the immediate left of the hydrophone observed in Figure 7.3.3 (b) may suggest that the tone-burst is in part reflected by the hydrophone, causing a region of interference.

If the hydrophone induces scattering of the acoustic wave, it follows that interference effects will be present in the region of the field to the left of the hydrophone. The FFT power distribution images described in Section 5.3.4.1 enable the component of the power spectrum at the fundamental frequency contained within the entire time history to be observed.

Four images are presented each representing the fundamental frequency component of the FFT power spectrum for a given acoustic field. Each is plotted on a logarithmic scale to aid visual clarity. In Figure 7.3.4, an unimpeded 10 cycle 250 kHz tone-burst is depicted in order for a comparison to be made between an unimpeded field and one containing a hydrophone. The observed distribution is well defined within the diverging field boundaries, and minimal interference patterns can be observed at the field extremities.

Figure 7.3.5 depicts the influence of a hydrophone on the same 250 kHz tone-burst. Here an image similar to that observed for an unimpeded field is produced; both in the spatially distributed field shape and colour scaled amplitude. This affirms the conclusion deduced from the time-resolved images, that the influence of the 7.9 mm diameter hydrophone on the 250 kHz acoustic tone-burst is negligible.

The FFT power image depicted in Figure 7.3.6 enables the influence of the hydrophone on the 500 kHz acoustic tone-burst to be visualised. Firstly, the spatially distributed shape and amplitude of the 'power' measured in the region to the right of the hydrophone demonstrates a change from that observed in the previous two images. Whilst the measured power in this region remains consistent in its centre, the spatial distribution is significantly reduced with radial distance. This implies that over the course of the measurement duration the acoustic energy detected across this region is reduced. It is deduced, therefore, that acoustic energy is prevented from reaching this region by absorption or scattering by the hydrophone. Another factor indicative of the perturbing hydrophone influence is the interference pattern evident throughout the image. This pattern is caused by the combination of forward propagating acoustic tone-burst and components of the field scattered by the hydrophone. These are most evident at the extremities of the field, where the logarithmic scale exaggerates the low amplitude differences. This result substantiates the conclusion made from the time resolved images, that the 7.9 mm diameter hydrophone has a noticeable impeding effect on the propagating 500 kHz acoustic tone-burst.

The FFT power image depicted in Figure 7.3.7 depicts a radical departure from those observed in the previous images. Here, the region beyond the hydrophone, to the right in the image, demonstrates a dramatic reduction in acoustic power. This implies that the hydrophone prevents a high percentage of the acoustic energy from propagating beyond it. The interference patterns visible in the region to the left of the hydrophone are demonstrably more complex than in the previous comparable images. This demonstrates the presence of increased quantities of scattered acoustic energy by its interference with the principal, forward propagating tone-burst. The image fully justifies the conclusion that the propagation of the 800 kHz acoustic tone-burst is drastically impeded by the presence of the 7.9 mm diameter hydrophone.

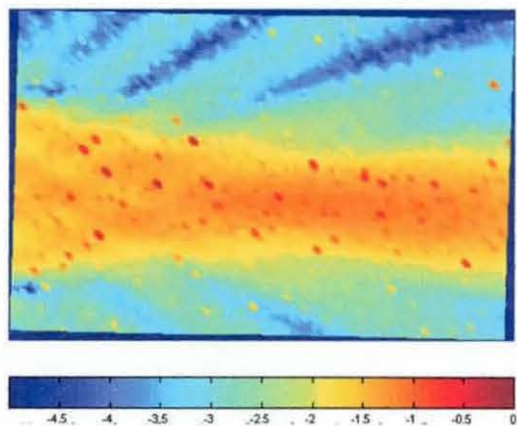


Figure 7.3.4: 250 kHz component of FFT power spectrum for unimpeded 10-cycle 250 kHz tone-burst

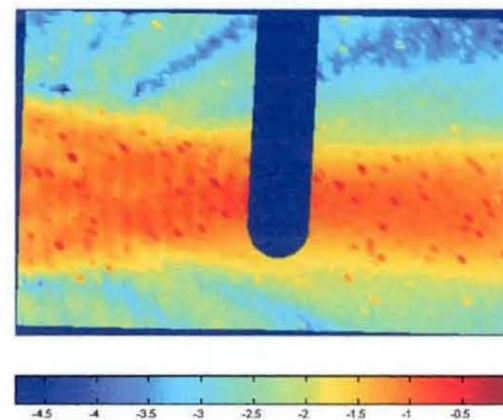


Figure 7.3.5: 250 kHz component of FFT power spectrum for 10-cycle 250 kHz tone-burst impeded by hydrophone

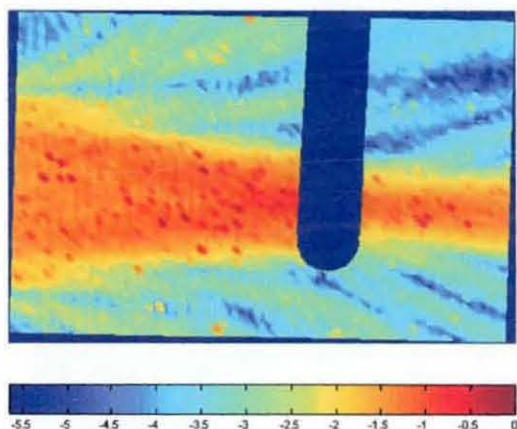


Figure 7.3.6: 500 kHz component of FFT power spectrum for 10-cycle 500 kHz tone-burst impeded by hydrophone

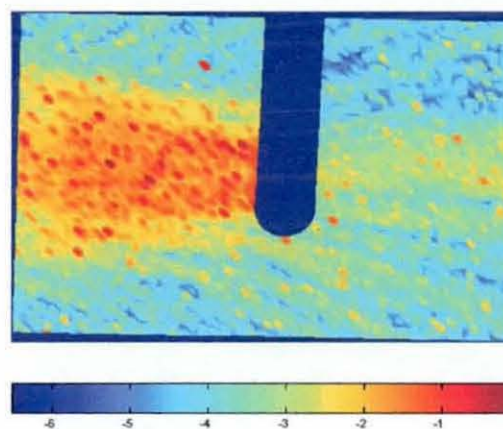


Figure 7.3.7: 800 kHz component of FFT power spectrum for 10-cycle 800 kHz tone-burst impeded by hydrophone

7.3.2 LDV Measurements from fields including a pellicle

The NPL Laser Interferometer is the current primary standard for the calibration of hydrophones in the frequency range 500 kHz to 15 MHz [73]. The PVDF pellicle used to reflect the optical beam as part of this calibration procedure and its associated supporting structures are the only potentially perturbing object required to be positioned in the field. Due to its very thin section (5 μm) and close impedance matching with water, it is envisaged that the perturbing influence of the PVDF is very small, particularly by comparison with a hydrophone. Experiments were undertaken to establish the influence of a PVDF pellicle, coated with a reflective layer of aluminium, significantly thinner than the thickness of the PVDF, on a propagating acoustic tone-burst. The shape of the beam was such that the principal tone-burst was directed through the pellicle without contact with the rigid aluminium mounting. Reflections from the mounting are likely to be of significantly larger amplitude.

The acoustic transducer used was the Panametrics V389 source described in Section 3.3.1.3 and the field generated was a 10 cycle, 500 kHz tone-burst. The pellicle was positioned at three distances from the front face of the source, one prior to, one within, and one beyond the focal region. Each field was scanned using the Polytec Scanning LDV system over a region measuring approximately 95 mm in width by 90 mm in height. A measurement of the acoustic field without the presence of a pellicle was also recorded.

The FFT power image and the DFT power image, both described in Section 5.3.4.1 were used to compare the influence of the pellicle on the propagation of the acoustic wavefront. It was anticipated that the FFT image, calculated from a Fourier Power Spectrum of the entire time history, would provide an indication of the presence and influence of reflected and scattered components. In contrast, the DFT power image, taken from seven complete cycles within the tone-burst would only provide an indication of the measured 'power' of the principal acoustic tone-burst. Such images calculated from the unimpeded field enable a direct comparison between each respective FFT and DFT power image to be made. The FFT power image of the

unimpeded field is depicted in Figure 7.3.8, and the DFT power image of the same field in Figure 7.3.9.

The images that follow depict the pellicle in the three positions within the field; Position 1 in Figure 7.3.10 and Figure 7.3.11, Position 2 in Figure 7.3.12 and Figure 7.3.13 and Position 3 in Figure 7.3.14 and Figure 7.3.15. The power distribution throughout the field was observed to remain largely unaffected by the suspended pellicle in both the FFT and DFT images. Few additional acoustic components were identified in any of the images, despite presentation on a logarithmic scale. A quantifiable measure of the similarity between the images was not obtainable due to the noise content of the images, which disrupted attempts to perform image subtraction. However, from these results it can be concluded that the presence of the PVDF pellicle does not perturb the acoustic field in a noticeable manner.

This experimental set-up involved the acoustic tone-burst passing through the aluminium annulus of the pellicle. As can be observed from the images shown in Figure 7.3.8 and Figure 7.3.9, the measured 'power' outside of the envelope of the principal acoustic beam is reduced by up to six orders of magnitude. This means that the amplitude of the acoustic signal reflected from the aluminium annulus would be negligible by comparison to the remainder of the field. However, where a transducer is used to generate a more distributed acoustic field, or where secondary side lobe acoustic signals are also emitted, the components scattered by the aluminium are likely to be more significant.

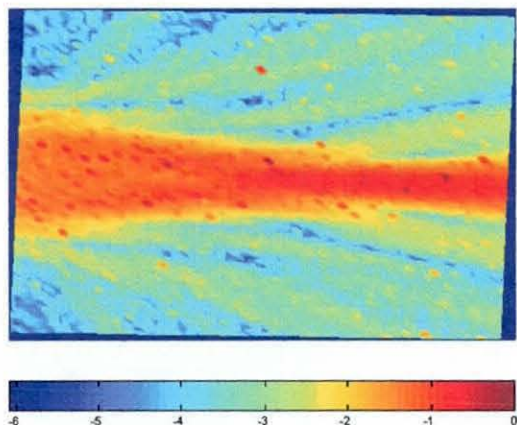


Figure 7.3.8: FFT power distribution image for 10-cycle, 500 kHz
acoustic tone-burst

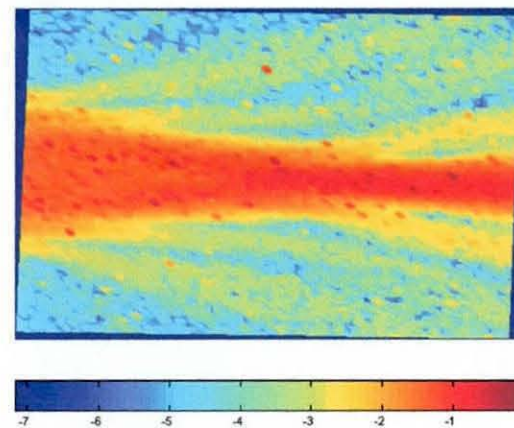


Figure 7.3.9: DFT power distribution image for 10-cycle, 500 kHz
acoustic tone-burst

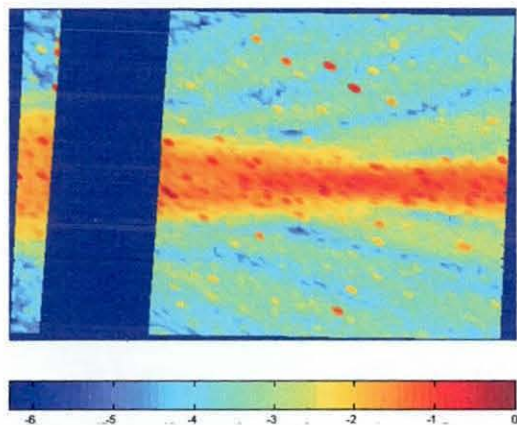


Figure 7.3.10: FFT power distribution image for 10-cycle, 500 kHz
acoustic tone-burst – pellicle position 1

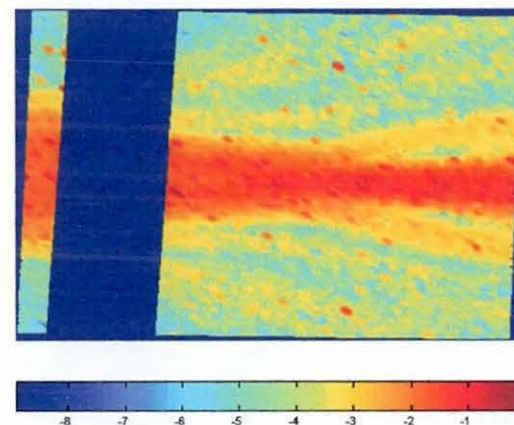


Figure 7.3.11: DFT power distribution image for 10-cycle, 500 kHz
acoustic tone-burst – pellicle position 1

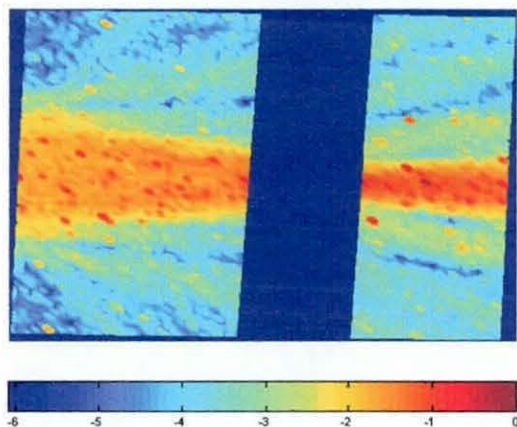


Figure 7.3.12: FFT power distribution image for 10-cycle, 500 kHz acoustic tone-burst – pellicle position 2

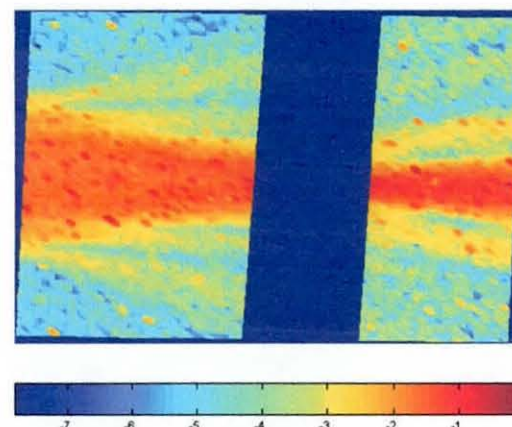


Figure 7.3.13: DFT power distribution image for 10-cycle, 500 kHz acoustic tone-burst – pellicle position 2

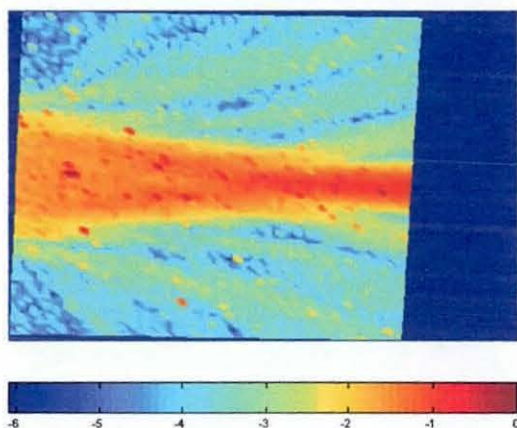


Figure 7.3.14: FFT power distribution image for 10-cycle, 500 kHz acoustic tone-burst – pellicle position 3

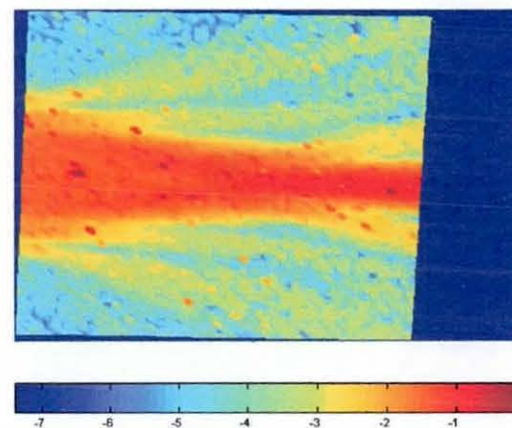


Figure 7.3.15: DFT power distribution image for 10-cycle, 500 kHz acoustic tone-burst – pellicle position 3

7.3.3 LDV Measurements from fields including rigid body obstacles

As has previously been stated in Section 2.3, it is usually desirable to avoid or remove potential scattering influences from within the acoustic field, particularly during calibration. Having examined the influence of physical devices intended to be submerged within an acoustic field, which are carefully designed to minimise field perturbation, attention was given to physical objects, which were known to scatter acoustic energy. Experiments were undertaken to assess the ability of the scanning LDV system to detect the interference between the principal acoustic tone-burst and scattered signals.

Some simple examples of perturbing obstacles were suspended directly within the path of a planar acoustic tone-burst and the resultant scattered acoustic field measured using the scanning LDV system. The obstacles used were designed to replicate the theoretical conditions suggested by Faran [61]. A 40 mm diameter stainless steel ball bearing was used to replicate the scattering by a perfect sphere and a variety of metallic bars and tubes were used to visualise scattering by cylinders. The acoustic frequency used was determined by the acoustic source used, which generated its most planar wave conditions at its 180 kHz resonance frequency. The wavelength of a 180 kHz acoustic wave in water at 16.5 °C is 8.17 mm.

7.3.3.1 Ball Bearing

A 40 mm diameter spherical ball bearing was suspended from an overhead gantry using a section of very thin (< 0.25 mm) wire. The ball bearing was positioned such that the acoustic axis passed through its centre, at a distance of approximately 100 mm from the front face of the source. The planar wavefront was directed towards the ball bearing and a time history of the rate of change of optical path length recorded at 3029 target grid positions. The duration of the time history was specified as 102.4 μ s, sufficient for the principal acoustic tone-burst to propagate across the field width and any scattered waves to travel outside of the interrogation region. The separation time of each of the images within the data capture was 0.1 μ s.

Two time sliced images are presented, depicting the acoustic tone-burst at two time instants. Figure 7.3.16 demonstrates the position of the acoustic tone-burst as it passes the ball bearing at a time t , approximately $70\ \mu\text{s}$ after the initiation of the acoustic source. Figure 7.3.17 depicts the acoustic tone-burst a further $25.5\ \mu\text{s}$ later. The position of the ball bearing is indicated by the dark circular area in the centre of the image. From these images, the manner in which the obstacle affects the propagation of the tone-burst can be visualised.

As may be anticipated, the amplitude of the detected rate of change of optical path length is seen to generally decrease with distance travelled from the source. This is predominantly due to the shallow divergence of the plane wave and energy losses within fluid, and is known to occur regardless of the presence of any obstacle in the field. The presence of the ball bearing does, however, cause the observed changes in measured amplitude in the region beyond the obstacle. Here, the amplitude remains comparatively high (1 to 2×10^{-5} m/s) in the areas adjacent to the edges of the ball bearing when compared with those detected in the area immediately beyond the centre of the ball (0.5 to 1×10^{-5} m/s). Little change in the wavelength of the signal or interference in the region in front of the obstacle can be observed.

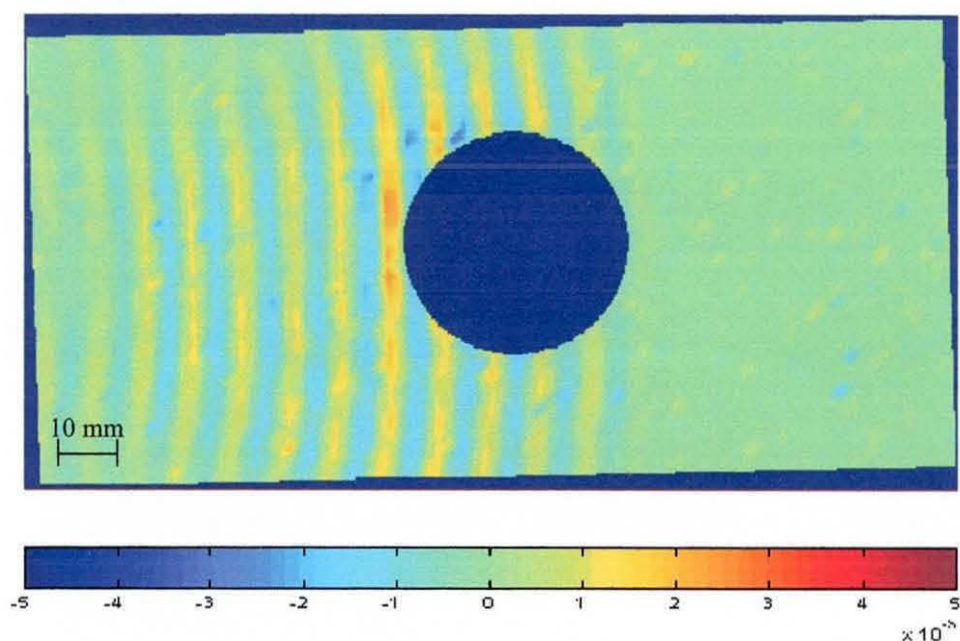


Figure 7.3.16: 180 kHz plane wave tone-burst incident on 40 mm diameter stainless steel ball bearing – Time = t (m/s)

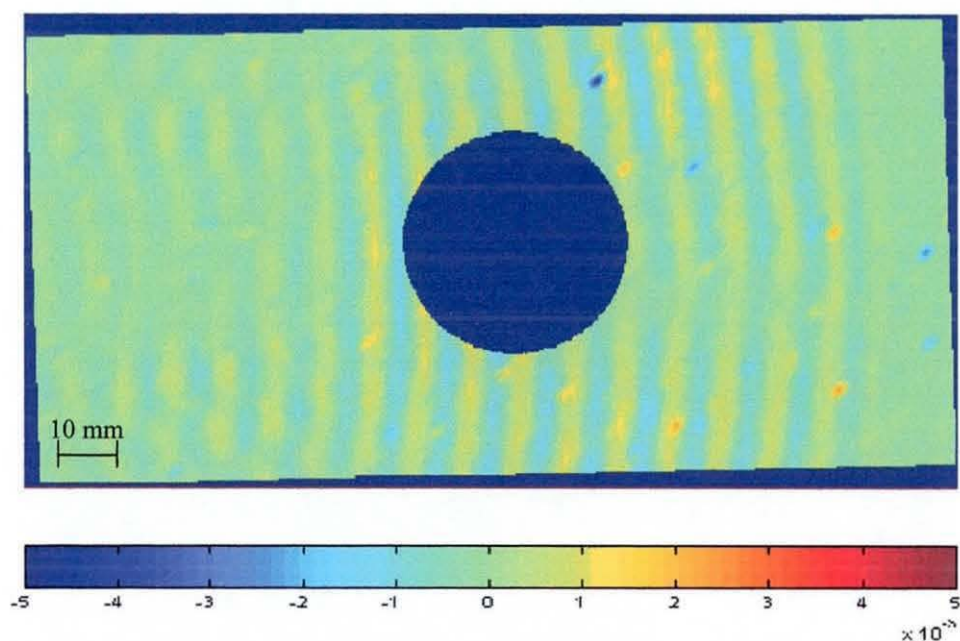


Figure 7.3.17: 180 kHz plane wave tone-burst incident on 40 mm diameter stainless steel ball bearing – Time = $t + 25.5 \mu\text{s}$ (m/s)

An improved assessment of the spatial distribution of amplitude can be derived from the FFT and DFT acoustic ‘power’ images depicted in Figure 7.3.18 and Figure 7.3.19 respectively. The method by which each of these images is generated enables certain different features to be identified in each and the colour scaling of each has been normalised to assist comparison.

In the FFT power image of Figure 7.3.18, a ‘rippled’ pattern can be observed throughout the region preceding the obstacle. This can be attributed to interference between the forward propagating principal tone-burst and the sound scattered by the obstacle. Other features of the image are the significant reduction of the measured power in the region beyond the ball bearing – more than 5 dB less than the measured power in the region preceding the obstacle.

By contrast, the DFT power image depicted in Figure 7.3.19 details only the power calculated from a DFT of 7 complete cycles of the most significant tone-burst within the measured signal. For this reason, the same ‘rippled’ effect described in the FFT power image can only be observed in a region of 3.5 acoustic wavelengths in width immediately prior to the obstacle. This is due to the fact that the algorithm written to undertake this procedure calculated the DFT from a time duration equivalent to 7 complete cycles at each point. Therefore, a propagating wavefront passing a point further than 3.5 acoustic wavelengths away from the scattering obstacle will complete 7 cycles before the bow of the scattered wave arrives back at the point to cause interference. In the region closer to the obstacle, interference will be present within the 7 cycle period. Overall, the image appears less influenced by interference patterns than the FFT equivalent.

Since the DFT is calculated from 7 cycles of the largest amplitude tone-burst within the time history, the image is not necessarily representative of the principal tone-burst particularly in the regions outside of the usual field boundaries. In these areas, it is conceivable that the amplitude of any scattered sound will be greater than that of the principal tone-burst, and hence the DFT will be calculated for the scattered sound tone-burst.

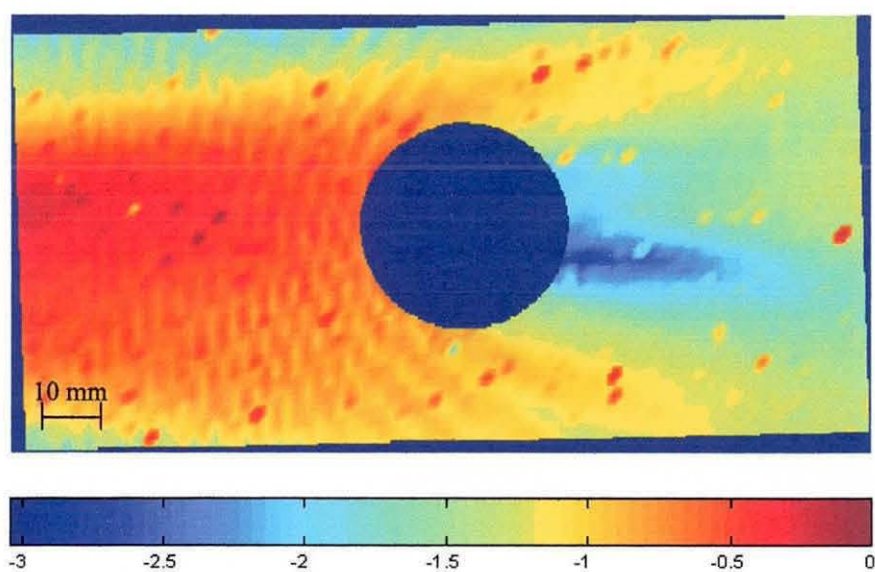


Figure 7.3.18: FFT Power image of 10 cycle, 180 kHz plane wave tone-burst incident on 40 mm diameter stainless steel ball bearing

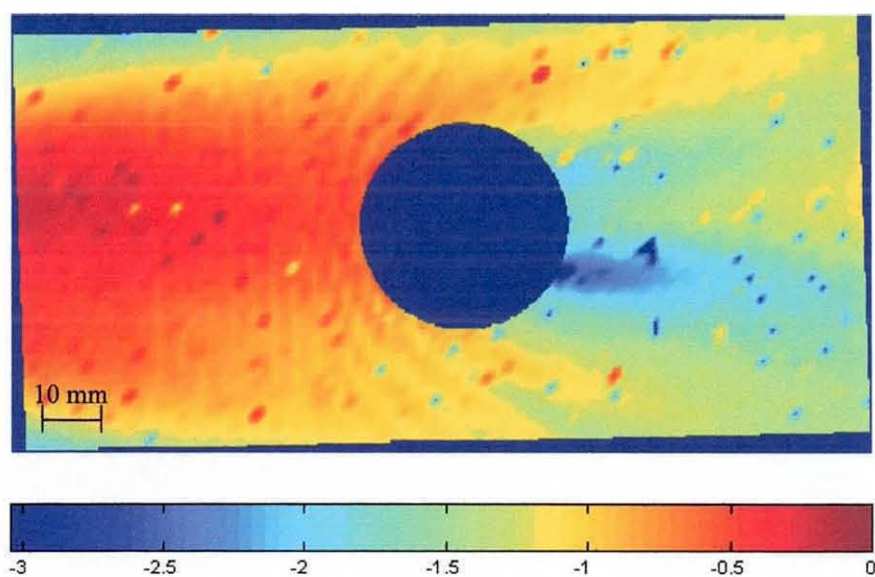


Figure 7.3.19: DFT Power image of 10 cycle, 180 kHz plane wave tone-burst incident on 40 mm diameter stainless steel ball bearing

An assessment of the spatial distribution of phase within the impeded field can be made from the FFT and DFT phase images depicted in Figure 7.3.20 and Figure 7.3.21. Each image represents the phase of the 180 kHz component of the measured rate of change of optical path length. Here, the FFT phase image shown in Figure 7.3.20 demonstrates a more consistent relationship than the DFT phase image of Figure 7.3.21. This is due to the fact that the entire signal, containing the principal tone-burst and reverberations of the source are combined with the scattered energy to calculate the phase. Despite the comparatively low signal amplitudes in the region beyond the obstacle observed in the power images, the number of cycles contained within the time history is sufficient to provide sufficient magnitude at 180 kHz when combined for a realistic phase to be calculated. In the DFT image, however, the restricted number of cycles used to calculate the phase causes the result to be subject to a greater uncertainty, indicated by the apparent lack of continuity observed in the same region in Figure 7.3.21.

The images generated from the field impeded by the ball bearing demonstrate the ability of a scanning LDV system to monitor the scattering of an acoustic tone-burst by an obstacle. However, given the nature of the scattering from the sphere in 3-dimensions, the majority of the acoustic energy will be travelling in a direction other than the normal to the laser beam, where the sensitivity of the system is maximised. Additionally, in the arrangement used a significant proportion of the acoustic tone-burst was not impeded by the obstacle, since the diameter of the field was larger than that of the ball bearing. This is evident in the images where the continuation of the planar tone-burst to the right of the obstacle can be clearly seen.

Whilst an appreciation of the shape and form of the scattered field can be gleaned from the results of this study, the combination of factors described means it is extremely difficult to obtain a quantitative measure of the scattered field strength within the field. Given that the laser beam from the LDV measures an integration of the refractive index change along its length, an arrangement whereby the predominant acoustic scattering was in a direction perpendicular to the laser beam incidence, would enable more refined measurements to be made.

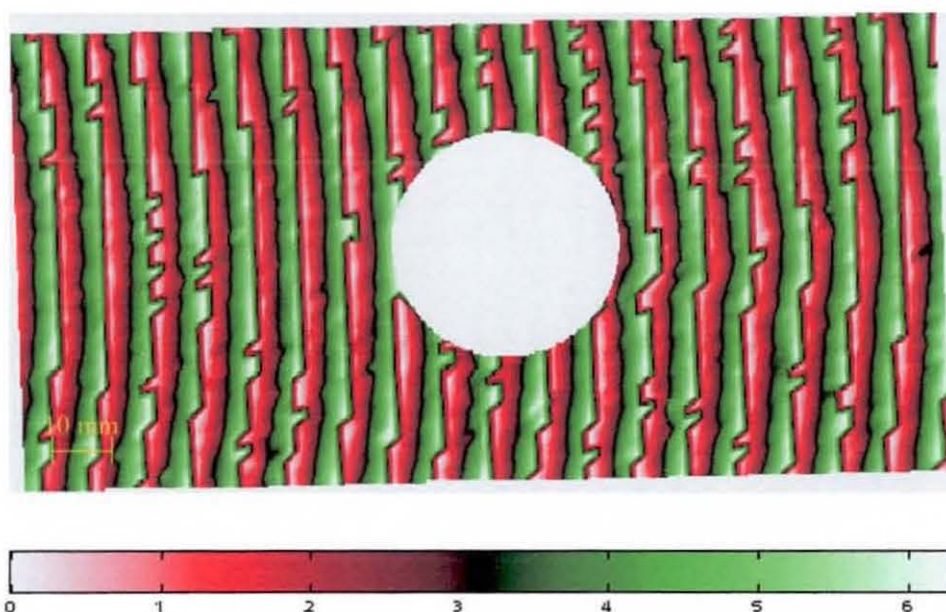


Figure 7.3.20: FFT Phase image of 10 cycle, 180 kHz plane wave tone-burst incident on 40 mm diameter stainless steel ball bearing

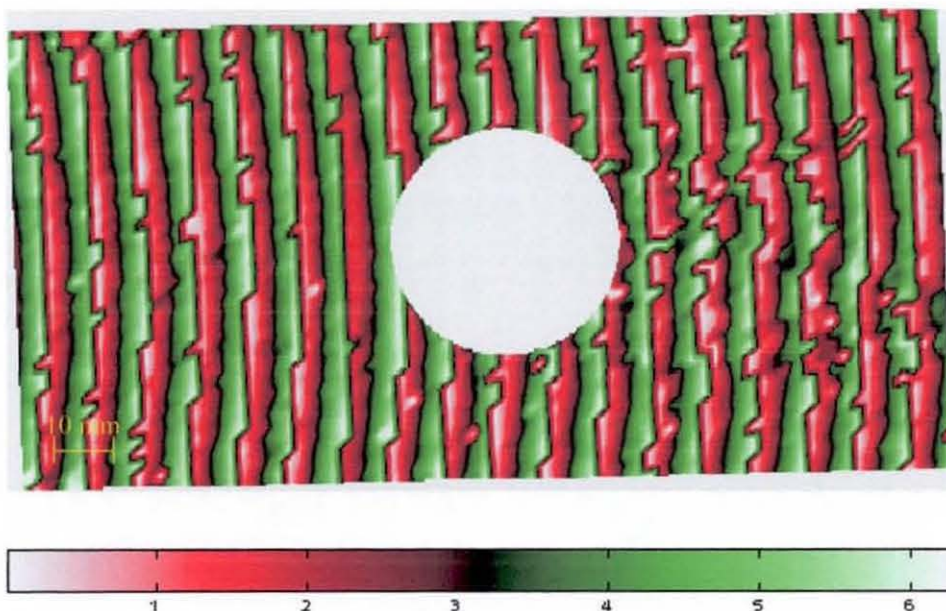


Figure 7.3.21: DFT Phase image of 10 cycle, 180 kHz plane wave tone-burst incident on 40 mm diameter stainless steel ball bearing

This was achieved by replacing the 3-dimensional scattering obstacle with one which offered a more 2-dimensional impedance. Cylinders, suspended with their axes parallel to the direction of the laser beam, were chosen to represent the scattering of a sphere at normal incidence along their entire length. Cylinders were also used in the investigations of Faran [61]. In each measurement case, whilst the lengths of the cylinders were not infinite, they were sufficient to protrude outside the boundaries of the field at each side. It was assumed that acoustic energy was incident only on the curved surfaces of each cylinder.

7.3.3.2 Steel Bar of 3 mm diameter

A 3 mm diameter steel bar was suspended in the field using thin wire, such that its major axis lay parallel to the direction of the laser beam. The 180 kHz planar acoustic tone-burst was generated by the source positioned approximately 100 mm from the cylinder. The various components were aligned such that the acoustic field was directed perpendicular to both the laser beam and the cylinder.

A time history of the rate of change of optical path length was recorded at 4134 target grid positions. Again, the duration of the time history was specified as 102.4 μs . with a resolution of 0.1 μs . Three time-sliced images are presented in Figure 7.3.22, depicting the acoustic tone-burst at three discrete time instants. With reference to the various images of Section 6.3.2, where the unimpeded field from a plane piston source was interrogated, it might be concluded that the shape and amplitude of the propagating acoustic tone-burst remains unaffected by the presence of the 3 mm bar. However, the image of Figure 7.3.22 (c) depicts a number of concentric acoustic pressure waves emanating from the bar, suggesting that energy is lost from the principal beam through scattering from the obstacle. It is suggested that this scattering of acoustic energy occurs throughout the duration of the tone-burst, but due to the low amplitude of the scattered waves by comparison with the principal tone-burst, their presence can not be identified in the time-resolved images until the principal tone-burst has passed.

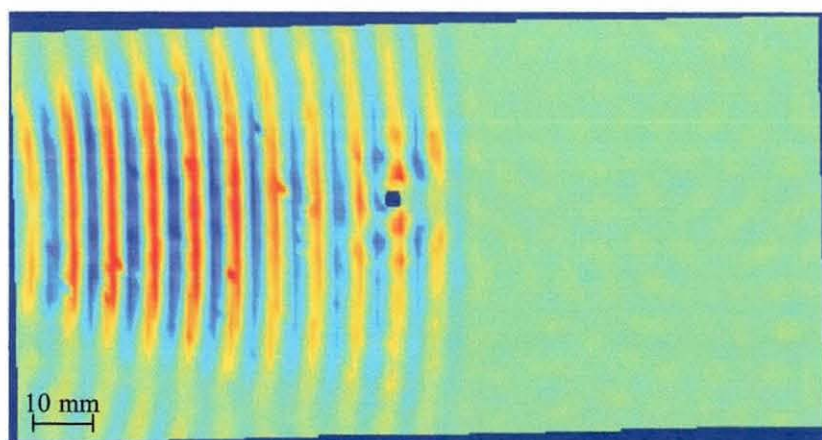


Figure 7.3.22 (a): $t = 7.5 \mu\text{s}$

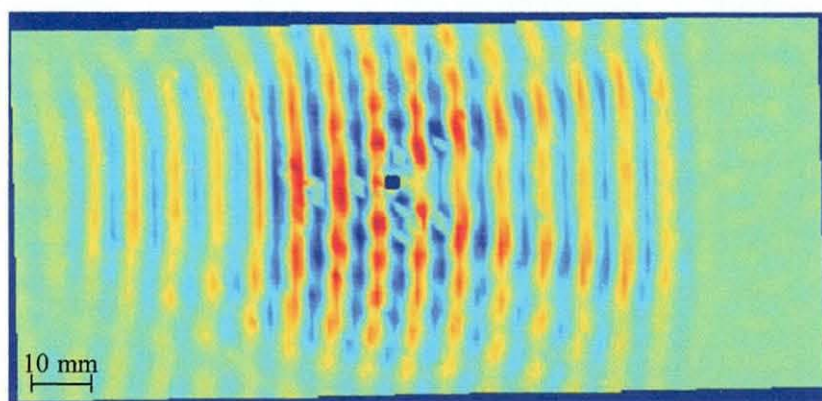


Figure 7.3.22 (b): $t = 20.0 \mu\text{s}$

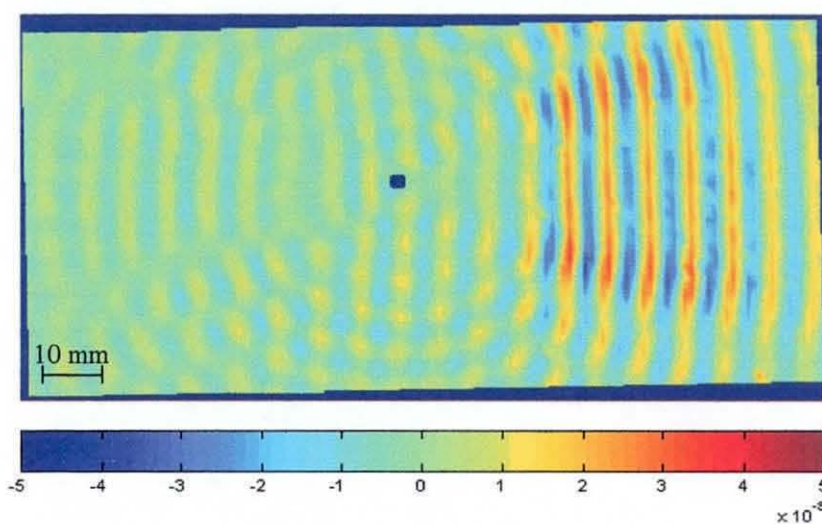


Figure 7.3.22 (c): $t = 30.0 \mu\text{s}$

Figure 7.3.22: 180 kHz plane wave tone-burst incident on 3 mm diameter cylindrical steel bar at three time instants (m/s)

One possible method of visualising the scattered wave in time would be to subtract the rate of change of optical path length measured at each target position in an impeded field from the equivalent data recorded from an unimpeded field. In this way, differences between the two sets of data, such as the scattered wave, could be identified. Such a procedure would be reliant on the scanning head and acoustic source being situated in identical positions. This process has not been investigated further due to the limited time available for this work.

The simplest method of identifying the presence of scattered energy is to examine the FFT and DFT power and phase images. The FFT image depicted in Figure 7.3.23, which represents the 180 kHz component of the principal tone-burst and any scattered components, demonstrates the refraction effects caused by the obstacle. The acoustic power distribution is high in the region to the left of the obstacle and in a number of 'streams' passing either side of the bar at increasingly diverging angles. Another important feature of the image is the interference patterns evident throughout the field. These are particularly apparent in areas of low acoustic 'power' such as the region immediately beyond the bar. Here a diagonal pattern of interference can be clearly observed.

The DFT image depicted in Figure 7.3.24, which represents the 180 kHz component of only the principal tone-burst, demonstrates the influence of the obstruction of the distribution of the principal acoustic power. The image contains less of the interference contained throughout the FFT image, but retains the general shape of the distributed power. A certain amount of what might be described as 'streaming' is observed, where discrete bands of power appear to flow around the obstruction, although, as was discussed in Section 7.3.3.1, the principal tone-burst signal recorded at positions close to the obstacle will also be influenced by reflected components.

The FFT and DFT Phase images are depicted in Figure 7.3.25 and Figure 7.3.26 respectively. Each image demonstrates the dominance of the principal planar tone-burst in establishing the 180 kHz phase distribution. However, a more circular pattern can be observed in the top and bottom corners of the extreme left of the FFT

image. This represents the areas where the influence of the scattered pressure wave becomes greater than that of the principal tone-burst.

In addition to the reflected component of the acoustic wave, consideration is given to the component transmitted into the bar at the water/steel boundary. A proportion of this transmitted wave is then reflected at the steel/water boundary at the far side of the bar, whilst the remainder is transmitted back into the water. Given the fact that the speed of sound in steel, ($c_{steel} = 5050$ m/s [38]) is much greater than that in water ($c = 1471.1$ m/s at 16.5 °C), the acoustic wave which has passed through the bar and returned to the water would be expected to propagate in advance of the remainder of the acoustic wave. The distance by which this component of the wave leads, d_{lead} , the remainder can be calculated by determining the time taken, t_{bar} , for the acoustic wave to travel through the steel bar with diameter, d_{bar} ,

$$d_{lead} = d_{bar} - c t_{bar} = d_{bar} \left(1 - \frac{c}{c_{steel}} \right) \quad (7.3.1)$$

For the 3 mm diameter steel bar, d_{lead} , is calculated to be 2.13 mm, which corresponds to a phase difference of 0.51π for a 180 kHz acoustic wave in water. This distance is clearly very small with respect to the dimensions of the scanning region, and as such, it is impossible to identify this lead in either of the phase distribution images given in Figure 7.3.25 and Figure 7.3.26. Consequently, it cannot be concluded that the transmitted component of the signal is of significant amplitude to be detected by the scanning LDV system.

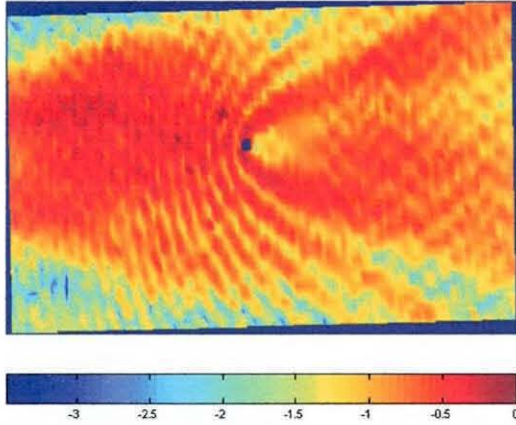


Figure 7.3.23: FFT Power image of 10 cycle, 180 kHz plane wave tone-burst incident on 3 mm diameter cylindrical steel bar

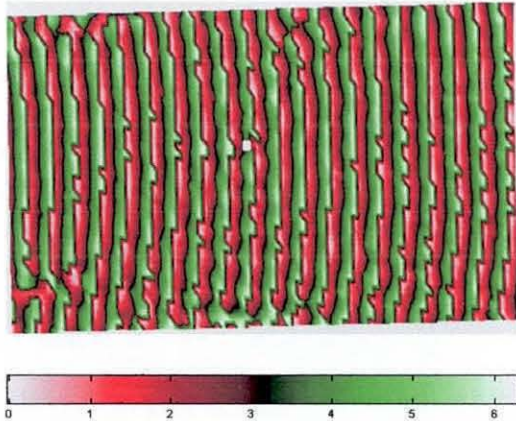


Figure 7.3.25: FFT Phase image of 10 cycle, 180 kHz plane wave tone-burst incident on 3 mm diameter cylindrical steel bar

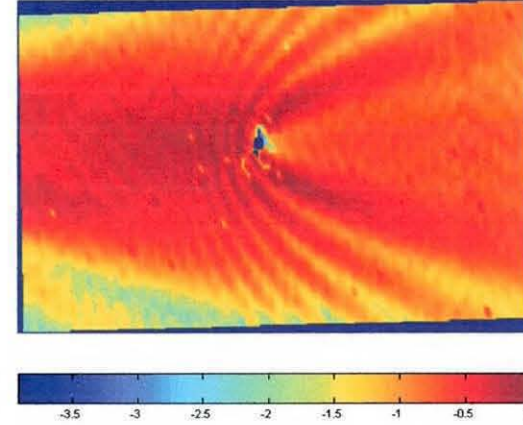


Figure 7.3.24: DFT Power image of 10 cycle, 180 kHz plane wave tone-burst incident on 3 mm diameter cylindrical steel bar

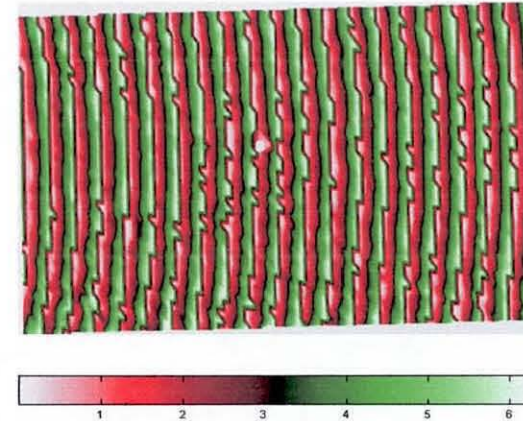


Figure 7.3.26: DFT Phase image of 10 cycle, 180 kHz plane wave tone-burst incident on 3 mm diameter cylindrical steel bar

7.3.3.3 Steel Bar of 9 mm diameter

A 9 mm bar was chosen as an example of an obstruction with a similar dimension to the acoustic wavelength. This was calculated to be 8.17 mm at a depth of 0.1 m and a temperature of 16.5 °C using Coppens mathematical approximation [3]. The bar was suspended using thin wire and positioned orthogonal to the direction of travel of the acoustic tone-burst. The bar was sufficiently long to protrude beyond the boundaries of the field both toward and away from the LDV scanning head. A measurement of the rate of change of optical path length was recorded at 3797 discrete target positions, each for a duration of 102.4 μ s with a resolution of 0.1 μ s.

Three images representing the rate of change of optical path length are depicted in Figure 7.3.27, where the magnitude and position of both the principal tone-burst and any scattered components can be visualised at a particular time instant. The times at which each image was recorded, triggered from the input to the acoustic source were (a) $t_1 = 20.8 \mu$ s, (b) $t_2 = 30.0 \mu$ s and (c) $t_3 = 37.0 \mu$ s.

From this series of images the presence of scattered acoustic signal can be established. The magnitude of the rate of change of optical path length measured at positions of equal phase approaching the obstruction in (a) was observed to be consistent to within $\pm 0.5 \times 10^{-5}$ m/s. However, in image (b) the magnitude was observed to reduce by up to 3×10^{-5} m/s in the region immediately prior to the obstruction in the x -direction. This illustrated interference between the scattered sound and the principal tone-burst prior to its incidence with the obstruction. The presence of scattered components was clearly evident in image (c), where concentric rings of the scattered pressure wave can be observed particularly in the region of the image to the left of the obstruction. The wavelength of the scattered sound in the image was measured to be 8 mm, indicating the frequency of the scattered sound is approximately equal to that of the principal tone-burst.

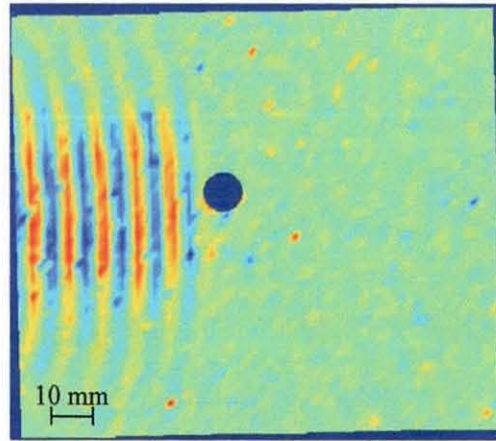


Figure 7.3.27 (a): $t_1 = 13.0 \mu\text{s}$

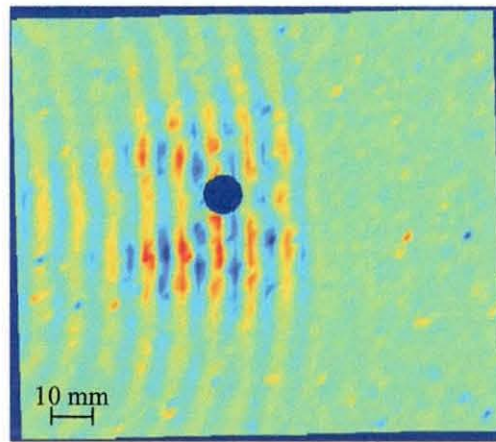


Figure 7.3.27 (b): $t_2 = 20.8 \mu\text{s}$

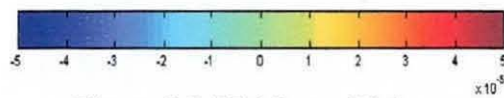
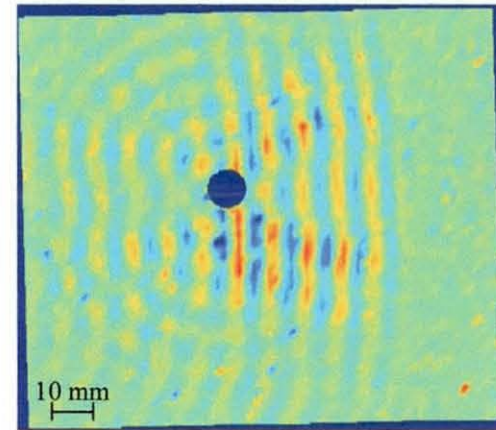


Figure 7.3.27 (c): $t_3 = 30.0 \mu\text{s}$

Figure 7.3.27: 180 kHz plane wave tone-burst incident on 9 mm diameter cylindrical steel bar at three time instants (m/s)

The power and phase distribution images confirmed the presence of scattered acoustic components within the field. Again the FFT images enabled the interference between the principal tone-burst and scattered sound to be visualised, most notably in the ‘rippling’ observed in the power image, depicted in Figure 7.3.28 and the combination of the planar phase distribution of the principal tone-burst with the circular pattern of the scattered sound, depicted in Figure 7.3.30. The power within the region immediately beyond the bar in the x -direction was shown to reduce by up to 1 order of magnitude with respect to the power observed in the region to the left of the obstruction.

The DFT power image shown in Figure 7.3.29 depicts less of a reduction in power within the region beyond the bar. Here the power of the principal tone-burst was observed to reduce by half an order of magnitude with respect to that observed in the region to the left of the obstruction. The presence of a significant amount of noise generated by the imperfect reflective target reduced the visual clarity of the DFT phase image, although the general distribution without the influence of any scattered components can be observed. Other causes of the increase in noise within the measurement include poor focusing of the laser beam on the target. Apparent inconsistencies exist in the phase measured outside of the boundaries of the field, which can be observed in Figure 7.3.31, although it should be stressed that in these regions the signal amplitude was sufficiently small for these to be immaterial.

When considering the component of the acoustic tone-burst transmitted through the steel bar, similar calculations to those described in Section 7.3.3.2 were undertaken. For a steel bar of 9 mm diameter, the transmitted acoustic component would be expected to lead the remainder of the planar wave by a distance of 6.34 mm, equivalent to a phase lead of 1.55π for a 180 kHz acoustic wave in water. In the FFT and DFT phase images depicted in Figure 7.3.30 and Figure 7.3.31 an inconsistency in the phase can be observed in the region to the right of the bar. This inconsistency might be interpreted either as a lead of approximately 1.5π or a lag of 0.5π . Unfortunately, the amplitude of the transmitted signal is too small to be easily identified in the time resolved images given in Figure 7.3.27, hence a definitive statement of the nature of the field in this region cannot be made.

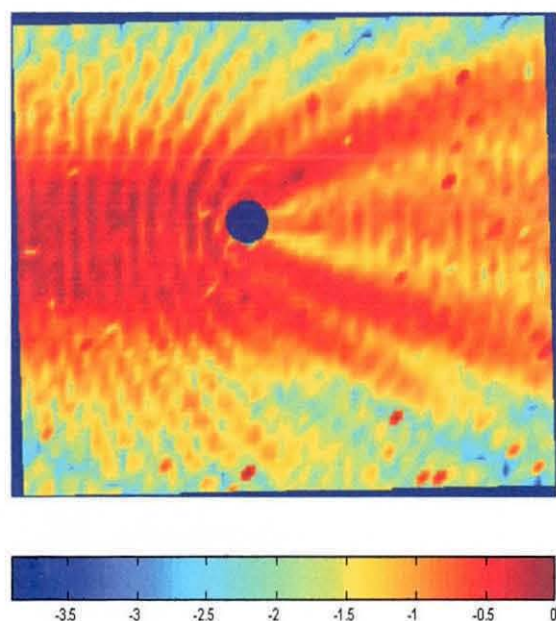


Figure 7.3.28: FFT power distribution image of 10-cycle, 180 kHz plane wave incident on 9 mm bar

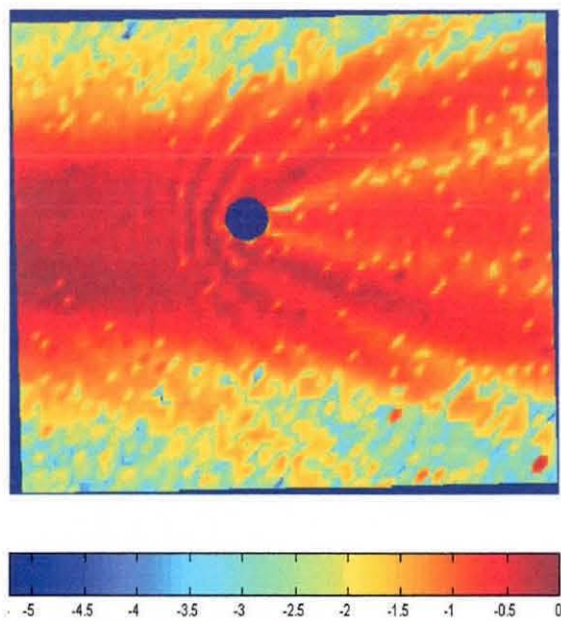


Figure 7.3.29: DFT power distribution image of 10-cycle, 180 kHz plane wave incident on 9 mm bar

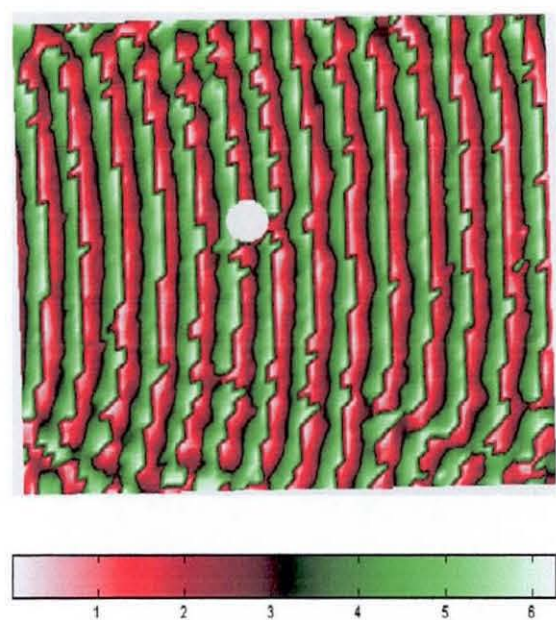


Figure 7.3.30: FFT phase distribution image of 10-cycle, 180 kHz plane wave incident on 9 mm bar

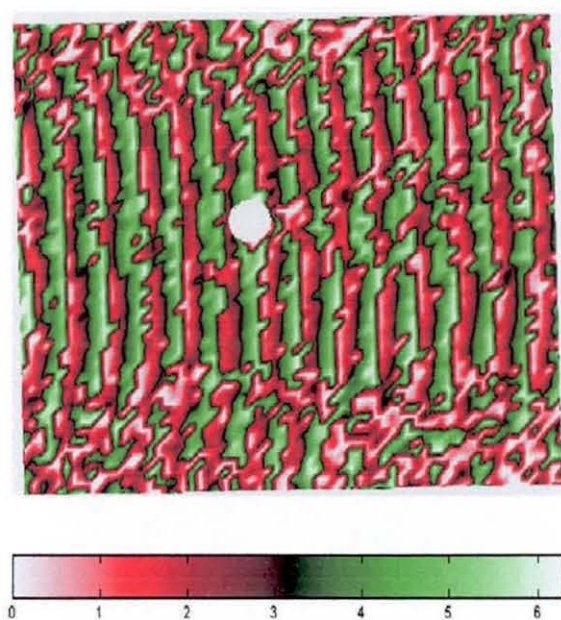


Figure 7.3.31: DFT phase distribution image of 10-cycle, 180 kHz plane wave incident on 9 mm bar

7.3.3.4 Steel Bar of 15 mm diameter

The same procedure was followed in recording measurements of the acoustic scattering caused by the presence of a 15 mm bar within the field. This bar represented an obstruction with dimension greater than the acoustic wavelength.

Images representing the rate of change of optical path length at three instants in time are depicted in Figure 7.3.32. The instants represented were as follows; (a) $t_1 = 13.0 \mu\text{s}$, (b) $t_2 = 20.8 \mu\text{s}$ and (c) $t_3 = 30.0 \mu\text{s}$. The presence of scattered acoustic components can be observed in each of the images shown. Image (a) depicts interference in the region immediately prior to the obstruction when only 2 cycles have passed the front edge of the bar. This interference becomes more evident in image (b) where a complex interference pattern can be observed. Regions of increased and decreased amplitude can be seen with recurring periodicity such that if lines connecting areas of equal phase were to be drawn, these might run in either of two possible directions, given by the principal tone-burst or the scattered sound. Image (c) depicts a similar pattern to that observed for each of the previous cylindrical obstructions where two series of pressure waves can be observed, one representing the principal tone-burst and the other the signal scattered by the bar.

The FFT and DFT images of power and phase are shown in Figure 7.3.33, Figure 7.3.34, Figure 7.3.35 and Figure 7.3.36. The influence of the obstructing 15 mm bar is clearly evident in the FFT power image from the rippled effect observed throughout the field and the significant reduction in power measured in the region immediately to the right of the obstruction, where the power is generally 2 orders of magnitude less than that in the region prior to the bar. The FFT phase image demonstrates the combined effect of the planar distribution of the principal tone-burst and circular distribution of the scattered wave.

The DFT power image demonstrates the distribution of the energy within the principal tone-burst without the presence of any reflections. The 15 mm bar can be shown to have a dramatic effect on the propagating tone-burst, where the minimum power in the region immediately beyond the bar is 3 orders of magnitude less than that measured in the region to the left of the obstruction.

Consideration was also given to the component of the acoustic tone-burst transmitted through the 15 mm steel bar. Calculations to establish the position distance of the transmitted wave suggest that it would lead that remainder of the acoustic tone-burst by 10.63 mm. This corresponds to a phase lead of 2.6π for a 180 kHz acoustic wave in water. Again a discrepancy in the phase continuity can also be observed in the region to the right of the bar in the FFT and DFT phase distribution images depicted in Figure 7.3.35 and Figure 7.3.36. However, the observed discrepancy is not equal to that calculated from the theory of the transmitted wave. An alternative theory is proposed from the time resolved images shown in Figure 7.3.32, where the diffractive effects of the principal tone-burst incident on the bar cause the direction of the acoustic propagation to change in this region. The diffracted acoustic waves dominate the interference pattern caused in the region to the right of the bar, overshadowing the influence of the transmitted signal. It might, therefore, be concluded that the signal transmitted through the steel bar is of insufficient strength to influence the field in the region to the right of the bar. The influence of the diffracted acoustic wave offers an explanation for the phase discontinuities observed in the measured fields obstructed by 3 mm and 9 mm bars.

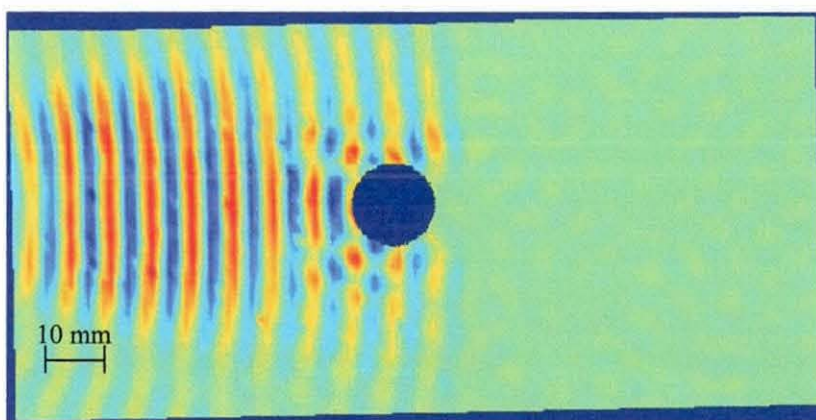


Figure 7.3.32 (a): $t_1 = 13.0 \mu\text{s}$

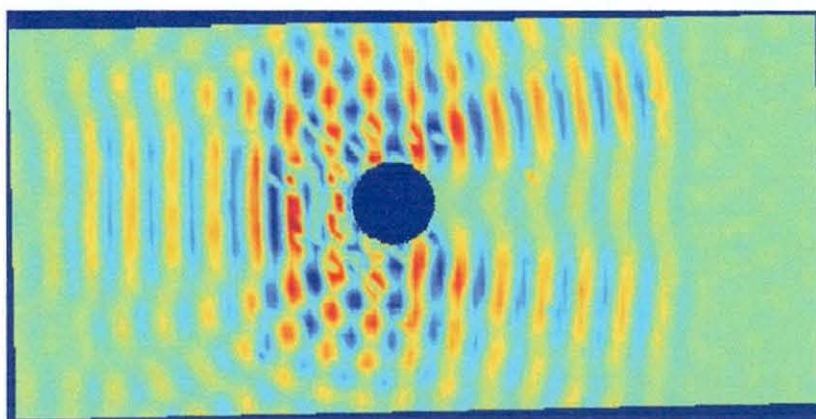


Figure 7.3.32 (b): $t_2 = 20.8 \mu\text{s}$

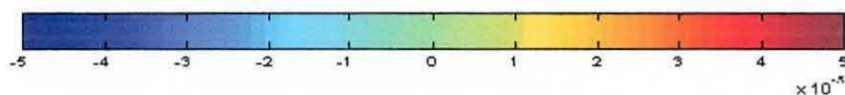
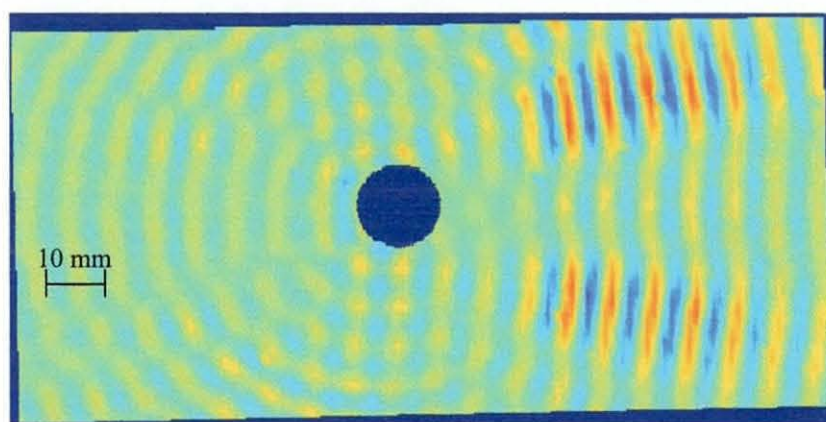


Figure 7.3.32 (c): $t_3 = 30.0 \mu\text{s}$

Figure 7.3.32: 180 kHz plane wave tone-burst incident on 15 mm diameter cylindrical steel bar at three time instants (m/s)

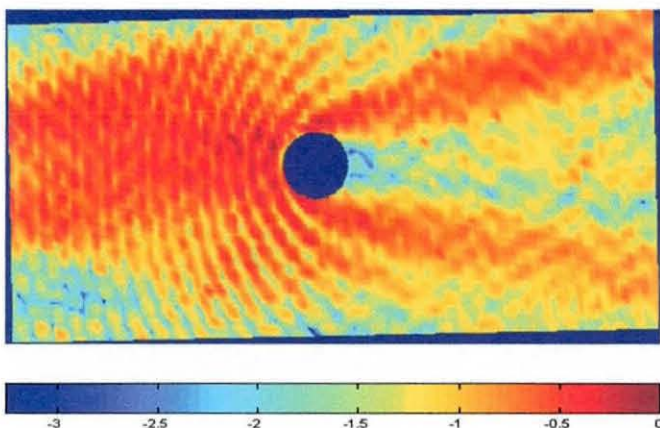


Figure 7.3.33: FFT Power image of 10 cycle, 180 kHz plane wave tone-burst incident on 15 mm diameter cylindrical steel bar

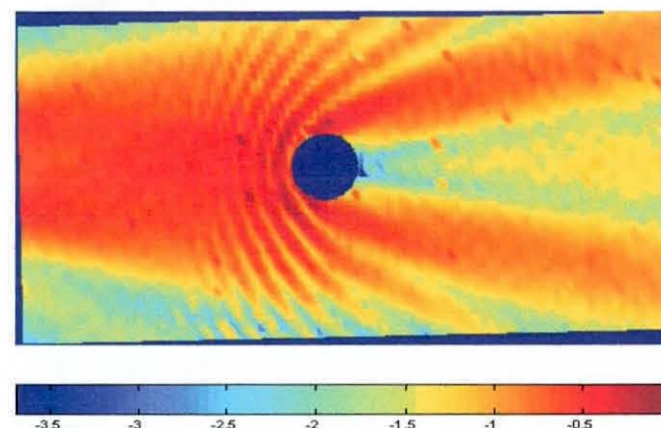


Figure 7.3.34: DFT Power image of 10 cycle, 180 kHz plane wave tone-burst incident on 15 mm diameter cylindrical steel bar

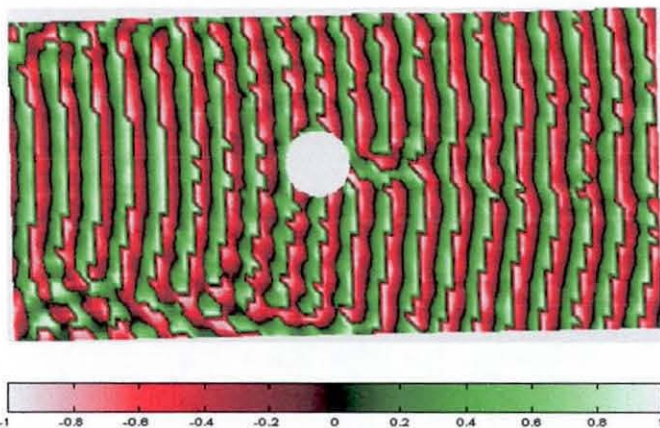


Figure 7.3.35: FFT Phase image of 10 cycle, 180 kHz plane wave tone-burst incident on 15 mm diameter cylindrical steel bar

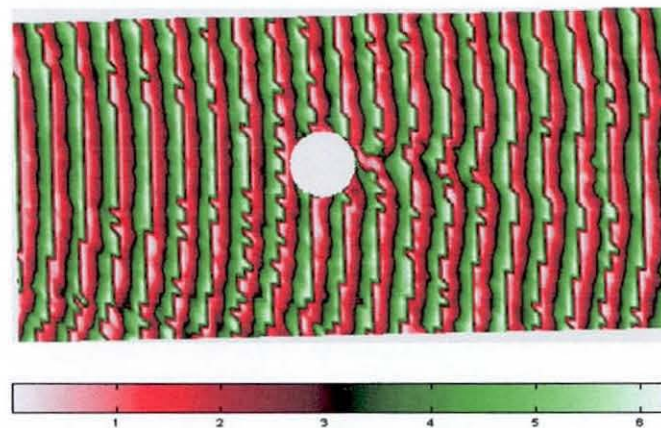


Figure 7.3.36: DFT Phase image of 10 cycle, 180 kHz plane wave tone-burst incident on 15 mm diameter cylindrical steel bar

7.3.3.5 Hollow Aluminium Tube of 12 mm diameter

In addition to the interrogation of acoustic fields impeded by solid cylindrical scatterers, attention was given to scattering by a hollow aluminium cylindrical scatterer. Again the obstruction was sufficiently long for each end to protrude beyond the radial boundaries of the field. Measurements of the rate of change of optical path length were recorded at 4242 discrete target positions for a duration of 102.4 μs with a resolution of 0.1 μs . Three images are presented in Figure 7.3.37, depicting the tone-burst at three time instants; $t_1 = 13.0 \mu\text{s}$ in (a), $t_2 = 20.8 \mu\text{s}$ in (b) and $t_3 = 30.0 \mu\text{s}$ in (c).

The principal acoustic tone-burst used was identical in frequency and amplitude to those generated in the interrogation of solid bar experiments. It is significant therefore, that the colour amplitude scale used for the time-resolved images depicted in Figure 7.3.37 was required to be increased by 50% from that used for the equivalent images from the solid bar experiments. This was necessary to cater for the magnitude of the regions of constructive interference between the principal tone-burst and scattered sound. This suggests that the strength of the signal scattered from the 12 mm aluminium tube is greater than that of the signal scattered by the 15 mm solid steel bar.

It is known that an acoustic wave incident on a boundary between one medium and another will generate a reflected and a transmitted wave [38]. Given the presence of two such boundaries, the water/aluminium of the outer diameter of the tube and the aluminium/water of the inner diameter, it may be argued that the overall reflected component of the acoustic wave is increased. It is concluded, therefore, that the required increase in the measurement range compared to the steel bar obstructions is due to the difference in material and construction of the obstacle. The speed of sound in aluminium is 6,300 m/s [38], which means that sound transmitted at the first interface and reflected at the second will return to the first interface, a total distance of 4 mm, after 0.63 μs . In this time the sound in water will have travelled ≈ 0.9 mm resulting in a minimal phase difference between the recombining waves.

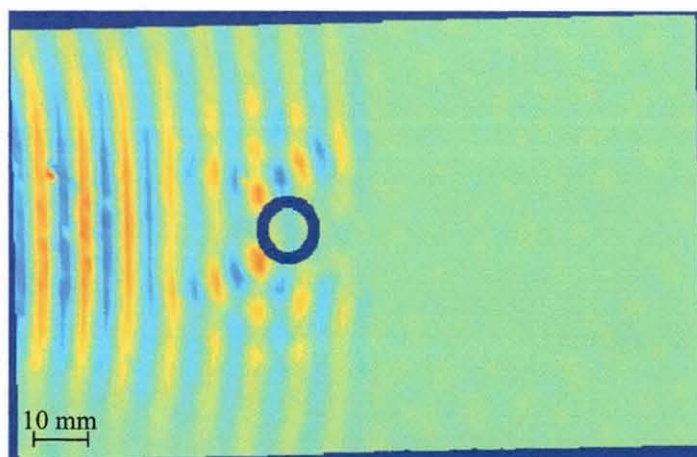


Figure 7.3.37 (a): $t_1 = 13.0 \mu\text{s}$

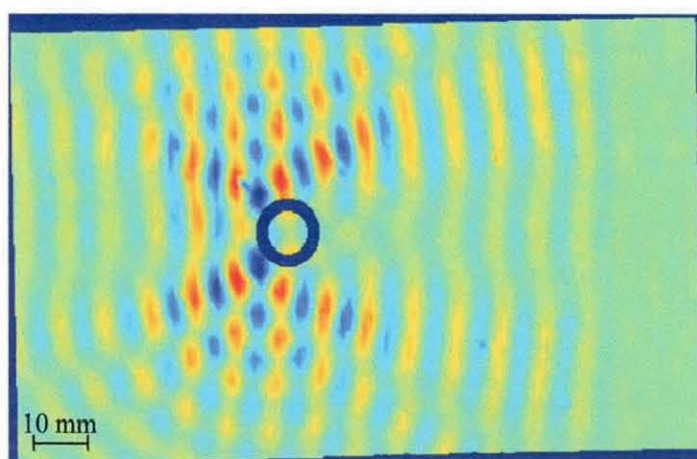


Figure 7.3.37 (b): $t_2 = 20.8 \mu\text{s}$

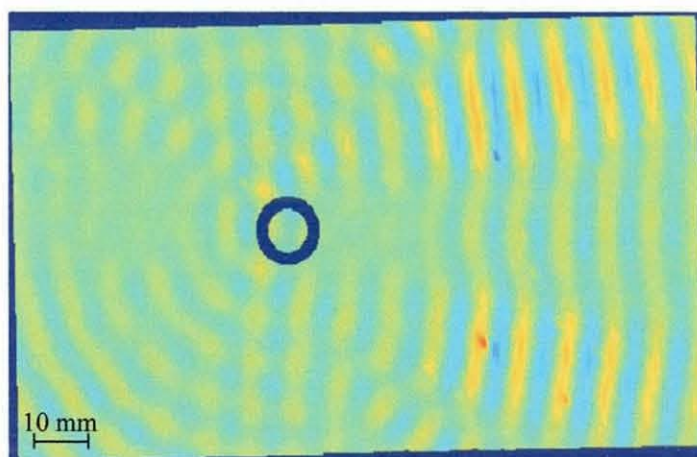


Figure 7.3.37 (c): $t_3 = 30.0 \mu\text{s}$

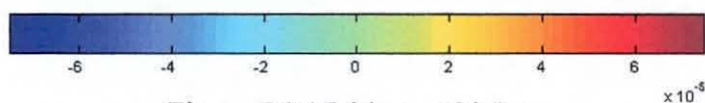


Figure 7.3.37: 180 kHz plane wave tone-burst incident on 12 mm diameter hollow cylindrical aluminium tube at three time instants

This study also offered the opportunity to study the acoustic propagation through the water within the centre of the tube. In each of the images depicted, continuity between positions of equal phase is observed to extend through this region, suggesting that a proportion of the acoustic energy is transmitted through the aluminium and into the water behind. A closer examination of this region might enable the position in space of the wavefront to be found to be ahead of those external to the tube, due to the increased sound speed in the aluminium. However such a conclusion cannot be drawn from the images presented in Figure 7.3.37.

The FFT images enabled the presence of reflected signal components to be confirmed in a similar manner to the equivalent images from the bar experiments. Interference patterns were observed throughout the power distribution image depicted in Figure 7.3.38, in addition to the ‘rippling’ and streaming in the regions preceding and surrounding the obstruction. The power within the region immediately beyond the obstruction was measured to be approximately 2 orders of magnitude lower than the power in the region immediately prior to the obstruction. The phase distribution depicted in Figure 7.3.40 was also consistent with that of a field including scattered energy, combining the planar shape of the principal tone-burst with the circular shape of the scattered wave.

The DFT images demonstrated similar phenomena to those observed in the other images, illustrating the presence of influence of scattered acoustic waves. The acoustic power in the region immediately beyond the obstruction was measured to be 3 orders of magnitude lower than that measured in the region prior to the tube, as depicted in Figure 7.3.39. The DFT phase image depicted in Figure 7.3.41 illustrated the planar distribution of phase throughout the field.

An examination of the phase in the region to the right of the bar again shows inconsistencies, as can be observed in Figure 7.3.40 and Figure 7.3.41. However, in this case it might be argued that the influence of the acoustic wave transmitted through the aluminium is greater than was the case with the steel bars through close scrutiny of the time-resolved image shown in Figure 7.3.37 (a). Here, a faint region depicting the first positive rate of change of optical path length of a propagating

tone-burst can be identified at a position ahead of the remainder of the field. This, combined with the increased amplitude of the rate of change of optical path length measured within the scattered field, suggests the influence of the scattered acoustic signal is greater for the case of the aluminium tube than the steel bar. Two potential suggestions are proposed for this observed difference; the difference in properties of aluminium and steel or the difference in geometric shape between the tube and the bar. Neither of these proposals can be definitively proved or disproved by the results of this study.

A comprehensive theoretical study of the relative strengths of reflected and transmitted acoustic signals from different material solid surfaces is presented by Kinsler *et al.* [38]. Whilst the exact experimental scenario described here is not discussed, consideration is given to the reflection and transmission of acoustic waves normally incident on a solid surface. An extension of this theory might enable the scattered acoustic field in the region beyond an obstruction to be understood.

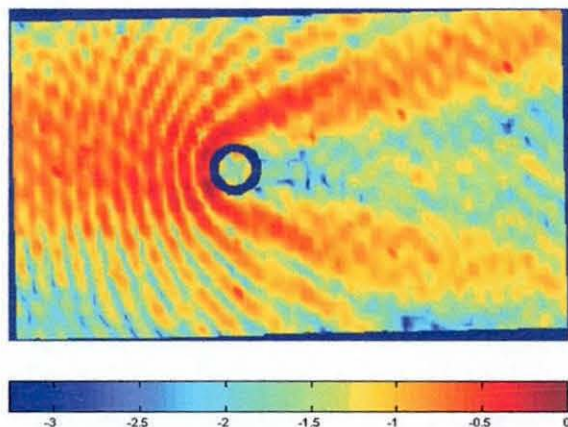


Figure 7.3.38: FFT Power image of 10 cycle, 180 kHz plane wave tone-burst incident on 12 mm diameter hollow aluminium tube

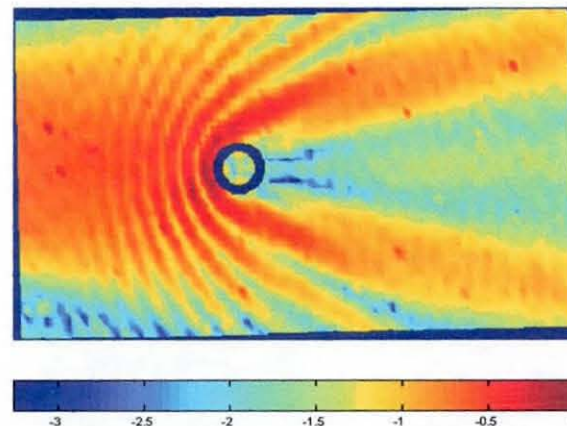


Figure 7.3.39: DFT Power image of 10 cycle, 180 kHz plane wave tone-burst incident on 12 mm diameter hollow aluminium tube

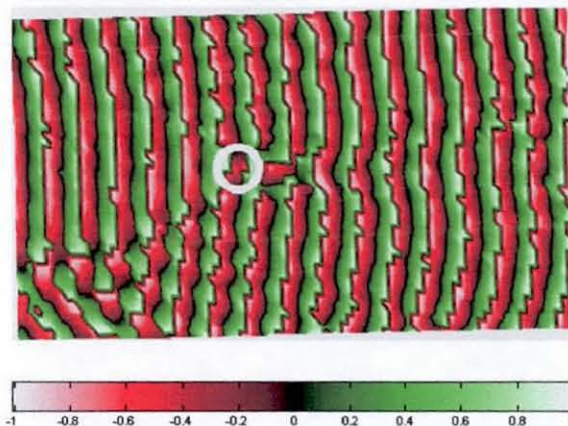


Figure 7.3.40: FFT Phase image of 10 cycle, 180 kHz plane wave tone-burst incident on 12 mm diameter hollow aluminium tube

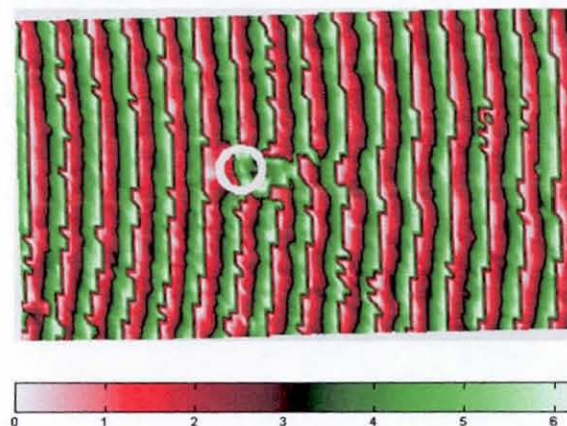


Figure 7.3.41: DFT Phase image of 10 cycle, 180 kHz plane wave tone-burst incident on 12 mm diameter hollow aluminium tube

7.4 CLOSURE

The work described in this chapter has successfully demonstrated the ability of the scanning LDV system to characterise scattered fields in detail. The excellent spatial and temporal resolution of the technique enable exceptionally detailed field reconstruction images to be generated. From these, a range of details and features of scattered fields can be identified.

Measurements recorded over a relatively large scanning area and temporal duration have enabled the components of the acoustic field reflected from the tank walls and the water surface to be monitored. In the experimental case presented, the interference caused by the components reflected from the floor and ceiling of the water were observed to be appreciable. The high coefficients of reflectivity of water/air and water/glass interfaces were significant factors in obtaining these results.

The scanning LDV technique has also been applied to investigate the perturbing influence of devices designed to be submerged in the field in order to record measurements of pressure. Measurements from tone-bursts at three frequencies demonstrated the general relationship of increased perturbation with increased frequency. The results demonstrated the negligible influence of the 7.9 mm diameter hydrophone at 250 kHz, although at 500 kHz and more drastically at 800 kHz, field perturbation was evident. Given that the hydrophone had a resonance at 550 kHz and was recommended for use in the frequency range 200 – 600 kHz, the evidence of field perturbation at 500 kHz was significant.

The perturbing influence of the pellicle was demonstrated to be minimal in the experimentation reported here. It was noted, however, that this conclusion was facilitated by the fact that the acoustic field used passed entirely through the centre of the aluminium annulus. It was anticipated that the incidence of an acoustic field on the aluminium annulus would generate scattered components and thus perturb the field.

In addition to the measurements made from fields where reflected and scattered acoustic components were undesirable, the scanning LDV system proved extremely effective in interrogating field scattering induced by rigid body obstructions, including a metallic sphere and a series of metallic cylinders. The subtle differences between the FFT and DFT data presentation were found to be of great benefit in identifying particular features of the scattered fields. The FFT was effective in gauging the extent of the scattering, whilst the DFT enabled the principal tone-burst to be observed in more detail. Consideration was also given to the theoretical propagation of sound through the obstruction, although in practice the influence of this transmitted sound was observed to be minimal.

The system was shown to be more effective in recording measurements from fields scattered by a cylinder rather than a sphere, due to the increased path length over which the refractive index changes were integrated.

Chapter 8

Conclusions

It can be concluded from this thesis that non-perturbing quantitative measurements of underwater acoustic fields can be made using the beam from a Laser Doppler Velocimeter. The instrument has been successfully demonstrated to accurately record the pressure induced refractive index changes with time along a finite line section of very small diameter (< 1 mm). This represents a novel development within the sphere of underwater acoustic measurements.

The highly innovative development of Laser Doppler Velocimetry as a non-perturbing tool for recording measurements from spatially and temporally distributed acoustic fields has enabled fields to be interrogated in multiple dimensions in rapid time. This is manifest by the extensive series of experimental interrogations presented in this work, which describe acoustic fields in 1 temporal and 2 spatial dimensions.

The development of this technique sits within the context of the conclusions drawn from the extensive review of relevant literature presented in Chapters 1 and 2, that there is a need for the development of advanced optical measurement techniques for use in underwater acoustic measurement scenarios. For instance, advances in the application of acoustic based procedures within clinical medicine continue to stretch the limitations of existing measurement and calibration methods. An inability to accurately characterise the field generated in procedures such as extra-corporeal shock wave lithotripsy would lead to a genuine risk to patient health due to the exceptionally high shock wave amplitudes employed.

Many optical metrology methods have been employed to record underwater acoustic measurements although an extensive review of these, given in Chapter 2, demonstrates inherent flaws or drawbacks in each of the techniques. The theory and

experimentation described in this work enhances the capability of optical metrology methods in general to derive acoustic quantities in a non-invasive manner.

An extensive mathematical model has been developed to enable the passage of an LDV beam through an acoustic field to be analysed. The model is built on well established physical theory of acousto-optic interaction and developed to cater for the case of a heterodyne or velocity interferometer such as an LDV. The theory has been advanced to permit interrogation at any arbitrary angle of incidence between the optical and acoustic beams

Measurements of the rate of change of optical path length along a line section through a field recorded by an LDV system have been demonstrated to exhibit excellent similarity in shape, duration and frequency content, with measurements of pressure recorded using a calibrated hydrophone from the same field. This method has proved to be effective at identifying the major temporal and spatial characteristics of both acoustic standing waves and tone-bursts. Indeed, in certain circumstances, measurements recorded using the beam of an LDV exhibit reduced noise and fewer spurious terms than their hydrophone equivalents.

For a particular line section through an 80 kHz acoustic tone-burst, agreement between the LDV measurement and the equivalent rate of change of optical path length derived from discrete pressure measurements along the line was within 5 dB. This discrepancy increased to 20 dB for measurements recorded at 500 kHz, but was attributed to the highly non-linear spatial pressure distribution generated by the focused transducer.

The minimum pressure amplitude required for a measurement to be made using the LDV was demonstrated to be lower than that required by the hydrophone for acoustic signals at both 80 kHz and 500 kHz. At 80 kHz, the LDV required a minimum pressure amplitude of 18.7 mPa compared to 46.8 mPa required by the hydrophone, whilst at 500 kHz, the LDV required a minimum pressure of 5.01 Pa compared to 19.46 Pa required by the hydrophone. The high level of variation across the bandwidth of the noise floor from each instrument required the development of a novel approach to derive the minimum resolvable signal. This was based around

defining a level, 4 standard deviations above the mean, as the minimum resolvable signal and proved to be an effective means of enabling the calculation to be completed.

The application of a scanning LDV system has been demonstrated to offer wide-ranging possibilities for the measurement of the spatial characterisation of an acoustic field. The ability of the scanning LDV system to rapidly record data from a series of discrete line sections through the field was a significant factor in the establishment of this method as a valuable tool for use in underwater acoustic measurement. It has been successfully demonstrated that the technique allows spatially resolved measurements to be made, which illustrate field components that have never previously been observed.

In addition to the novel manner in which measurements are recorded, unique mathematical processing techniques have been developed, which maximise the quantity and quality of information derivable from the measured data. In contrast to the conventional representation of acoustic signals on two-dimensional axes, imaging methods were proposed and successfully utilised to enable complex fields to be simply visualised. A series of specific image generation procedures were developed, each of which enabled a particular quantity of interest to be observed. These were extracted from both the temporal and frequency spectra of the measured data.

The extensive presentation of experimental results given in Chapter 5 and Chapter 6 demonstrate the capabilities of the scanning LDV technique to interrogate pulsed acoustic fields of different frequency, shape and duration. The resultant images enable the precise position in time and space of each of the tone bursts to be identified. Additionally, the power and phase distribution images allow the spatial distribution of the field to be clearly demonstrated.

Important distinctions were made between the methods of calculating the frequency spectra of the data recorded at each measurement position. The differences between the methods of calculating the FFT and DFT frequency spectra enabled further specific investigations of the spatial distribution of individual parameters to be

completed. The FFT data was shown to indicate the presence and influence of reflected, scattered or other spurious components within the field. Conversely, the DFT data was shown to be representative of the principal tone burst.

This difference was of particular importance in the interrogation of scattered fields presented in Chapter 7. Here the unique ability of the scanning LDV system to record information from both the principal tone-burst and the scattered field and represent them independently was demonstrated by the extensive range of experimental results. A plethora of different features were identified from each of the images, such that an understanding of the precise passage of an acoustic tone-burst through an obstructed volume was developed.

The LDV instruments used have been demonstrated to benefit from their inherently large bandwidths, which far exceed those of conventional resonant hydrophones. When applied to the measurement of acoustic tone-bursts this enables signals to exhibit minimal rise and fall transients before and after steady state acoustic conditions.

The fidelity of the velocity signal generated by the LDV system was confirmed through direct comparison with the NPL Laser Interferometer, the primary standard for underwater acoustic measurements in the frequency range 500 kHz to 20 MHz in the UK. Agreement between the two instruments was found to be within 4% and 7% for two drive voltages at an acoustic frequency of 500 kHz and 2.5% and 1% for the same two drive voltages at 1 MHz.

Assessment of the motion of the PVDF pellicle used as part of the current primary standard was undertaken when suspended in the field generated by a focused transducer at 1 MHz. The results of this study demonstrated both the high non-linearity of the generated field but also the mechanical properties of the pellicle, which restrict its ability to faithfully follow the localised acoustic displacements. Velocity, and consequently displacement amplitude was observed to reduce drastically with radial distance from the acoustic focus, and significant phase discrepancies were also noted with distance from the focus.

In conclusion, the theoretical and experimental work presented in this thesis describes a novel method of recording measurements from underwater acoustic fields. The technique has been demonstrated to be highly accurate, benefit from an extremely large bandwidth, an ability to resolve measurements of spatially distributed parameters in excellent detail and permit data recording in rapid time. The additional post measurement processing and manipulation techniques allow complex data to be visualised in an accurate and straightforward manner. The development of this measurement technique has exceeded the initial objectives for the research and has opened up many avenues which additional work might explore.

Chapter 9

Further Work

Having successfully demonstrated the ability of Laser Doppler Velocimetry to quantitatively characterise underwater acoustic pressure fields, the research reported here has created further opportunity for extending the studies and providing greater characterisation of acoustic parameters. It is also important to set this work into context and describe some of the potential developments and exploitations of the technique, which might be of benefit to the scientific community.

The first major potential area of development is the refinement of the techniques described in this work to enable measurements of increased spatial and temporal resolution with reduced error. This might take the form of improved practical experimentation, or alternatively advanced software enabling the interpretation of measurements. It is anticipated that the successful implementation of this would provide the underwater acoustic calibration community with a valuable tool in their quest for improved fundamental standards, whilst providing the manufacturers or clinical users with essential information regarding the spatial distribution of energy within the field generated by a particular transducer.

A separate development would be aimed at facilitating the derivation of pressure at single points within the field. The review of literature pertaining to the application of optical metrology for acoustic measurements presented in Section 2.4 has revealed the potential for such derivation using tomographic methods [91–93]. The ability to derive temporally resolved single point pressure measurements in a non-perturbing manner is considered to be of significant benefit, reflected by the aims outlined in the UK Department of Trade and Industry (DTI) National Measurement System Programme for Quantum Metrology 2001–2004 [54].

9.1 RECOMMENDATIONS FOR FUTURE DEVELOPMENT OF UNDERWATER ACOUSTIC LDV MEASUREMENT METHODS

The process of recording measurements using either a standard or scanning LDV system is straightforward, although the process of deriving useful measured quantities from the generated data is highly complex. Fundamentally this is due to the 4-dimensional complexities of the acousto-optic interaction causing the refractive index changes. The most useful measurements were made using the Polytec scanning LDV system, although additional issues had to be overcome before useful information could be obtained. This was due in part to the method by which the PSV-200 software interpreted and processed the 'velocity' signal obtained. Despite the optical path length representing an integral of the refractive index with distance to and from the target, the instrument assumed a constant refractive index and attributed any measured change to a movement of the target. For the majority of airborne analysis this assumption is acceptable but, as demonstrated in this work, when applied to underwater acoustics it is not. Therefore, if Laser Doppler Velocimetry is to become a widely used tool in underwater acoustics, considerable development of the software is required.

Other areas requiring development include reducing the noise content of the images generated from the LDV data. Whilst appropriate filtering measures might be incorporated into software, further practical investigation is required to optimise the quality of the light returned from the target. Factors known to influence the quality of the light returned include the optical clarity of the media through which the light passes, including the glass windows or walls of the tank, the air and the water. Light scattered from any suspended particulates in the air and water, each moving with a variety of velocities, will introduce erroneous Doppler frequency shifts into the returned light. Methods of eliminating these components, or minimising their influence would increase the overall fidelity of measurements. Further investigation into the optimum retro retro-reflective material to be used for the target is also required.

In terms of the application of the technique, it is hoped that improved measurements of the spatial distribution of acoustic fields generated by transducers will be possible,

providing feedback to enable design improvements to be made with increased ease. In addition to the investigation of un-impeded fields, it is envisaged that the technique would enable laboratory based measurements from scattered fields to be undertaken. This would facilitate the relative scattering strengths of a range of tissue or material to be established in a fast, robust and straightforward manner.

9.2 TOMOGRAPHIC DERIVATION OF SINGLE POINT PRESSURE DATA FROM LDV MEASUREMENTS

The mathematical process of tomography allows the reconstruction of images from which projection sums have been calculated. The process of creating a projection sum is analogous with the integration of refractive index with distance experienced by the LDV laser beam. Appropriate mathematical algorithms can then be used to obtain an image representative of the original field from the measured data. Two such readily available *Matlab* commands, *radon* and *iradon* represent the projection and reconstruction stages of this process and permit simple exploitation of the technique:

Radon computes the projection of the image intensity along a radial line oriented at a specific angle.

Iradon reconstructs the image from a data array consisting of parallel beam projections and a numerical string representing the angles at which this data was generated.

Given that the rate of change of optical path length data measured by the scanning LDV represents the integral of refractive index with distance, it follows that the spatial distribution of refractive index can be reconstructed using the *iradon* function. An input requirement of this function is that projection data at multiple angles are available. However, a single LDV measurement scan provides an integration in only 1 angular direction.

Given the circular cross-sectional construction of the majority of transducers used in this work, it might be assumed that the acoustic fields generated exhibit rotational

symmetry. Therefore, as an investigative study into the feasibility of tomographic reconstruction of scanning LDV data, a single time-resolved measurement from a 500 kHz field generated by the Panametrics V389 was assumed to represent projections in all angular directions. These were then used to derive a time-resolved spatial distribution of a quantity proportional to the refractive index, and subsequently the pressure. Due to insufficient information concerning the precise dimensions of the integration length and additional processing time-constraints, the absolute refractive index and pressure could not be obtained. Consequently, the results presented in Figure 9.2.1 depict a dimensionless scaled quantity proportional to the pressure.

The images shown in Figure 9.2.1 depict sections in x and y of approximately 100×100 mm at the stated time instants. They represent the *iradon* transform of a single vertical line of discrete points from an LDV scan.

It might be anticipated that the spatial distribution of the generated field would exhibit negligible pressure amplitudes in the regions outside of the principal beam. However, this is not the case in the results obtained here due to a number of extenuating circumstances. The first, and perhaps most significant, of these reasons is that the acoustic axis was not exactly central within the original scan. Therefore, when this scan was used to represent measurements at different angular projections, errors were introduced. These are manifest by the presence of a number of central peaks where only one might be anticipated. Additionally, the influence of any erroneous measurement points within the original scan is increased by the assumption of rotational symmetry. This offers an explanation as to the presence of concentric pressure rings in the regions outside of the principal beam. A third contributory factor is the fact that the *iradon* transform assumes parallel beam projection which was not the case in the measurements recorded using the scanning LDV.

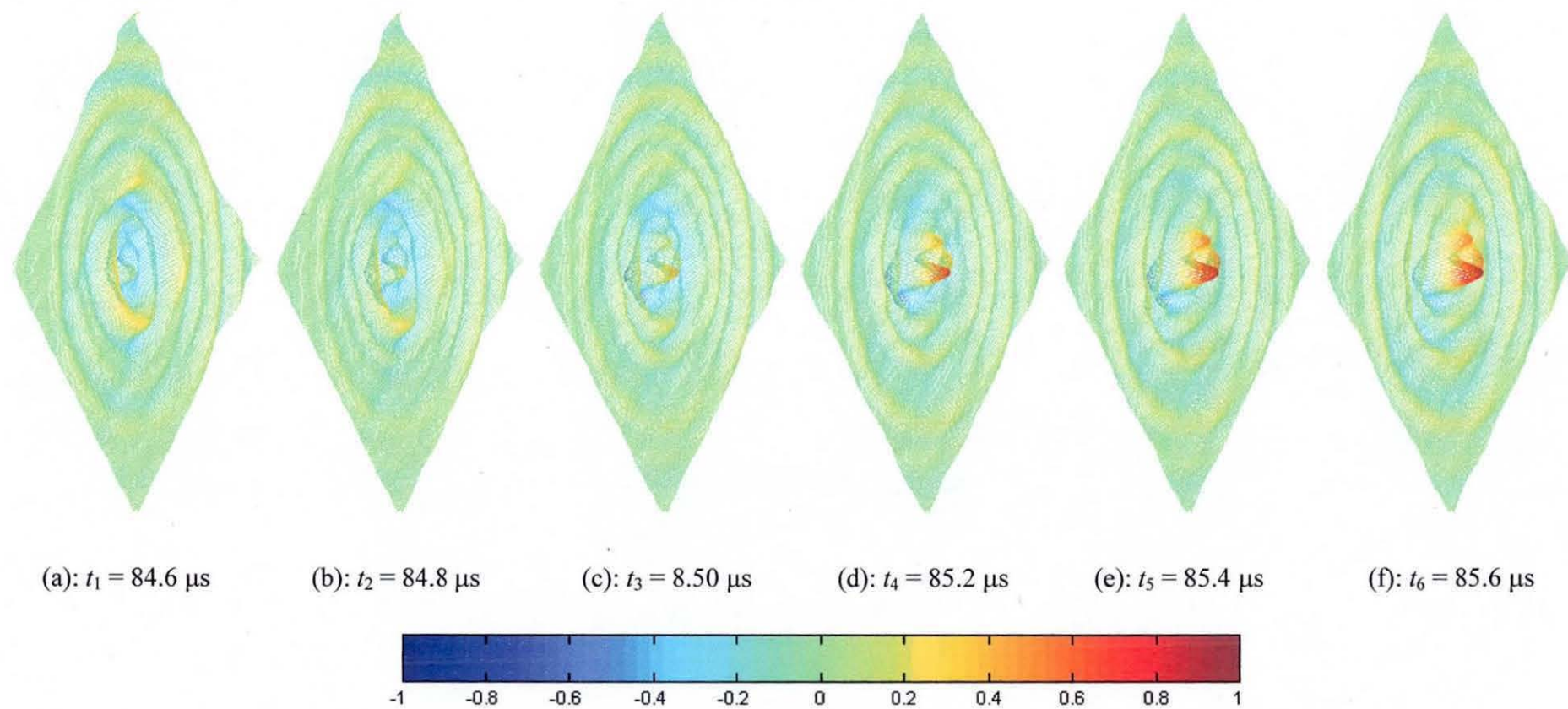


Figure 9.2.1: Tomographically reconstructed spatial distribution of acoustic pressure at six time instants

The tomographic data can be represented in a number of different ways, such as in the graph presented in Figure 9.2.2. The blue trace depicts the time-resolved pressure at the intersection of the laser line with the acoustic axis, as measured by the ITC 6128 probe hydrophone. The red trace represents the time-resolved normalised pressure derived from a single point at the centre of the reconstructed section. A visual comparison of the two signals shows very close similarity, both in the shape of the measured tone-burst and the period of oscillation.

These preliminary investigations demonstrate the potential of this technique to obtain temporally resolved single point pressure measurements from rotationally symmetrical acoustic fields. At this stage an assessment of the limitations or uncertainties associated with the technique cannot be made.

As a method of eliminating the need for an assumption of rotational symmetry, a mounting fixture was designed which enabled the source transducer to be rotated in 1° increments. This fixture was fabricated from aluminium and is shown holding the Met-Optic transducer in Figure 9.2.3. The fixture allowed LDV scans to be completed at sufficient angular positions for the *iradon* transform to be undertaken. Unfortunately, rotation of the fixture was found to introduce lateral movement of the source, which caused position of the acoustic axis to change in each angular measurement. Consequently, the derived distribution of pressure within the section exhibited similar discrepancies to those displayed in Figure 9.2.1. Therefore additional design considerations would need to be given to fixtures and mechanisms before further detailed work could be completed.

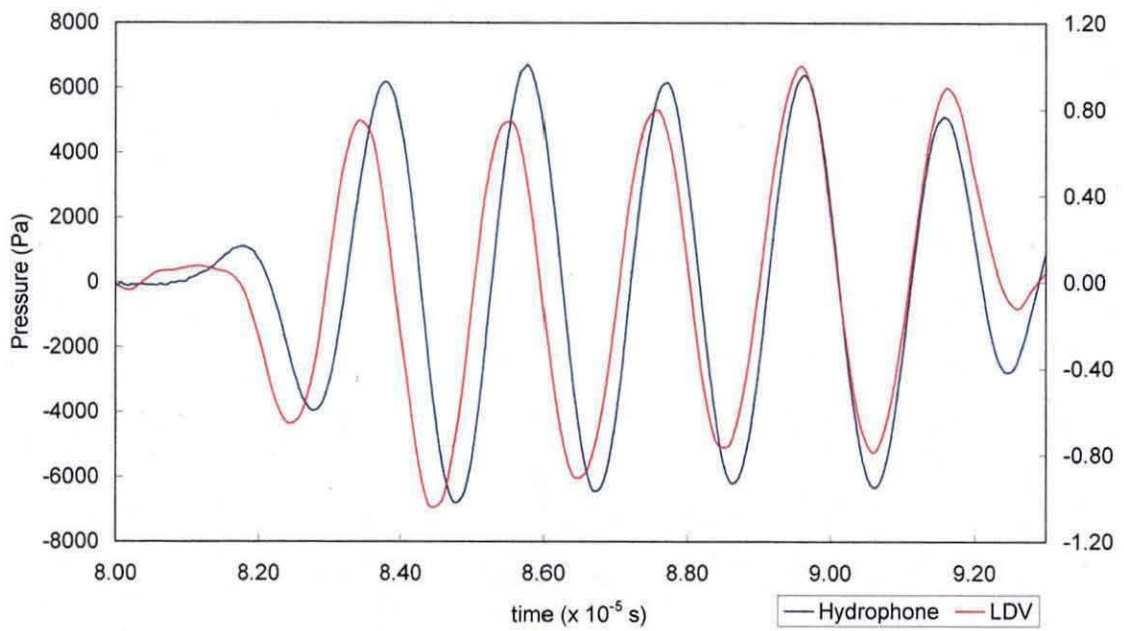


Figure 9.2.2: Pressure amplitude measured by ITC 6128 hydrophone and derived from tomographic reconstruction of LDV scan

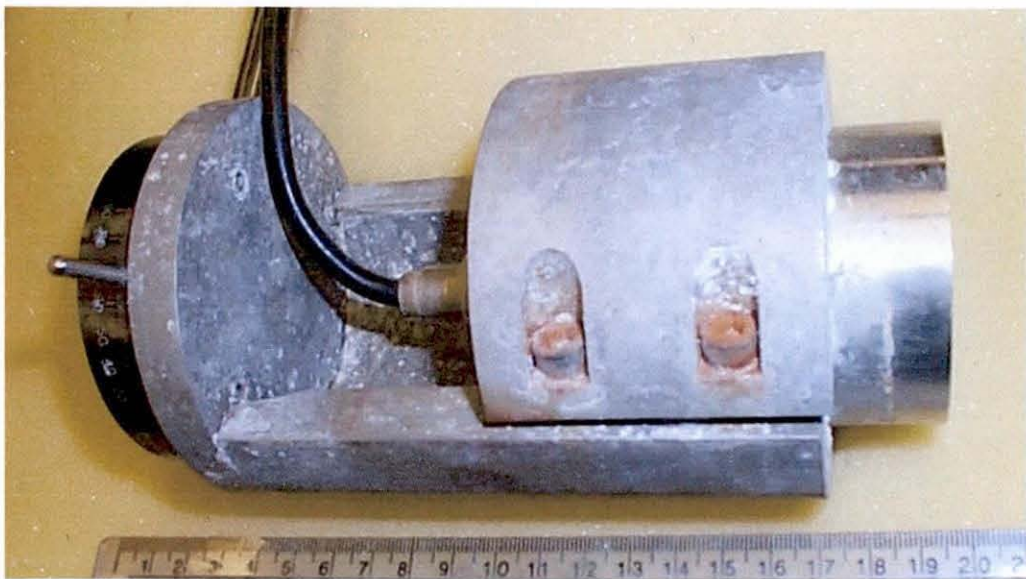


Figure 9.2.3: Met-Optic Plane Piston Transducer mounted within rotatable test fixture

Chapter 10

References

- 1 MacCurdy, E. "The Notebooks of Leonardo da Vinci, arranged, rendered into English and introduced by Edward MacCurdy", Volume 1, Jonathan Cape, London, 1942
- 2 Newton, I., "Newton's principia: The mathematical principles of natural philosophy – translated by A. Motte", Putnam, 1850
- 3 Haines, G., "Sound Underwater", David and Charles, Newton Abbot, London, ISBN 0-7153-6219-4, 1974
- 4 Coppens, A. B., "Simple equations for the speed of sound in Neptunian waters", The Journal of the Acoustical Society of America, **69** (3), 862-863, 1981
- 5 Rayleigh, J. W. S., "The Theory of Sound, Volume I", 2nd edition, revised and enlarged, Dover Publications, New York, 1945
- 6 Rayleigh, J. W. S., "The Theory of Sound, Volume II", 2nd edition, revised and enlarged, Dover Publications, New York, 1945
- 7 Curie, J. and Curie, P., "Développement, par pression, de l'électricité polaire dans les cristaux hémiedres à faces inclinées", Comptes rendus des Séances de l'Académie des Sciences, **91**, 294-295, 1880
- 8 Joule, J. P., "On a new class of Magnetic Forces", Annals of Electricity, Magnetism and Chemistry, **8**, 219-224, 1842
- 9 Joule, J. P., "On the effects of magnetism upon the Dimensions of Iron and Steel Bars", Philosophical Magazine, **30**, 76-87 and 225-241, 1847
- 10 Villari, E., "Change of Magnetization by Tension and by Electric Current", Annalen der Physik und Chemie, Leipzig, **128**, 1865

- 11 Khazan, "Transducers and their elements", Prentice Hall, ISBN 0-13-929480-5, 1994
- 12 Richardson, M.L.F., "Apparatus for warning a ship of its approach to large objects in a fog." Br. Pat. No. 9423., 1912
- 13 Chilowsky, C. and Langevin, P., "Echo Ranging with Electrostatic Transducer", French Pat. No. 502,913, published 29 May 1920
- 14 Smith, F. D., "The absolute measurement of sound intensity", Proc. Phys. Soc., London, **41**, 487, 1929
- 15 Klein, E., "Absolute sound intensity in liquids by spherical torsion pendula", The Journal of the Acoustical Society of America, **9**, 812, 1938
- 16 MacClean, W. R., "Absolute measurement of sound without a primary standard", The Journal of the Acoustical Society of America, **12**, 140, 1940
- 17 Cook, R. K., "Absolute pressure calibration of microphones", The Journal of the Acoustical Society of America, **12**, 415, 1941
- 18 IEC 565, "The calibration of hydrophones" International Electrotechnical Commission, Geneva, Switzerland, 1977
- 19 BS 5652, "Specification for the calibration of hydrophones", 1979
- 20 Sokolov, S.Y. "Ultrasonic methods of detecting internal flaws in metal articles", Zavodskaya Laoratoriya, **4**, 1468-1473, 1935
- 21 Dussik, K. T., "On the possibility of the application of high frequency sound waves as a diagnostic aid" Z. Neur., **174**, 490, 1942
- 22 Dussik, K. T., Dussik, F., Wyt, L., "Hyperphonography of the Brain" Wiener med. Wschr., **97**, 435, 1947
- 23 Wild, J. J., "The use of ultrasonic pulses for the measurement of biological tissues and the detection of tissue density changes", Surgery, **27**, 183-188, 1950

- 24 Wild, J. J., Neal, D., "Use of high-frequency ultrasonic waves for detecting changes of texture in living tissues", *The Lancet*, 655-657, March 24, 1951
- 25 French, L. A., Wild, J. J., Neal, D., "Detection of cerebral tumors by ultrasonic pulses", *Cancer*, 705-708, July 1950
- 26 Wild, J. J., Reid, J. M. "Application of Echo-Ranging Techniques to the Determination of Structure of Biological Tissues", *Science*, 226-230, February 29, 1952
- 27 Wild, J. J., Reid, J. M., "Further pilot echographic studies on the histologic structure of tumors of the living intact human breast", *American Journal of Pathology*, **28**, 839-861, 1952
- 28 Wild, J. J., Reid, J. M., "The effect of Biological Tissues on 15-mc Pulsed Ultrasound", *The Journal of the Acoustical Society of America*, **25** (2), 270-280, March 1953
- 29 Donald, I., MacVicar, J., Brown, T. G., "Investigation of Abdominal Masses by Pulsed Ultrasound", *The Lancet*, 7 June 1958
- 30 Satomura, S., "Ultrasonic Doppler Method for the Inspection of Cardiac Functions", *The Journal of the Acoustical Society of America*, **29** (11), 1181-1185, 1957
- 31 McLeod, F. D. "A directional Doppler flowmeter", *Digest of the 7th International Conference on Medical and Biological Engineering*, 213, 1967
- 32 Wells, P. N. T., "A range gated ultrasonic Doppler system", *Medical and Biological Engineering*, **7**, 641-652, 1969
- 33 Baker, D. W., "Pulsed ultrasound Doppler blood-flow sensing", *IEEE Transactions on Sonics Ultrasonics* ., **17**, 170-185, 1970
- 34 Maslak, S. H., "Acoustic Imaging Apparatus", US Patent No.4,140,022, February 1979

- 35 Preston, R. C. (ed), "Output Measurements for Medical Ultrasound", Springer-Verlag, ISBN 3-540-19692-7
- 36 Ter Haar, G. R., "Biological effects of ultrasound in clinical applications, in Ultrasound: Its chemical, physical, and biological effects", VCH Publishers, New York, 1988
- 37 Graff, K. F., "A History of Ultrasonics, chapter 1 of Physical Acoustics", **15**, Academic Press, 1981
- 38 Kinsler, L. E., Frey, A. R., Coppens, A. B., Sanders, J. V. "Fundamentals of Acoustics, Fourth Edition", John Wiley and Sons Inc., New York, Chichester, Weinheim, Brisbane, Singapore, Toronto, ISBN 0-471-84789-5, 2000
- 39 "The Oxford compact English Dictionary", Oxford University Press, ISBN 0-19-860064-X, 1996
- 40 Wilson, O. B., "Introduction to Theory and Design of Sonar Transducers", Peninsula Publishing, Los Altos California, USA, ISBN 0-932146-22-8, 1988
- 41 Bobber, R. J., "Underwater Electroacoustic Measurements", Peninsula Publishing, Los Altos California, USA, ISBN 0-932146-19-8, 1988
- 42 Wilson, W. D., "Speed of Sound in Distilled Water as a Function of Temperature and Pressure", The Journal of the Acoustical Society of America, **31**, (8), 1067-1072, 1959
- 43 Wilson, W. D., "Speed of Sound in Sea Water as a Function of Temperature, Pressure and Salinity", The Journal of the Acoustical Society of America, **32**, (6), 641-644, 1960
- 44 Lovett, J. R., "Comments Concerning the Determination of Absolute Sound Speeds in Distilled and Seawater and Pacific Sofar Speeds", The Journal of the Acoustical Society of America, **45**, (4), 1051-1053, 1968

- 45 Leroy, C. C., "Development of Simple Equations for Accurate and More Realistic Calculation of the Speed of Sound in Seawater", *The Journal of the Acoustical Society of America*, **46**, (1), 216-226, 1969
- 46 Lovett, J. R., "Merged seawater sound-speed equations", *The Journal of the Acoustical Society of America*, **63**, (6), 1713-1718, 1978
- 47 Frye, H. W. and Pugh, J. D., "A New Equation for the Speed of Sound in Seawater", *The Journal of the Acoustical Society of America*, **50**, (1), 384-386, 1971
- 48 Del Grosso, V. A., "New Equations for the speed of sound in natural waters (with comparisons to other equations)", *The Journal of the Acoustical Society of America*, **56**, (4), 1084-1091, 1974
- 49 Chen, C-T. and Millero, F.J., "Speed of sound in seawater at high pressures", *The Journal of the Acoustical Society of America*, **62**, (5), 1129-1135, 1977
- 50 Mackenzie, K. V., "Nine-term equation for the sound speed in the oceans", *The Journal of the Acoustical Society of America*, **70**, (3), 807-812, 1981
- 51 Hecht, E., "Optics 2nd Edition", Addison-Wesley Publishing Company, Inc., USA, ISBN 0-201-11611-1
- 52 Robinson, S. P., "Hydrophones", Chapter 4, "Output Measurements for Medical Ultrasound", Preston, R. C. (ed), Springer-Verlag, ISBN 3-540-19692-7
- 53 Preston, R. C., Bacon, D. R., Livett, A. J., Rajendran, K.J., "Pvdf membrane hydrophone performance properties and their relevance to the measurement of the acoustic output of medical ultrasonic equipment", *J Phys E Sci Instrum*, **16**, 786-796, 1983
- 54 National Measurement System, "NMS Programme for Quantum Metrology, April 2001 – March 2004", Department of Trade and Industry, London, UK, 2001

- 55 Filipczyński, L., "Absolute measurements of particle velocity, displacement or intensity of ultrasonic pulses in liquids and solids", *Acustica*, **21**, 173-180, 1969
- 56 Filipczyński, L., Etienne, J., "Capacitance hydrophones for pressure determination in lithotripsy", *Ultrasound in Medicine and Biology*, **16**, 157-165, 1990
- 57 Filipczyński, L., Etienne, J., Kujawska, T., Wojcik, J., Zienkiewicz, B., "Acoustical distortions in capacitance hydrophones and the effect of diaphragms in measurements of shock wave pulses", *Archives of Acoustics*, **23** (2), 251-266, 1998
- 58 Dunn, F., Averbuch, A. J., O'Brien, W. D. Jr., "A Primary Method for the Determination of Ultrasonic Intensity with Elastic Sphere Radiometer", *Acustica*, **38**, 58-61, 1977
- 59 Zeqiri, B., "Overview of Measurement Techniques", Chapter 3, "Output Measurements for Medical Ultrasound", Preston, R. C. (ed), Springer-Verlag, ISBN 3-540-19692-7
- 60 Preston, R. C., "The NPL Ultrasound Beam Calibrator", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, **35** (2), 122-139, 1988
- 61 Faran, J. R., "Sound Scattering by Solid Cylinders and Spheres", *The Journal of the Acoustical Society of America*, **23** (4), 405-418, July 1951
- 62 Kheifets, E. I., "Quantitative analysis of sound fields visualised by holographic techniques", *Sov. Phys. Acoust.*, **19** (3), 279-285, 1973
- 63 Zhen, Y. E., "Recent Developments in Underwater Acoustics: Acoustic Scattering from Single and Multiple Bodies", *Proceedings of the National Science Council ROC(A)*, **25** (3), 137-150, 2001
- 64 Robinson, S. P., Bangash, M. A., "A comparison of hydrophone calibration by free-field reciprocity and by optical interferometry in the frequency range

- 200kHz to 1MHz", Proceedings of the Institute of Acoustics, **20** (3), 139-146, 1998
- 65 Robinson, S. P., Preston, R. C., "A survey of European calibration facilities for underwater acoustics", NPL Report RSA(EXT)32, National Physical Laboratory, Teddington, Middlesex, UK, TW11 0LW, ISSN 0955-9655, 1992
- 66 Robinson, S. P., Green, G. J., Preston, R. C., Peirlinckx, L., Kofoed, L., Skodborg, C., Roy, A., Mori, Y., Brenner, A., Kruger, D., Buogo, S., Cannelli, G., Troiano, L., Runborg, C., Gooch, G., "International comparison of free-field hydrophone calibrations in the frequency range 10 kHz to 315 kHz", *Metrologia*, **36** (4), 287-296, 1999
- 67 Preston, R. C., Robinson, S. P., "European comparison of ultrasonic hydrophone calibrations", *Metrologia*, **36** (4), 345-349, 1999
- 68 Preston, R. C., Bacon, D. R., Corbett, S. S., Harris, G. R., Lewin, P. A., McGregor, J. A., O'Brien, W. D., Szabo, T. L., "Interlaboratory Comparison of Hydrophone Calibrations", *IEEE Transactions of Ultrasonics, Ferroelectrics and Frequency Control*, **35** (2), 206-213, 1988
- 69 Enyakov, A. M., Likhatchev, S. M., Platonov, V. A., Yuan, W. J., Wang, Y. B., Li, J. Q., "Russian-Chinese international comparison of hydrophone calibration methods", *Metrologia*, **36** (4), 297-304, 1999
- 70 Robinson, S. P., Doré, G. R., "Uncertainty in the calibration of hydrophones at NPL by the three transducer spherical wave reciprocity method in the frequency range 10 kHz to 500 kHz", NPL Report RSA(EXT)054, National Physical Laboratory, Teddington, Middlesex, UK, TW11 0LW, ISSN 0955-9655, 1994
- 71 Drain, L. E., Speake, J. H., Moss, B. C., "Displacement and vibration measurement by laser interferometry", Proceedings of the European Congress on Optics applied to Metrology, S.P.I.E., 136, 52-57, 1977

- 72 Bacon, D. R., Drain, L. E., Moss, B. C., Smith, R. A., "A new primary standard for hydrophone calibrations", *Physics in Medical Ultrasound*, Institute of Physical Sciences in Medicine, Report No. 47, 30-35, 1986
- 73 Bacon, D. R., "Primary Calibration of Ultrasonic Hydrophones Using Optical Interferometry", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, **35** (2), 152-161, March 1988
- 74 Esward, T. J., Robinson, S. P., "Extending the frequency range of the NPL primary standard laser interferometer for hydrophone calibrations to 60 MHz", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, **46** (3), 737-744, 1999
- 75 Preston, R. C., Robinson, S. P., Zeqiri, B., Esward, T. J., Gelat, P. N., Lee, N. D., "Primary calibration of membrane hydrophones in the frequency range 0.5 MHz to 60 MHz", *Metrologia*, **36** (4), 331-343, 1999
- 76 Debeye, F., Sears, F., "On the scattering of light by supersonic waves", *Proceedings of the National Academy of Science*, **18**, 409, 1932
- 77 Lucas, R., Biquard, P., "Propriétés Optiques des Milieux solides et liquides soumis aux vibrations élastiques ultra sonores", *J. Phys. Radium – 7th series*, **3**, 464-477, 1932
- 78 Raman, C. V., Nath, N. S. N., "The diffraction of light by high frequency sound waves: Part I", *Proceedings of the Indian Academy of Science*, **2**, 406-412, 1935
- 79 Raman, C. V., Nath, N. S. N., "The diffraction of light by high frequency sound waves: Part II", *Proceedings of the Indian Academy of Science*, **2**, 413-420, 1935
- 80 Willard, G. W., "Ultra-sound waves made visible", *Bell Lab Record*, **5**, 194-200, 1947
- 81 Haran, M. E., "Visualization and Measurement of Ultrasonic Wavefronts", *Proceedings of the IEEE*, **67** (4), 454-466, 1979

- 82 Klein, W. R., Cook, B. D., "Unified Approach to Ultrasonic Light Diffraction", IEEE Transactions on Sonics and Ultrasonics, **14** (3), 123-134, 1967
- 83 Monchalin, J-P., "Optical Detection of Ultrasound", IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, **33** (5), 485-499, 1986
- 84 Cook, B. D., "The measurement of high frequency sound fields by optical techniques", SPIE, **2358**, 278-280, 1994
- 85 Foucault, J. L., Ann. de l'observatoire imp. de Paris, **5**, 197, 1859
- 86 Toepler, A., "Beobachtungen nach einer neuen optischen Methode", Max Cohen und Sohn, Bonn, 1864
- 87 Blomme, E., Leroy, O., "Diffraction of light by ultrasound: Closed analytical expression for the spectra up to order 2", Journal of the Acoustical Society of India, **11**, 1-6, 1983
- 88 Blomme, E., Leroy, O., "Diffraction of light by ultrasound: finite analytical expressions for the spectra up to order 3", Acoustica, **57**, 168-174, 1985
- 89 Blomme, E., Leroy, O., Sliwinski, A., "Acoustically induced light polarization effects in isotropic media", SPIE, **2643**, 2-11, 1995
- 90 Jerrard, H. G., "Birefringence induced in liquids and solutions by ultrasonic waves", Ultrasonics, 74-81, April-June, 1954
- 91 Reibold, R., Molkenstruck, W., "Light Diffraction Tomography Applied to the Investigation of Ultrasonic Fields. Part I: Continuous Waves", Acustica, **56**, 180-192, 1984
- 92 Reibold, R., Kwiek, P., "On ultrasound light diffraction", Ultrasonics, **31** (5), 307-313, 1993
- 93 Reibold, R., Kwiek, P., "Extension of light diffraction tomography beyond the weak acousto-optic interaction", Acustica, **81**, 43-52, 1995

- 94 Kwiek, P., Reibold, R., "Determination of an Ultrasound field Using Light Diffraction", *Acustica – acta acustica*, **82**, 376-378, 1996
- 95 Reibold, R., Kwiek, P., "Uncertainty considerations of ultrasonic field mapping by light diffraction tomography", *Ultrasonics*, **35**, 187-193, 1997
- 96 Reibold, R., Kwiek, P., "Ultrasound field mapping by light-diffraction tomography: A review", *SPIE*, **2643**, 66-79, 1995
- 97 Leendertz, J. A., Butters, J. N., "An image shearing speckle pattern interferometer for measuring bending moments", *Journal of Physics E*, **6**, 1107-1110, 1973
- 98 Rastogi, P. K. (ed), "Optical Measurement Techniques and Applications", Artech House Inc, ISBN 0-89006-516-0, 1997
- 99 Rastogi, P., Inaudi, D., "Trends in Optical Non-Destructive Testing and Inspection", Elsevier, ISBN 0-08-043020-1, 2000
- 100 Dupont, O., Dewandel, J. L., Legros, J. C., "Use of electronic speckle pattern interferometry for temperature distribution measurements through liquids", *Optics Letters*, **20** (17), 1824-1826, 1995
- 101 Spagnolo, G. S., Ambrosini, D., Paoletti, D., "Electronic speckle pattern shearing interferometry for determining free convection heat transfer coefficient", *The European Journal of Applied Physics*, **6**, 281-284, 1999
- 102 Lokberg, O. J., "Sound in flight: measurement of sound fields by use of TV holography", *Applied optics*, **33** (13), 2574-2584, 1994
- 103 Lokberg, O. J., "Recording of sound emission and propagation in air using TV holography", *Journal of the Acoustical Society of America*, **96** (4), 2244-2250, 1994
- 104 Rustad, R., Lokberg, O. J., Pedersen, H. M., Klepsvik, K., Storen, T., "TV holography measurements of underwater acoustic fields", *Journal of the Acoustical Society of America*, **102** (3), 1904-1906, 1997

- 105 Rustad, R., "Acoustic field of a medical ultrasound probe operated in continuous wave mode investigated by TV holography", *Applied Optics*, **37** (31), 7368-7377, 1998
- 106 Lokberg, O. J., Espeland, M., Pedersen, M., "Tomography reconstruction of sound fields using TV holography", *Applied Optics*, **34** (10), 1640-1645, 1995
- 107 Espeland, M., Lokberg, O. J., Rustand, R., "Full field tomographic reconstruction of sound fields using TV holography", *Journal of the Acoustical Society of America*, **98** (1), 280-287, 1995
- 108 Gren, P., Schedin, S., Li, X., "Tomographic reconstruction of transient acoustic fields recorded by pulsed TV holography", *Applied Optics*, **37** (5), 834-840, 1998
- 109 Steel, W. H., "Interferometry (2nd edition)", Cambridge University Press, ISBN 0-512-31162-4 1983, 1983
- 110 Jones, R., Bergquist, B. D., "Interferometric Techniques for fundamental static or dynamic pressure measurements and transducer calibration", *Journal of Physics E: Scientific Instruments*, **10**, 1265-1271, 1977
- 111 Gabor, D., "A New Microscopic Principle", *Nature*, **161**, 777-778, 1948
- 112 Kwiek P., Reibold, R., "Holographic Investigation of Transient Ultrasonic Fields", *Acoustics Letters*, **7** (11), 167-172, 1984
- 113 Grousson, R., Mallick, S., "Study of flow pattern in a fluid by scattered laser light", *Applied Optics*, **16** (9), 2334-2336, 1977
- 114 Hann, D. B., Greated, C. A., "Measurement of acoustic particle velocity using particle image velocimetry techniques", *Acustica-Acta Acustica*, **83**, 354-358, 1997

- 115 Hann, D. B., Greated, C. A., "Particle image Velocimetry for the measurement of mean and acoustic particle velocities", *Measurement Science and Technology*, **8**, 656-660, 1997
- 116 Hann, D. B., Greated, C. A., "The Measurement of flow velocity and acoustic particle velocity using particle-image velocimetry", *Measurement Science and Technology*, **8**, 1517-1522, 1997
- 117 Campbell, M., Cosgrove, J. A., Greated, C. A., Jack, S., Rockliff, D., "Review of LDA and PIV applied to the measurement of sound and acoustic streaming", *Optics and Laser Technology*, **32**, 629-639, 2000
- 118 Luxmoore, A. R., "Optical transducers and techniques in engineering measurement", *Applied Science Publishers Ltd.*, ISBN 0-85334-203-2, 1983
- 119 Taylor, K. J., "Absolute measurement of acoustic particle velocity", *Journal of the Acoustical Society of America*, **59** (3), 691-694, 1976
- 120 Vignola, J. F., Berthelot, Y. H., Jarzynski, J., "Laser detection of sound", *Journal of the Acoustical Society of America*, **90** (3), 1275-1286, 1991
- 121 Greated, C. A., "Measurement of acoustic velocity fields", *Strain*, 21-24, February 1986
- 122 Sharpe, J. P., Greated, C. A., "The measurement of periodic acoustic fields using photon correlation spectroscopy", *Journal of Physics D: Applied Physics*, **20**, 418-423, 1987
- 123 Hann, D., Greated, C. A., "Acoustic measurements in flows using photon correlation spectroscopy", *Measurement Science and Technology*, **4**, 157-164, 1993
- 124 Hann, D., Greated, C., "The Measurement of Sound Fields Using Laser Doppler Anemometry", *Acustica-acta acustica*, **85**, 401-411, 1999
- 125 Hann, D. B., Jack, S. H., Greated, C. A., "Laser Doppler Measurements in Complex Sound Fields", *Proceedings of the 7th international conference in*

Laser Anemometry: Advances and Applications, GALA, University of Karlsruhe, 8.-11 September 1997

- 126 Galloway, P. C. M., Hardalupas, Y., Prassas, I., "Ultrasound Measurement by Laser Doppler Anemometry", Proc. 10th Int. Symposium on Applications of Laser Techniques in Fluid Mechanics, Lisbon, Portugal, 10-13 July 2000
- 127 Crickmore, R. I., Jack, S. H., Hann, D. B., Greated, C. A., "Laser Doppler anemometry and the acousto-optic effect", Optics and Laser Technology, **31**, 85-94, 1999
- 128 Jack, S. H., Hann, D. B., Greated, C. A., "Influence of the acousto-optic effect on laser Doppler anemometry signals", Review of Scientific Instruments, **69** (12), 4074-4081, 1998
- 129 Jack, S. H., Hann, D. B., Greated, C. A., "The influence of a standing wave on laser Doppler signals", Measurement Science and Technology, **10**, 1279-1285, 1999
- 130 Šlegrová, Z., Bálek, R., "Interferometric Measurement of Acoustic Pressure", Audio Technologies and Processing, Czech Technical University, Prague, Czech Republic, 2001
- 131 Scruby, C. B., Drain, L. E., "Laser Ultrasonics Techniques and Applications", Adam Hilger, Bristol, ISBN 0-7503-0050-7, 1990
- 132 Williams, D. C., "Optical Methods in Engineering Metrology", Chapman & Hall, London, ISBN 0-412-39640-8, 1993
- 133 Pickering, C. J. D., Halliwell, N. A., "The Laser Vibrometer: A Portable Instrument", Journal of Sound and Vibration, **107** (3), 471-485, 1986
- 134 Huang, J., Achenbach, J. D., "Dual-probe laser interferometer", The Journal of the Acoustical Society of America, **90** (3), 1269-1274, September 1991
- 135 Crickmore, R. I., "The Laser Doppler Hydrophone", 7th International Conference, German Association of Laser Anemometry, September 1997

- 136 Crickmore, R. I., "The Use of a Laser Hydrophone as a means of Acoustic Calibration", *Proceedings of the Institute of Acoustics*, **20** (3), 123-130, 1998
- 137 Wang, Y., Huang, Y., "Calibration of hydrophones using optical technique", **26** (1), 29-33, *Acta Acustica (China)*, 2001
- 138 Image reproduced from the International Transducer Corporation
- 139 Laser Doppler Vibrometer, User Manual and Calibration Certificates, Polytec GmbH, D-76337, Waldbronn, Germany
- 140 Raman, C. V., Nagendra Nath, N. S., "The diffraction of light by high frequency sound waves: Part 1", *Proceedings of the Indian Academy of Sciences*, **2**, 406-420, 1935
- 141 Raman, V., Venkataraman, K. S., "Determination of adiabatic piezo-optic coefficient of liquids", *Proceedings of the Royal Society*, **171**, 137-147, 1939
- 142 Reisler, E., Eisenberg, H., "Refractive Index and Piezo-optic Coefficients of Deuterium Oxide, Methanol and Other Pure Liquids", *The Journal of Chemical Physics*, **43**, 3875-3880, 1965
- 143 Batchelor, G.K., "An introduction to fluid dynamics", Cambridge University Press, Cambridge, 1967
- 144 Eisenberg, H., "Equation for the Refractive Index of Water", *The Journal of Chemical Physics*, **43**, 3887-3892, 1965
- 145 Bajpai, A. C., Mustoe, L. R., Walker, D., "Engineering Mathematics", John Wiley and Sons, ISBN 0-471-04376-1, 1984
- 146 Rothberg, S. J., Halliwell, N. A. "Laser vibrometry on solid surface – the effects of laser speckle", *Journal of Laser Applications*, **6** (1): 38-41, 1994
- 147 Nyquist, H., "Certain Topics in Telegraph Transmission Theory", *A.I.E.E. Transactions*, **47**, 617-644, 1928

Appendix A

Publications arising from this work

Harland, A.R., Petzing, J.N. and Tyrer, J.R., "Assessment and Application of LDV to Underwater Acoustic Measurements", Proceedings of Photon '02 - Applied Optics and Optoelectronics Conference, Cardiff, UK, September 2002, pp 47-48, ISBN 0-7503-0916-4.

Harland, A.R., Petzing, J.N. and Tyrer, J.R., "Underwater Pressure Field Measurements Using Non-Perturbing Optical Metrology Techniques", Proceedings of the National Measurement Conference 2001, NMC 2001 & BEMC 2001, National Physical Laboratory, Harrogate, UK, 2001, 1 pp, [CD-ROM].

Harland, A.R., Petzing, J.N. and Tyrer, J.R., "Non-Invasive Measurements of Underwater Pressure Fields Using Laser Doppler Velocimetry", Journal of Sound and Vibration, **252**(1), 2002, pp 169-177, ISSN 0022-460X

Harland, A. R., Petzing, J. N., Tyrer, J. R., Bickley, C. J., Robinson, S. J., Preston, R. C., "Application and Assessment of Laser Doppler Velocimetry for Underwater Acoustic Measurements", *accepted for publication in Journal of Sound and Vibration*

