ACADEMIC PRESS

Available online at www.sciencedirect.com

SCIENCE DIRECT

Journal of Sound and Vibration 265 (2003) 627–645

JOURNAL OF SOUND AND VIBRATION

www.elsevier.com/locate/jsvi

Application and assessment of laser Doppler velocimetry for underwater acoustic measurements

A.R. Harland[a], J.N. Petzing[a,*], J.R. Tyrer[a], C.J. Bickley[b], S.P. Robinson[b], R.C Preston[b]

[a] *Wolfson School of Mechanical & Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK*

[b] *National Physical Laboratory, Teddington, Middlesex TW11 0LW, UK*

Received 17 October 2001; accepted 29 July 2002

Abstract

The majority of traditional methods for making underwater acoustic pressure measurements involve placing all or part of a measurement transducer in the acoustic field. A variety of optical metrology techniques have been developed in an attempt to reduce or remove any perturbing effects. An example of this is the use of laser interferometry which has been developed as the primary method of calibrating hydrophones in the frequency range 500 kHz–20 MHz at the National Physical Laboratory (NPL). This technique involves suspending a thin Mylar pellicle in the acoustic field and recording the displacement of the pellicle surface using a Michelson Interferometer. This study details a comparison of a Laser Doppler Velocimeter (LDV) with the NPL Laser Interferometer, which gives a good correlation where agreement is within approximately 4% and 7% for two different power levels from a 500 kHz plane piston transducer and within 2.5% and 1% for the same power levels from a 1 MHz plane piston transducer. A novel, non-perturbing method of recording temporally resolved acoustic pressure distributions in water using an LDV is also described. The technique is shown to benefit from the consistent frequency response of the LDV detection system, such that the measured output resembles the drive voltage input to the transducer more closely than a similar hydrophone measurement. For the experimental arrangement described, the LDV system is shown to be sensitive to minimum pressure amplitudes of nominally 18.9 $mPa/\sqrt{Hz}$.

*Corresponding author. Tel.: +44-1509-227616; fax: +44-1509-227648.
E-mail address: j.petzing@lboro.ac.uk (J.N. Petzing).

doi:10.1016/S0022-460X(02)01460-8

1. Introduction

The propagation of mechanical sound waves in a dense media such as water is central to many communication and imaging techniques used in marine and medical environments. The principle of the majority of imaging techniques requires a measurement of the scattered acoustic energy to be made. The quality of the image produced is largely dependent on the fidelity of the measured acoustic distribution, coupled with an accurate description of the initial source field. From an industrial perspective, the need for accurate methods of characterizing sound fields is critical to improving efficacy and efficiency of acoustic-based equipment and techniques.

Another reason for accurate measurements arises from safety issues with respect to medical applications. One example is shock wave lithotripsy, where a controlled sound source is used to mechanically manipulate or even destroy human tissue. In these and similar techniques, it is imperative that the output power and spatial distribution of the sound field is known. In situ measurements are not possible, so a thorough characterization of the generated sound fields must be undertaken before the user can have confidence that the equipment is clinically safe.

The separation of the water molecules and the Nyquist sampling theory govern the maximum frequency transmittable in water [1]. The wavelength of sound in water is inversely proportional to the frequency, such that a signal of 1 Hz has a wavelength of approximately 1.5 km, whereas a signal of 1 kHz has a wavelength of 1.5 m. Sound waves will propagate at a speed determined by the characteristics of the media through which it passes. Much theoretical and experimental data is available describing the variation of sound speed in water with respect to such variables as temperature, salinity and ambient pressure or depth [2–6].

The primary instrument for making underwater acoustic measurements is the hydrophone. However, measurements made using such devices are subject to comparatively large errors, typically in the order of ± 1 dB, of the pressure amplitude [7]. These are due at least in part to the unfavourable environment in which measurements are typically made. Where several independent or semi-independent measurements can be made, the accuracy can be improved to ± 0.5 dB [7]. Since a hydrophone is required to be submerged in the field in order to record a measurement, it follows that the field will be perturbed to a degree by its presence. Certain measures, such as ensuring the size of the hydrophone is significantly smaller than the wavelength of the sound being measured and surrounding the hydrophone element with a material of a close impedance matching with water will reduce the perturbation, but it can never be truly eliminated.

An essential tool in establishing the accuracy of measurements made using a particular device is its traceability to a calibration standard. The requirements of the US Navy during the 1940s led directly to MacLean [8] and Cook [9] both devising the reciprocity method of calibrating electroacoustic transducers in 1940 and 1941, respectively. This procedure involves relating the performance of the device being calibrated with that of a device known to have a receiving sensitivity directly proportional to its transmitting sensitivity. Reciprocity is a well-established method of making accurate and reliable measurements and is widely used around the world [10]. Indeed, it is the current primary standard for underwater acoustic measurements in the UK for the frequency range 2–500 kHz, with overall uncertainties of ± 0.5 dB at 95% confidence levels [11,12].

At higher frequencies, optical calibration methods have been developed. In the UK, the primary calibration standard for the frequency range 500 kHz–20 MHz is the NPL Laser

Interferometer [13,14]. This system involves reflecting the target beam of a Michelson Interferometer off a thin (typically 5 μm), gold-coated Mylar pellicle suspended in the acoustic field. The displacement measured by the interferometer is then converted into values of pressure at the point of incidence. The random uncertainty of the technique is typically $\pm 1\%$ or better and the overall uncertainty (expressed for a confidence level of 95%) varies from $\pm 3.3\%$ to $\pm 4.7\%$ across the frequency range of 500 kHz–20 MHz. The interferometer is also routinely used as the primary standard for hydrophone calibration up to 60 MHz [14].

A major factor contributing to the low uncertainty values obtainable from the NPL Laser Interferometer is that the Mylar pellicle placed in the field is less obtrusive than a hydrophone. Attempts to improve the accuracy of measurements, both in industrial and calibration environments, have focused mainly on other optical metrology techniques, due to their non-perturbing nature [15–20].

Recently, the need for quality assurance in product specification, design and manufacture has placed increased demands on the underwater acoustics measurement infrastructure. As a consequence, the UK Department of Trade and Industry (DTI) National Measurement System Programme for Quantum Metrology 2001–2004 [21] proposes a ‘new generation of fundamental standards for acoustics based on optical methods’. 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 is:

> to lay the foundations for the development of new optically based primary calibration methods for realizing 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 absolute point measurements and whole-field mapping.

The work reported here represents a unique development in metrology instrumentation for the non-perturbing measurement of underwater acoustic parameters. This technique offers the potential as a viable alternative to existing imaging or calibration methods, and as such, initial theoretical and developmental application of the technique is discussed.

2. Theoretical analysis

Laser Doppler Velocimetry (LDV) is traditionally a technique for making non-invasive measurements of surface motion or fluid flow [22]. The principle of operation is based upon the detection of the Doppler frequency shift, Δf_D, caused when coherent light is scattered from a moving target.

The frequency shift is measured electronically by mixing the light returning from the target with a reference beam taken from the original coherent source on the surface of a photodetector. The current output from the photodetector is proportional to the light intensity and oscillates with a frequency equal to that of the difference between the two beams. Unfortunately, this system is ambiguous in its measurement of the direction of the motion, and it is for this reason that a carrier frequency, f_R, greater in magnitude than the maximum Doppler frequency shift, is included in either the reference or target beam. This centres the frequency range of $\pm\Delta f_D$ around f_R, as depicted in Fig. 1, thus enabling the direction of the motion to be resolved.

Consequently, the light measured by the LDV is described as follows:

$$E_T(t) = E_T \cos[\omega t + \varphi_r - 2ka_v \sin \omega_v t], \tag{1}$$

where ω is the laser light frequency, 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 signal is demodulated using the carrier frequency, a time-resolved analogue voltage, representative of the rate of change of optical path length is produced.

For the majority of practical applications, the scaled output voltage from an LDV system is assumed to represent the velocity of the target from which the beam is reflected. However, the performance of the LDV can also be modified by changes in the refractive index of the media through which it passes. These effects are significantly greater in dense media such as water where the characteristic impedance is approximately 3500 times that of air, the usual media in which the

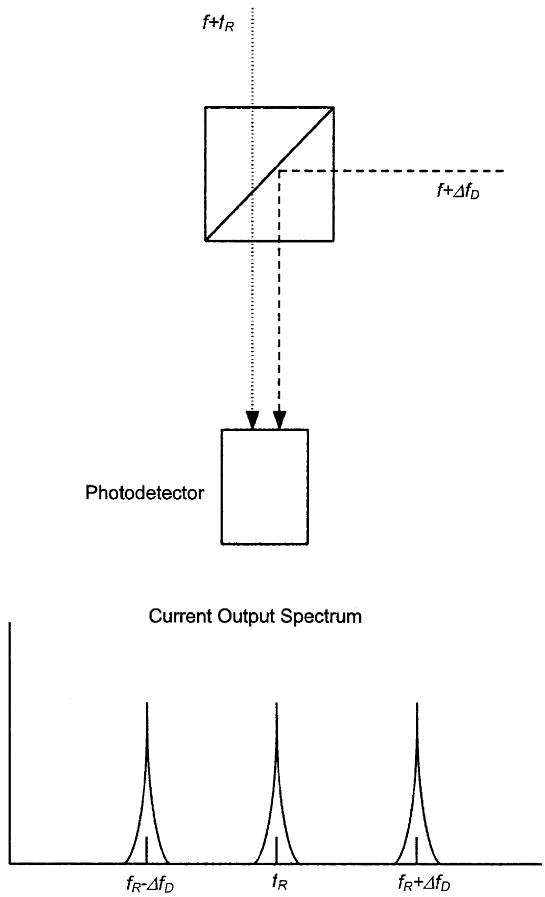


Fig. 1. Basic operation of a laser Doppler velocimeter.

instrument is used. The optical path length, defined as the product of refractive index with distance travelled by an optical beam, is consequently modified by variations in pressure along the beam. Therefore, it is important to consider the voltage output to be representative of the overall rate of change of optical path length, consisting of both the velocity of the reflecting target and that caused by the pressure induced refractive index changes within the volume. In the experimentation reported in Sections 3.3 and 4.3, the voltage output from the LDV is entirely representative of the changes within the media, since the position of the reflecting target was fixed.

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. If the acoustic field consists of a continuous wave of single frequency, f, the time-resolved pressure amplitude at a point along the line, $P(z,t)$, can be described as

$$P(z,t) = P_0(z)\sin(2\pi ft + \phi(z)), \tag{2}$$

where $P_0(z)$ and $\phi(z)$ are the unknown amplitude and phase distributions along the line, respectively.

The refractive index at a point along the line, $n(z,t)$ is related to the pressure variation

$$n(z,t) = N_0 + \left(\frac{\partial n}{\partial P}\right)_s P(z,t), \tag{3}$$

where N_0 is the ambient refractive index of the media, and $(\partial n/\partial P)_s$ is the adiabatic piezooptic coefficient [23].

From this the optical path length, $L(t)$ can be given as

$$L(t) = L_0 + 2\int_0^z n(z,t)\,\mathrm{d}z,$$
$$L_0 = 2N_0 Z, \tag{4}$$

where L_0 is the ambient optical path length through the media, and Z is the width of the acoustic field.

Hence the rate of change of optical path length, $\mathrm{d}L(t)/\mathrm{d}t$, is

$$\frac{\mathrm{d}L(t)}{\mathrm{d}t} = \frac{\mathrm{d}(2\int_0^z n(z,t)\,\mathrm{d}z)}{\mathrm{d}t}. \tag{5}$$

Thus, the variation in pressure amplitude and phase along a line section through a volume can be shown to influence the rate of change of optical path length as follows:

$$\frac{\mathrm{d}L(t)}{\mathrm{d}t} = \frac{\mathrm{d}(2\int_0^z ((\partial n/\partial P)_s P_0(z)\sin(2\pi ft + \phi(z)))\,\mathrm{d}z)}{\mathrm{d}t}. \tag{6}$$

3. Experimental methodology

In each of the experiments described, the acoustic excitation consists of a single-frequency tone-burst containing a finite number of cycles. This was achieved using a Hewlett-Packard HP8111A pulse/function generator in tandem with a Philips PM5134 function generator. A time delay, sufficiently long to allow the sound to die away is included between these signals, to minimize interference between successive bursts. The time taken for a burst to die away is determined by the reverberation characteristics of the tank. The choice of frequency was restricted by the need to record a finite number of cycles of sound, usually 10, before the first sound reflected from surface interfaces arrived to interfere with the measurement. The waveforms were recorded on a LeCroy 9314CL Digital Oscilloscope and consisted of an average of 20 independent tone bursts triggered from the source input voltage. The LDV used was a Polytec Scanning Vibrometer, consisting of an OFV-056 Scan Head and an OFV-3001-S LDV controller.

3.1. Comparison of LDV and NPL Laser Interferometer

A direct comparison was made between the LDV and NPL Laser Interferometer (NPL LI). Whilst the geometric arrangement of each instrument was the same, the quantities measured by each were different. The LDV used the difference in frequency between the target and reference beams to provide a measure of the rate of change of optical path length (velocity), whereas the NPL LI compared the phase of the target and reference beams to provide a measure of the change of optical path length (displacement). Each instrument was used to measure the motion of a 100 mm diameter, 5 μm in thick Mylar 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 Fig. 2. 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.

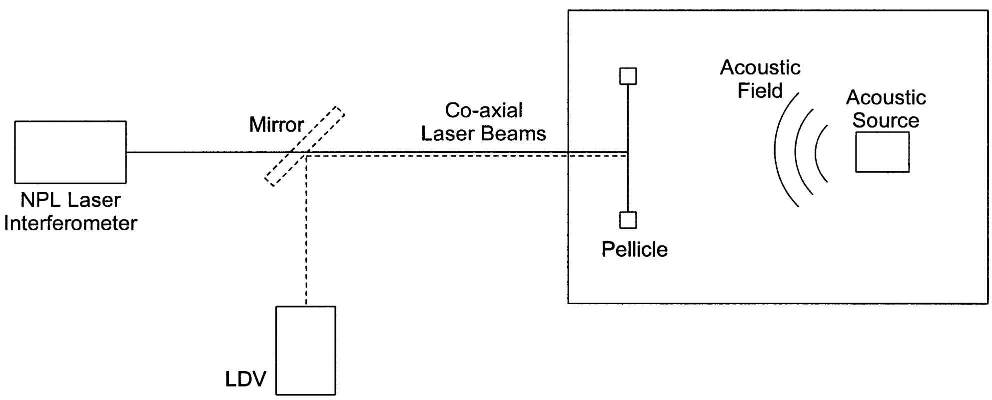


Fig. 2. Measurements from a pellicle using NPL Laser Interferometer and LDV.

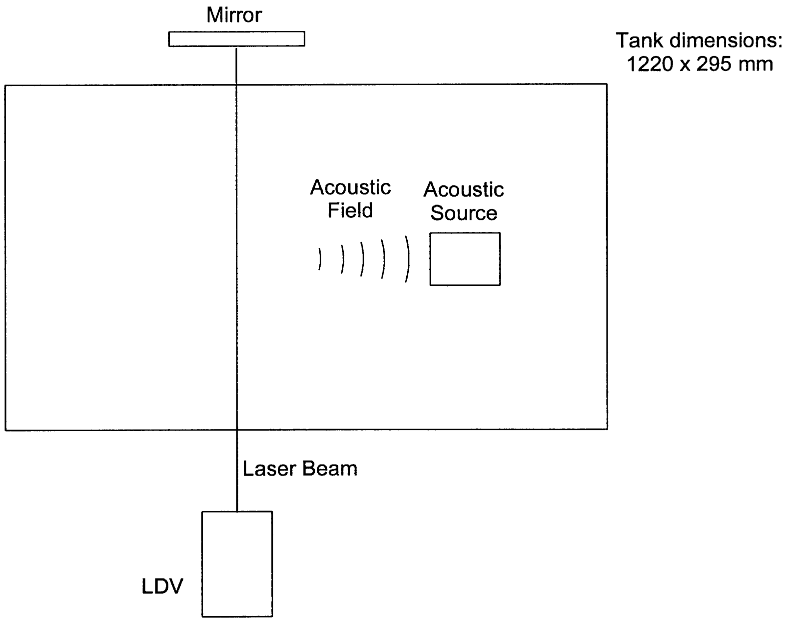


Fig. 3. LDV measurements directly from an acoustic field.

3.2. Measurements directly from an acoustic field

As has been previously reported [24], an LDV system can be used to identify the presence, and temporal distribution of an acoustic field at a linear intersection through an acoustic field, given by the position of the optical beam. The laser beam passed through the acoustic field and was reflected back along its axis by a mirror placed on the opposing side of the acoustic field, outside of the acoustic environment. This arrangement greatly simplifies the alignment procedure and also doubles the path travelled by the beam, thus increasing the sensitivity by a factor of two. For the geometry of the tank and acoustic field used in the laboratory, it is assumed that time taken for the light to travel from the laser to the reflecting mirror and return to the collecting optics (3.3×10^{-9} s), is negligible in comparison to the period of the acoustic wave being measured (2.0×10^{-6} s). The arrangement used to complete such measurements is shown in Fig. 3.

3.3. Comparison of LDV with hydrophone measurements

A specific line section through a 500 kHz frequency acoustic field was interrogated by the LDV for the 1, 10 and 20 cycle tone-bursts. Single-point hydrophone measurements of pressure were then recorded using an ITC6128 hydrophone at fixed positions along the same line through the field, as depicted in Fig. 4. The time-resolved pressure measurements were then scaled to obtain time-resolved refractive index changes using the temperature-dependent adiabatic piezo-optic coefficient, estimated by interpolation to be 1.491×10^{-10} Pa^{-1} for water at 16.5°C [23]. The adiabatic partial derivative is used since the acoustic period is too short for any heat transfer to take place.

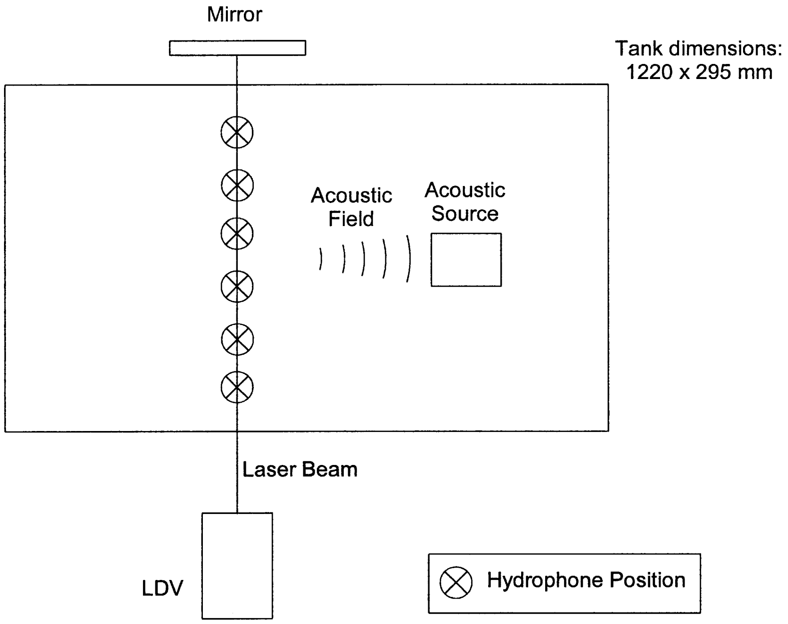


Fig. 4. Discrete hydrophone measurements along the optical axis of the LDV.

These time histories were then integrated with distance along the line using a simple trapezoidal integration method and knowledge of the separation of the hydrophone measurements (20 mm), to obtain a value for the change in optical path length along the axis of the beam. The result was then doubled to account for the dual pass of the beam through the acoustic field. Since the LDV records a measure of the first time differential of optical path length, the optical path length derived from the hydrophone measurements was differentiated with time to enable a direct comparison to be made with the LDV. The ambient optical path length is of immaterial interest since the term is lost during the differentiation.

3.4. Calculation of minimum resolvable amplitude of LDV measurements

In characterizing 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. The noise floor is a measure of the purity of the signal and can be established by examining the content of the magnitude spectral density (MSD) of a section of LDV signal where no acoustic field is being detected. It is dependent on both the optics, electronics and software of the LDV, as well as the properties of the media and reflective target.

The noise voltage signal from the LDV was integrated with time to provide a measure of the path length change and appropriately scaled to obtain approximate values of peak pressure. The scaling factor used was calculated as being the pressure amplitude of the central discrete hydrophone measurement of the 20-cycle tone-burst divided by the displacement amplitude of the

LDV measurement for the same acoustic signal. Similarly, the noise voltage from the hydrophone was converted into values of pressure using its sensitivity factor.

Magnitude spectral densities were calculated from the pressure data for each trace. Convention within acoustics theory and application dictates the minimum resolvable signal level to be 3 dB greater than the typical noise over a given frequency range in the MSD.

4. Results and discussion

4.1. Comparison of LDV and NPL Laser Interferometer

A three-way comparison was made between the LDV, the NPL Laser Interferometer 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 NPL 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 all three devices.

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.

As shown in Table 1, at 500 kHz, agreement between the two optical measurements is within 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 experimental set-up, thus it can be concluded that the agreement between the NPL LI and the LDV is similar to that of the two

Table 1
NPL Laser Interferometer and LDV data from a 50 kHz plane piston transducer

	Drive voltage (mV)		Displacement (nm)	Velocity (m/s)
500 kHz Plane piston transducer	350	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	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 2
NPL Laser Interferometer and LDV data from a 1 MHz plane piston transducer

	Drive voltage (mV)		Displacement (nm)	Velocity (m/s)
1 MHz Plane piston transducer	350	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	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
NPL Laser Interferometer and LDV data from a 1 MHz focused transducer

	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}

hydrophone measurements. Furthermore, it is an indication of one of the possible routine sources of uncertainty when using hydrophones.

For the plane piston transducer at 1 MHz, as shown in Table 2, the agreement is an improvement on the 500 kHz measurements; within 2.5% at 350 mV 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 the two hydrophones.

The results from the 1 MHz focused transducer shown in Table 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.

4.2. *Measurements directly from an acoustic field*

A comparison of the shape and form of the drive voltage to the transducer, shown in Fig. 5a, with the output voltage (representing the rate of change of optical path length) from the LDV when passed through an acoustic field, shown in Fig. 5b, shows good agreement. For the 20-cycle

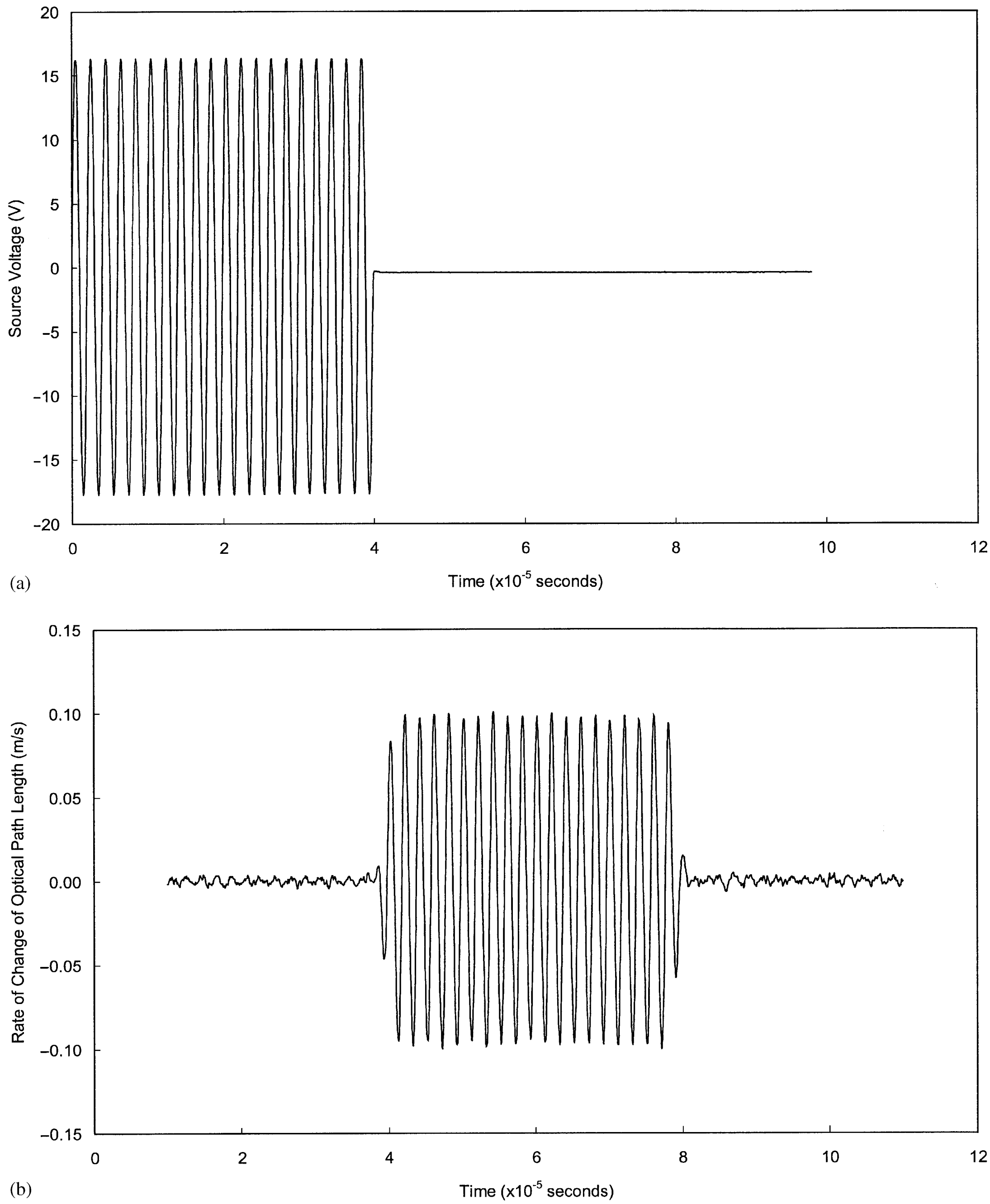
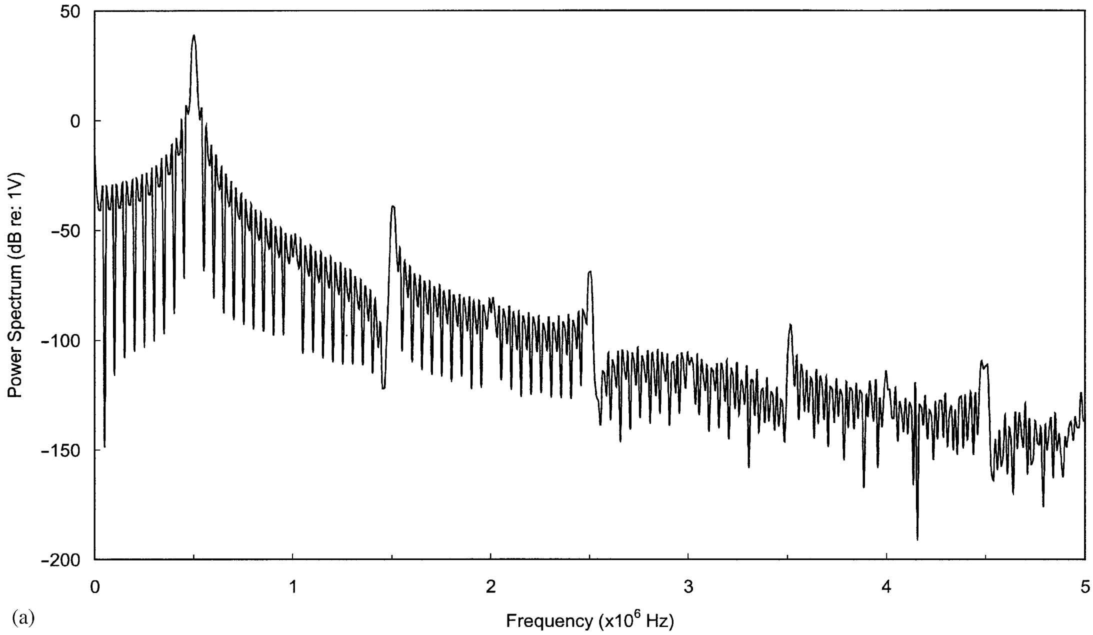
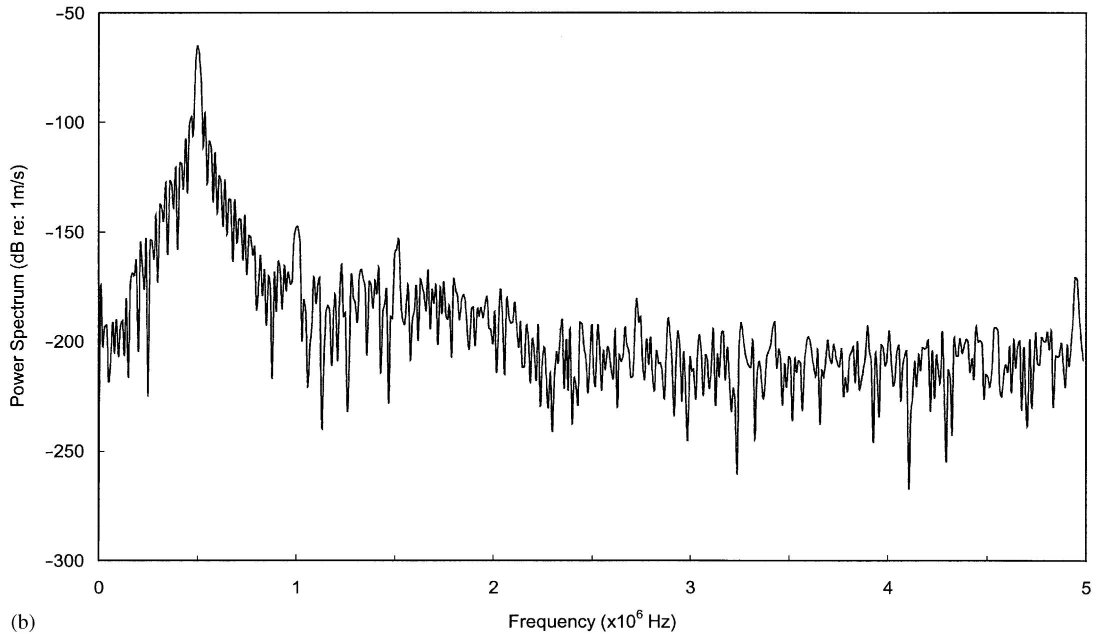


Fig. 5. (a) Drive voltage to the acoustic transducer. (b) Rate of change of optical path length measured by LDV.

tone-burst, the number of cycles recorded is consistent with the drive voltage and DFTs of the signals, shown in Figs. 6a and b respectively, demonstrate the consistency in the fundamental frequency components in each trace. It is valid to make such a comparison since the transducer



(a)



(b)

Fig. 6. (a) Power spectrum of drive voltage to acoustic transducer. (b) Power spectrum of rate of change of optical path length measured by LDV.

used had a low-Q and was used near to its resonance frequency. For this reason the acoustic signal would be expected to bear close resemblance with the input drive signal. This comparison highlights the broad band, non-perturbing benefits of the LDV technique over those of a hydrophone, which may introduce artefacts into the measured signal. In general, however, the acoustic signal may not be as closely representative of the drive signal due to the presence of turn-on and turn-off transients, and other resonance effects.

4.3. Comparison of LDV with hydrophone measurements

Measurements of a 500 kHz signal of 1, 10 and 20 cycles in duration, respectively, from a focused transducer repeated at 50 Hz were made by passing the LDV through the field. Two such measurements were made of each tone-burst and an average signal calculated for each.

Discrete measurements were then taken at 12 positions along the line of the optical beam using an ITC6128 hydrophone. These, together with knowledge of the spacing between the hydrophone positions (20 mm) were used to give an approximation of the rate of change of optical path length as described by the opto-acoustic theory (Section 2). Results for 1- and 20-cycle tone-bursts are given in Figs. 7a and b, respectively, where the solid line represents the LDV measurement and the broken line represents the rate of change of optical path length derived from the hydrophone measurements. A DFT of an integer number of cycles within the tone-burst was calculated for each measurement. The amplitudes of the 500 kHz component, shown in Table 4 demonstrate a consistent correlation where the measurement from the LDV is approximately 40% of the derived equivalent from the hydrophone measurements.

For the case of the 20-cycle tone-burst measurement the two signals can be seen to differ in phase by approximately 180°. Closer inspection of the initial detection of the signal by both devices reveals that the derived hydrophone measurement leads the LDV measurement by 8×10^{-7} s. This equates to a distance travelled by the sound of approximately 1.2 mm in water. The centre of the hydrophone element was aligned with the laser beam from the LDV at each measurement position to within approximately 1 mm. Since the distance from the laser beam to the front surface of the hydrophone casing was approximately 4 mm, it can be concluded that the apparent centre of the hydrophone for these measurements is midway between its front surface and its geometric centre. Such an effect is to be anticipated, since only when the acoustic wavelength is much greater than the element size will the apparent hydrophone centre coincide with the geometric hydrophone centre. 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.

An example of the difference between the physical measurement device and the optical technique is also evident during the signal decay, as shown in Fig. 8.

The signal derived from the hydrophone measurements (dotted line) consists of the main 20 cycles followed by 3–5 cycles where the element is 'ringing'. An approximation of the ringing frequency was made by measuring the duration of the first 4 of these cycles to be 7.3 μs. This corresponds to a frequency of approximately 550 kHz, which is known to be a resonance frequency of the hydrophone. A similar 'ringing' can also be observed in the 1-cycle hydrophone measurement. The LDV measurement in each case contains the 1- or 20-cycle tone-burst without any further oscillations originating from the physical properties of the measurement device (solid line in Fig. 8). Consequently, any further signal processing of the LDV data would result in fewer spurious data and noise terms.

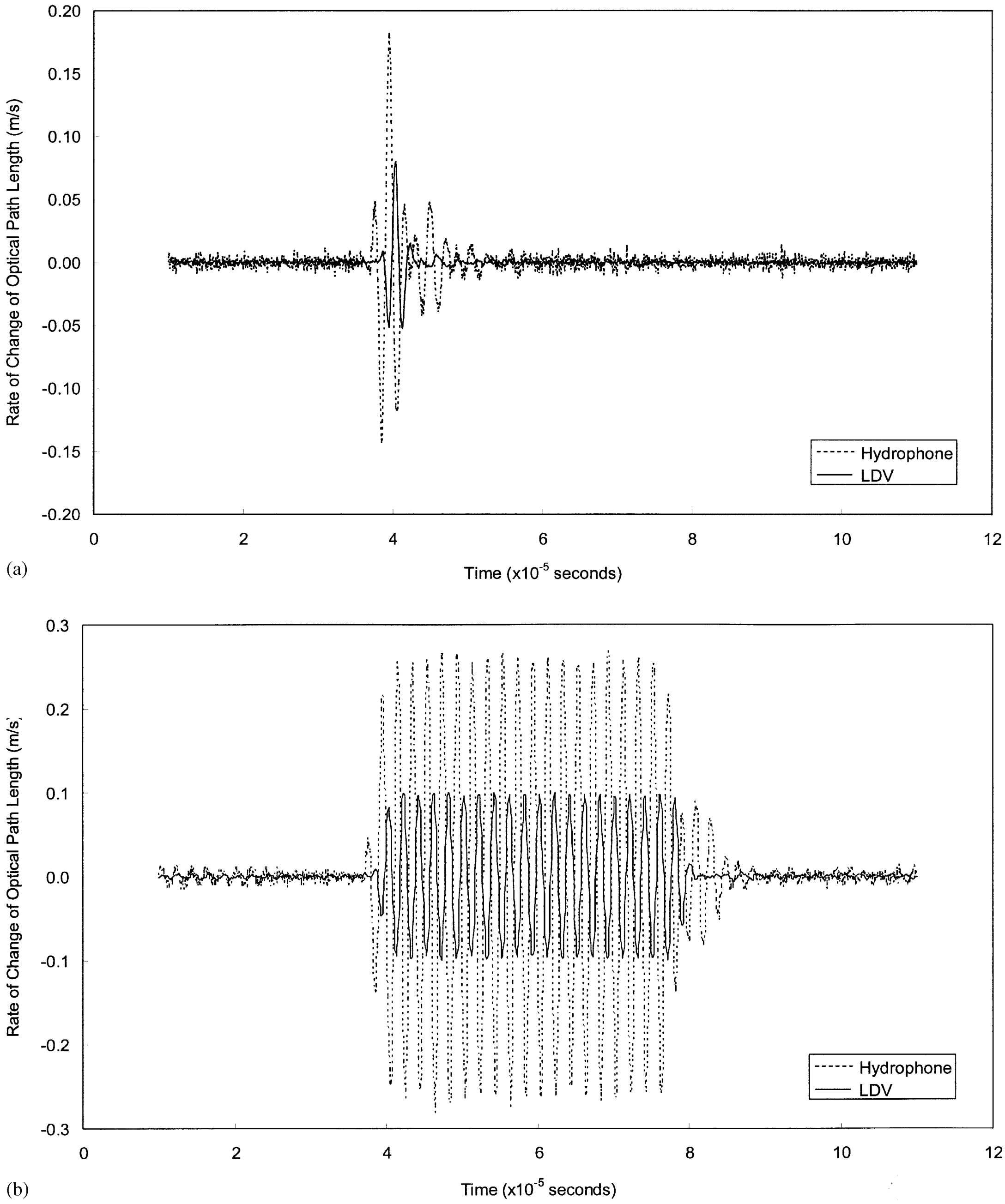


Fig. 7. (a) LDV and hydrophone measurements of 1-cycle tone-burst. (b) LDV and hydrophone measurements of 20-cycle tone-burst.

At 500 kHz, the initial response of the hydrophone is good since it is close to its 550 kHz resonance frequency. In the case of the 1-cycle measurement however, a DFT of a wider sample of data, shown in Fig. 9a demonstrates the influence of this resonance, since the largest frequency

Table 4
Rate of change of optical path length measured by the LDV and derived from the hydrophone using the measured spacing increments

	Tone-burst	Measured rate of change of optical path length (m/s)	
		LDV	Hydrophone
500 kHz	1-cycle	62.6×10^{-3}	153.1×10^{-3}
Focused	10-cycle	93.9×10^{-3}	252.8×10^{-3}
transducer	20-cycle	97.1×10^{-3}	255.7×10^{-3}

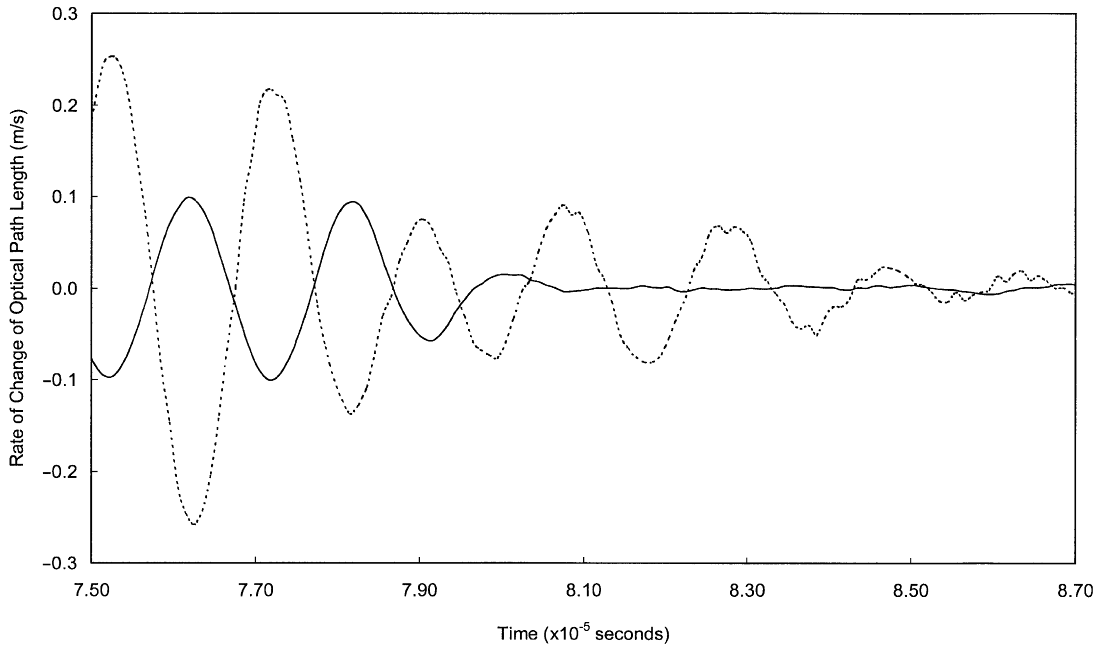


Fig. 8. Post signal decay of 20-cycle tone-burst measured by LDV and Hydrophone.

component is found at 550 kHz, followed closely by another known resonance at 380 kHz. For the case of the 20-cycle DFT, shown in Fig. 9b, the frequency of the acoustic field overshadows that of the resonance frequency.

Due to the highly non-linear spatial pressure distribution of a field generated by a focused transducer, it was appreciated that the integration of discrete measurements of pressure, each separated by 20 mm, with distance using a trapezoidal approximation would not truly account for the tight focus of the pressure field. Since the measurement at the focus is at least an order of magnitude greater in amplitude than those nearer the edge of the tank, but is known to decay very rapidly with radial distance from its centre, any discrepancy between the central hydrophone position and the location of the focus of the field would drastically influence the integration. The discrepancy between the LDV measurement and the equivalent quantity derived from the hydrophone measurements was attributed to this source of error in the integration process.

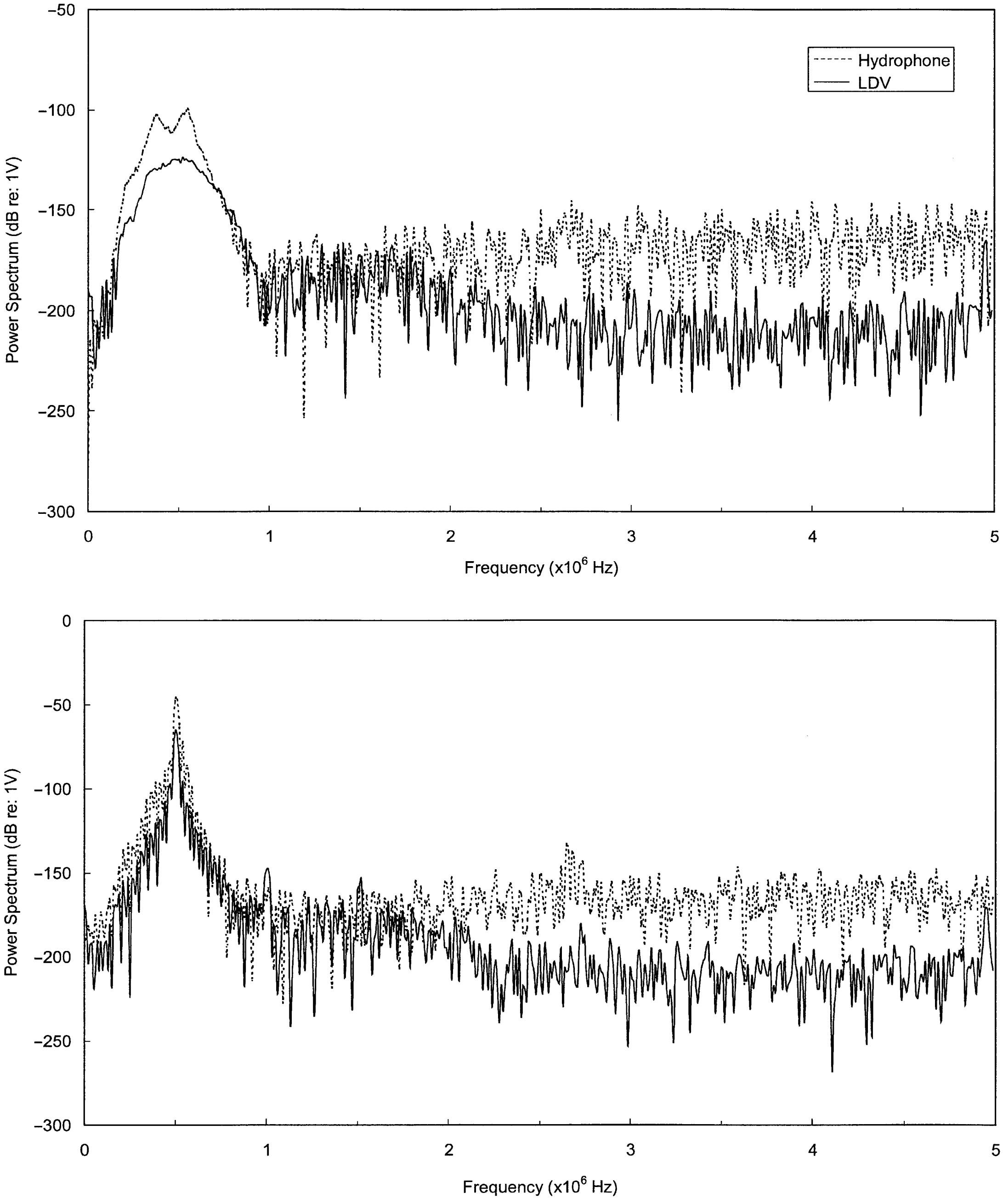


Fig. 9. (a) Power spectrum of LDV and hydrophone measurements of 1-cycle tone-burst. (b) Power spectrum of LDV and hydrophone measurements of 20-cycle tone-burst.

Table 5
Calculation of the minimum resolvable pressure amplitudes of the LDV and the hydrophone

	LDV	Hydrophone	
Noise floor	−82.4	−92.4	(dB re: 1 Pa/$\sqrt{}$Hz)
Min sensitivity	18.9×10^{-3}	11.4×10^{-3}	(Pa/$\sqrt{}$Hz)

4.4. Calculation of minimum resolvable amplitude of LDV measurements

Calculations were undertaken to establish the minimum resolvable pressure amplitude of both the LDV system and the hydrophone in the configuration previously described. The LDV data used was the signal generated prior to the arrival of the acoustic tone-burst in the comparison experiment of Section 4.3. The hydrophone data used was the equivalent section of signal from the hydrophone measurement at the centre (focus) of the field. The noise floor values given in Table 5 represent an average of the MSD in a 5 MHz band. Under more controlled conditions, where the acoustic signal is allowed to fully die away before a measurement of the noise is made, it is anticipated that the values would be less both for the LDV and the hydrophone.

A signal level of 3 dB greater than the noise floor equates to a minimum resolvable signal level of approximately 18.9 mPa/$\sqrt{}$Hz for the LDV and approximately 11.4 mPa/$\sqrt{}$Hz for the hydrophone. Increasing the number of averages taken is likely to reduce these values. Other measures designed to maximise the quality of the reflected light from the mirror and reduce potential vibrations of the LDV or reflecting mirror would also reduce the minimum signal resolvable using the LDV.

5. Conclusions

The Laser Doppler Velocimeter (LDV) has been demonstrated to offer an alternative to existing techniques for the measurement of underwater acoustic pressure. In contrast to the traditional reciprocity method of calibration, optical techniques avoid the reliance on possessing well-behaved reciprocal transducers. Significantly, in the case of LDV, secondary elements within the acoustic volume (pellicle) are not required to complete the measurement.

It has been shown to agree well with the NPL Laser Interferometer, the current primary standard in the UK and a calibrated membrane hydrophone, although it served also to highlight the problems involved in the alignment of the components, particularly in the case of a focused transducer.

The LDV has also been shown to be capable of identifying the spatial and temporal presence of an acoustic signal without perturbing the acoustic volume in any way, by measuring the pressure-induced refractive index changes in the volume. Rate of change of optical path length measurements from the LDV have been shown to recreate the drive signal to the acoustic source, both in shape, duration and frequency content. It is appreciated that the use of a low-Q transducer at resonance facilitated this.

A comparison of the rate of change of optical path length as measured by the LDV, with the first time differential of the hydrophone pressure measurements integrated with distance along the optical axis through the acoustic field, have shown a consistent correlation. The LDV signal is approximately 40% of the amplitude of the derived hydrophone measurement in each measurement scenario. This difference can be attributed to the highly non-linear spatial distribution of the pressure amplitude along the line section generated by the focused transducer used. The discrepancy could also be attributed to errors in the hydrophone sensitivity, which was found to be highly frequency dependent at 500 kHz. Additionally, errors would have been present in the measurement of the distance between discrete hydrophone positions, the measurement of temperature and the interpolation of the piezo-optic coefficient.

The broadband frequency response of the LDV system was shown to offer significant benefit in providing a faithful reproduction of the acoustic field. This was demonstrated in the LDV measurement where far fewer spurious pressure cycles were present than in the case of the hydrophone measurement. Here, ringing in the hydrophone element suggested the acoustic signal to be longer in duration than was the case. From the DFT of the single cycle tone-bursts, it can be seen that the response of the hydrophone is characterised by the resonance frequency components, making it unlikely for an accurate pressure measurement to be made. However, the frequency components of the LDV signal are shown to represent the original signal more accurately.

Spatially locating the measurement position within the acoustic volume, which is extremely important when making accurate phase measurements, was found to be more accurate using the LDV than the hydrophone, where the apparent hydrophone centre was displaced from the geometric hydrophone centre. This ability for improved resolution in spatial positioning is a significant benefit of the LDV technique. Furthermore, the approximate minimum resolvable signal of the LDV system (18.9 $mPa/\sqrt{Hz}$) was shown to compare well with that of the hydrophone (11.4 $mPa/\sqrt{Hz}$).

Given the ability of the LDV to record signals representative of the pressure amplitude and phase directly from an acoustic field, it follows that an adapted LDV system would have the potential to be used to map the whole-field spatial distribution of an acoustic field. Work of this nature has begun, the results of which will be reported in due course.

Acknowledgements

Acknowledgement is given to Dr. Steve Rothberg of Loughborough University for his assistance and advice in this work. Special thanks must also be given to Roger Traynor of LAMBDA Photometrics Ltd. for the loan of the Polytec Laser Doppler Velocimetry equipment, and the technical assistance provided by LAMBDA Photometrics Ltd. and Polytec GmbH.

References

[1] R.C. Preston (Ed.), Output Measurements for Medical Ultrasound, Springer, Berlin, 1991, ISBN 3-540-19692-7.
[2] A.B. Coppens, Simple equations for the speed of sound in Neptunian waters, The Journal of the Acoustical Society of America 69 (3) (1981) 862–863.

[3] C.-T. Chen, F.J. Millero, Speed of sound in seawater at high pressures, The Journal of the Acoustical Society of America 62 (5) (1977) 1129–1135.
[4] K.V. Mackenzie, Nine-term equation for the speed of sound in the oceans, The Journal of the Acoustical Society of America 70 (3) (1981) 807–812.
[5] V.A. Del Grosso, New equation for the speed of sound in natural waters (with comparisons to other equations), The Journal of the Acoustical Society of America 56 (4) (1974) 1084–1091.
[6] G.S.K. Wong, S. Zhu, Speed of sound in seawater as a function of salinity, temperature and pressure, The Journal of the Acoustical Society of America 97 (3) (1995) 1732–1736.
[7] R.J. Bobber, Underwater Electroacoustic Measurements, Peninsula Publishing, Los Altos California, USA, 1988, ISBN 0-932146-19-8.
[8] W.R. MacLean, Absolute measurement of sound without a primary standard, The Journal of the Acoustical Society of America 12 (1940) 140–146.
[9] R.K. Cook, Absolute pressure calibration of microphones, The Journal of the Acoustical Society of America 12 (1941) 415–420.
[10] IEC 60565, The calibration of hydrophones, International Electrotechnical Commission, Geneva, 1977.
[11] S.P. Robinson, M.A. Bangash, A comparison of hydrophone calibration by free-field reciprocity and by optical interferometry in the frequency range 200 kHz to 1 MHz, Proceedings of the Institute of Acoustics 20(3) (1998) 139–146.
[12] S.P. Robinson, G.R. Doré, Uncertainties 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)0054, 1994.
[13] D.R. Bacon, Primary calibration of ultrasonic hydrophones using optical interferometry, IEEE Transactions Ultrasonics, Ferroelectrics and Frequency Control 35 (2) (1988) 152–160.
[14] R.C. Preston, S.P. Robinson, B. Zeqiri, T.J. Esward, P.N. Gélat, N.D. Lee, Primary calibration of membrane hydrophones in the frequency range 0.5 MHz to 60 MHz, Metrologia 36 (1999) 331–343.
[15] C.V. Raman, N.S. Nagendra Nath, The diffraction of light by high frequency sound waves: Part 1, Proceedings of the Indian Academy of Sciences 2 (1935) 406–420.
[16] P. Kwiek, W. Molkenstruck, R. Reibold, Optical mapping of ultrasonic fields using Bragg incidence, Ultrasonics 36 (1998) 775–781.
[17] R.I. Crickmore, The use of a laser hydrophone as a means of acoustic calibration, Proceedings of the Institute of Acoustics 20(3) (1988) 123–130.
[18] J.F. Vignola, Y.H. Berthelot, J. Jarzynski, Laser detection of sound, The Journal of the Acoustical Society of America 90 (3) (1991) 1275–1286.
[19] S.H. Jack, D.B. Hann, C.A. Greated, The influence of a standing wave on laser Doppler signals, Measurement Science and Technology 10 (12) (1999) 1279–1285.
[20] T.A. Pitts, J.F. Greenleaf, Three-dimensional optical measurement of instantaneous pressure, The Journal of the Acoustical Society of America 108 (6) (2000) 2873–2883.
[21] National Measurement System, NMS Programme for Quantum Metrology, Department of Trade and Industry, London, UK, April 2001–March 2004.
[22] D.C. Williams, Optical methods in Engineering Metrology, Chapman & Hall, London, 1993, ISBN 0-412-39640-8.
[23] C.B. Scruby, L.E. Drain, Laser Ultrasonics Techniques and Applications, Adam Hilger, Bristol, 1990, ISBN 0-7503-0050-7.
[24] A.R. Harland, J.N. Petzing, J.R. Tyrer, Non-invasive measurements of underwater pressure fields using Laser Doppler Velocimetry, Journal of Sound and Vibration 252 (1) (2002) 169–177.