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ABSTRACT

This report summarises the work undertaken on a project whose overall aim was to progress towards the development of fundamental standards for acoustics based on optical methods. The favoured approach for achieving this for sound in water is particle velocity measurement using heterodyne interferometry and a reflecting membrane in the acoustic field. This report focuses on the pilot facility established for this using a new 'all-fibre' heterodyne interferometer and a reflective membrane supported in the acoustic field. For sound in air, the adopted method is Laser Doppler Anemometry using photon-correlation analysis techniques.

This report is part of the Deliverable for the Phase Four Work Package for Project 3.6 of the NMS Quantum Metrology Programme for the UK Department of Trade and Industry. The Phase Four Work Package also included a number of other Deliverables which included the output of two journal papers and the delivery of an all-fibre heterodyne interferometer for sound in water. A total of four journal papers have been drafted and the optical measurement system is due for delivery within a month of the end of the project. The project was undertaken by a consortium of the National Physical Laboratory and Loughborough University, with Laser Optical Engineering Ltd. as a sub-contractor for the sound in water aspect of the project and University of Edinburgh, with Qinetiq as a sub-contractor for the sound in air aspect of the project. The project also benefited from a guest worker from the Hangzhou Applied Acoustics Research Institute, China.

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Approved on behalf of the Managing Director, NPL
by Dr R C Preston, authorised by Director for Quality of Life Division

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1 INTRODUCTION

1.1 Project details

This project aims to lay the foundation for a new generation of primary acoustical measurement standards based on optical techniques for both sound in air and sound in water. The project entitled 'Fundamental standards for acoustics based on optical methods' is Project 3.6 of the National Measurement System (NMS) 2001-2004 Quantum Metrology Programme of the UK Department of Trade and Industry. The project is being undertaken by a consortium of the National Physical Laboratory (NPL), Loughborough University (LU), Edinburgh University (EU), with Laser Optical Engineering Ltd. (LOE) and QinetiQ as sub-contractors. This report details progress on Phase Four and aims to summarise the overall project.

Phases One, Two and Three of the project work were reported in the Phase One [1], Two [5] and Three [6] reports respectively. The Phase One report included a comprehensive review of the literature, detailed the requirements for new sound in water and sound in water air standards and provided the rationale for using optical methods. This report further proposed the use of Laser Doppler Anemometry using photon correlation for the sound in air aspect of the project. The Phase Two report proposed the use of an all-fibre heterodyne interferometer for reflecting from a membrane in the acoustic field and detailed the development and initial testing of the all-fibre heterodyne interferometer. The Phase Three report presented the results of a series of sound in water acoustic measurements using a number of optical techniques. The method of using a thin, narrow membrane was explored in details and shown to provide accurate velocity measurement from a few kilohertz to over 500 kHz. Progress on the development and testing of the all-fibre heterodyne interferometer was also reported showing comparison results with a reference hydrophone.

1.2 Background

For a user of a microphone or hydrophone, most often the important performance characteristic is its free-field sensitivity as a function of frequency. The definition of free-field sensitivity of a microphone or hydrophone, is 'the ratio of the open-circuit voltage from the transducer to the sound pressure in a plane progressive wave at the position of the acoustic centre of the transducer in its absence'. A direct calibration method would therefore involve the determination of the sound pressure at the point of interest, placing the transducer in the field so that its acoustic centre aligned with that point, and measuring the resulting open-circuit voltage. However, such calibration methods do not exist currently.

Reciprocity calibration is the established and internationally recognised method for the primary calibration of microphones and hydrophones. Here, two transducers are placed in the field where the calibration is to be conducted (e.g. a free-field chamber or open water tank), usually facing each other and separated by a known distance. One is driven by an electrical current and is used as a sound transmitter. It emits waves that are assumed to be plane when they reach the second transducer. The second transducer then responds to the sound pressure, resulting in an output voltage. The ratio of the output voltage to the input current, and the ratio of the sound pressure acting on the receiver to the volume velocity produced by the transmitter, are known as the electrical and acoustical transfer impedances respectively. If these can be determined, then the sensitivity product of the coupled transducers can be derived. Introducing a third transducer and repeating the process enables each to be calibrated individually. Therefore, the reciprocity method can be implemented without the need to measure absolute field parameters (e.g. sound pressure). This has been its strength and the main reason why it displaced other calibration methods in the 1960s. However its indirect approach leads to debate about whether it should be considered as a primary calibration method. It also leads to fundamental limitations on the degree to which uncertainty in realising the acoustic pascal can be reduced in the future.

An optical method of acoustic detection, which enabled the determination of an acoustic field quantity at a point, would not have the same dependence on transducer characteristics and would facilitate a more direct realisation of the acoustic pascal. Optical methods provide the potential for very accurate velocity and thus pressure measurement at a point in the acoustic field, traceable to the wavelength of light. This report describes work undertaken within Project 3.6 of the National Measurement System (NMS) 2001-2004 Quantum Metrology Programme to develop optical methods which could further be developed as future primary standards for both sound in air and sound in water using laser Doppler anemometry and laser Doppler interferometry respectively.

2 SOUND IN WATER

2.1 Introduction

As described in the Phase One report [1], the current primary standard calibration method for hydrophones used in underwater acoustics is the three-transducer spherical-wave reciprocity method [2]. Although this method is long established and widely used, in terms of a primary standard it has a number of limitations:

- It is reliant on at least one of the hydrophones being reciprocal (i.e. linear, passive and reversible), a difficult thing to prove in practice to better than 1% or 2%.
- The method depends on assumptions about the geometry of the acoustic field, for example that it is spherically spreading. This is sometimes difficult to achieve in a laboratory tank.
- The method does not make a direct measurement of an acoustical quantity, and hence does not directly establish the SI unit of acoustic pressure.

In the frequency range 1 kHz to 500 kHz, the overall uncertainties in the reciprocity method are of the order of 5% (expressed for a 95% confidence level). Whilst this level of accuracy meets the needs of many current industrial customers, for the most demanding requirements there is a need to improve the absolute accuracy by a factor of two. Furthermore, there is currently little "headroom" between existing primary standards and the uncertainties of approximately 0.5 dB to 1 dB sought by the majority of users.

In order to perform a free-field calibration of a hydrophone, it must be exposed to a known acoustic pressure, p, in a plane-wave field at the position of the hydrophone before it was introduced. Although interferometry does not provide a direct measure of acoustic pressure, it offers a method to measure directly the acoustic particle velocity, u, from which the acoustic pressure can be derived using equation (1) for a plane-wave acoustic field.

$$p = \rho c u \tag{1}$$

where ρ is the density and c is the speed of sound in the medium. Thus an acoustic pressure of 50 Pa is equivalent to an acoustic particle velocity of 30 μm s^{-1}. Direct measurement of acoustic particle velocity can be achieved by employing a laser Doppler interferometric technique, where the interferometer is designed to be sensitive to a frequency shift between the reference arm and the measurement arm. The Doppler frequency shift, $\delta\nu$, can be related to the laser wavelength λ and the particle velocity vector u by the following equation [3]:

$$\delta\nu = \frac{2u}{\lambda}\cos\beta\cos\left(\frac{1}{2}\phi\right) \tag{2}$$

where β is the angle the velocity vector u makes with the bisector of the incident and reflected beams. In practice, the incident and reflected beams are aligned so that they traverse similar paths such that $\phi \to 0$. The Doppler shift can therefore be written as:

$$\delta\nu = \frac{2u}{\lambda}\cos\beta\ . \tag{3}$$

With knowledge of the laser wavelength, this Doppler beat frequency obtained from the detector allows determination of the absolute particle velocity.

The method for calibration would then be similar to the direct comparison method used at NPL for the calibration of hydrophones above 500 kHz [4].

The choice of interferometer design and configuration for this project was dictated by a number of factors:

- The requirement for a measurement within the acoustic field.
- Complete understanding of signal processing.
- The ability to provide traceability to the wavelength of light via a quantified route.

As described in the Phase One Report [1], the desired method of acoustic pressure determination is the measurement of acoustic particle velocity, using a heterodyne interferometer with the measurement beam incident on a reflective, acoustically compliant membrane in the acoustic field.

2.2 Design and development of all-fibre heterodyne interferometer

The initial target specification for the sound-in-water facility were covered in detail in the Phase One report [1]. However, the parts of the specification particularly related to the interferometer design were:

- Frequency calibration range of 1 kHz to 500 kHz;
- Measurement is required of the acoustic pressure or some other field parameter, particle velocity for example, from which the acoustic pressure can be derived;
- Spatial resolution of 0.3 mm to approximate a point receiver;
- RMS noise equivalent velocity of 10 μm s^{-1} is required in a 200 kHz bandwidth;
- Facility designed to reduce the interaction of the acoustic and optical beams. Any interaction that occurs should do so in a manner that is well understood so that corrections may be applied;
- Robust system such that it can be applied for use in the large NPL open tank. This means delivering the interferometer measurement beam to a depth of 2.5 m to the central area of a 5.5 m diameter tank.

To meet this specification it was decided that an all-fibre design of heterodyne interferometer would be required given that existing commercial bulk optic designs did not meet required criteria. The reasons for this were covered extensively in the Phase One [1], Phase Two [5] and Phase Three [6] reports along with design highlights of the developed all-fibre heterodyne interferometer. Some of the advantages of the developed system are:

i. Commercial systems are effective black box units which if and when calibrated are done so against vibration standards similar to accelerometers. Hardware and software signal processing is used with many interdependent options making the interpretation of measured signals complex which inhibit and complicate traceability. The all-fibre interferometer developed for this project is modularised to allow characterisation of every stage. Measurement of the Doppler signal provides traceability to the wavelength of light, meaning that traceable measurement of the Doppler frequency shift allows traceable measurement of acoustic velocity. The Doppler decoder stage on the all-fibre vibrometer can be calibrated against existing frequency standards.

ii. The heterodyne configuration coupled with optical Doppler measurement provides far greater low frequency stability than a standard phase or homodyne interferometer.

iii. The use of Doppler analysis overcomes the linear dynamic range limitations of phase locked interferometers.

iv. Measurement of the Doppler shift further makes the interferometer more robust to environmental conditions that may affect the light level.

v. All commercial vibrometers are based on 633 nm laser light which is not suited for propagation in water. The developed all-fibre heterodyne interferometer uses a 532 nm laser source for low attenuation in water. Using 532 nm also allows an Nd:YAG laser to be used in place of a standard He-Ne laser. This allows single frequency mode operation at much higher power levels than is possible with a He-Ne type. The all-fibre design would not be feasible with the power available from a frequency stabilised He-Ne laser.

vi. The Nd:YAG laser has a much greater coherence length than a He-Ne laser and so the all-fibre interferometer does not exhibit sensitivity variations (noise floor level) with stand-off distance; an effect which is experienced on commercial vibrometers.

vii. The all-fibre design provides greater robustness to environmental conditions and gives the potential for operation underwater.

viii. The all-fibre interferometer makes us of fibre that does not maintain the polarisation of the light. Although this makes isolation of back reflection to the laser more technically challenging, it also means that the interferometer is not hindered when collecting de-polarised light from a target. Scattered light from a diffuse surface can be described using Lambert's cosine law of diffusion [3]. For this type of scattering surface the returned light level is reduced because of this diffusion but in addition to this, the light is also completely depolarised. Commercial vibrometer and interferometer systems use polarising beam splitters to separate the returning light component to combine with the reference arm. If the reflected light from the acoustic target is depolarised, the AC component separated for producing the Doppler signal will be significantly reduced (even if a large amount of light is collected) and lead to an increased noise floor at the Doppler decoder output. In such an application, the all-fibre interferometer would only be affected by the light level loss due to Lambertian scattering and would use all the available returned light to produce the Doppler signal.

ix. Commercial vibrometers are marketed for the purpose of vibration measurement as a robust alternative to accelerometers and are therefore designed for high velocity applications. These velocities may extend from a few mm/s to several m/s. For underwater measurement, a much smaller dynamic range with greater sensitivity is required, from fractions of a mm/s to a maximum of 10 mm/s.

x. Generally, commercial devices do not offer the required frequency range with the sensitivity required in this project. The all-fibre heterodyne interferometer is designed to operate specifically within in the acoustic bandwidth require (1 kHz to 500 kHz).

The completed 'optical' unit is shown in Figure 1 with the optical delivery head in the foreground. The signal processing unit will be provided with a modularised design to allow easy replacement of future Doppler decoding modules for increased bandwidth or dynamic range to suit applications.

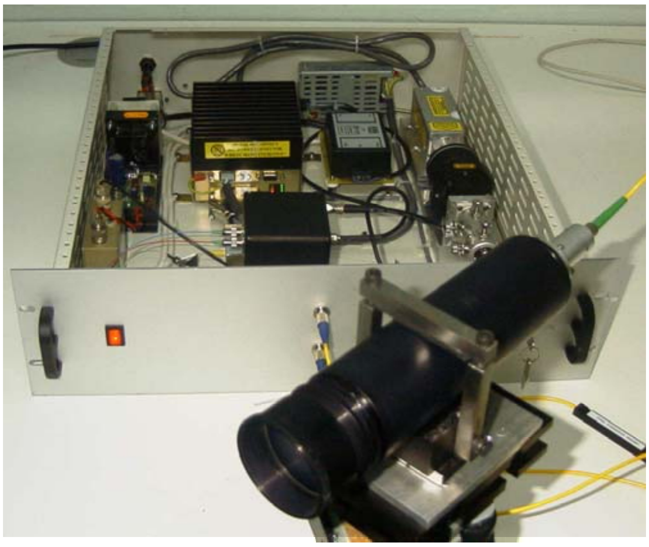

Figure 1. Optical stage of the LOE all-fibre interferometer.

The performance specified during the proposal stages for the sound in water aspect of the project were a 0.3 mm spatial resolution, a 500 kHz bandwidth and a velocity equivalent noise floor of 10 μm s^{-1} in a 200 kHz bandwidth. Although very ambitious, only the noise floor has not currently exceeded that specified. The spatial resolution and the bandwidth capability far exceed those specified. The noise floor during the most recent measurements was around 30 μm s^{-1} in a 200 kHz bandwidth. A number of improvements have actually been implemented since these last measurements which have both increased the light level and decreased noise on the FM carrier. It is believed that these improvements should at least bring the noise floor down to the level of the specification. It should be noted that all noise floor measurements were performed from a membrane in the tank after passing through an access window and around 1-2 m of water. In air, from an optical mirror, one would expect the velocity equivalent noise floor to far exceed that specified.

2.3 Hydrophone calibration using optical method

A series of measurements were performed in the NPL small test tank using an optically reflective, acoustically compliant strip membrane as shown in Figure 2 to obtain a three-way comparison between the LOE all-fibre interferometer, a commercial vibrometer and a reference hydrophone.

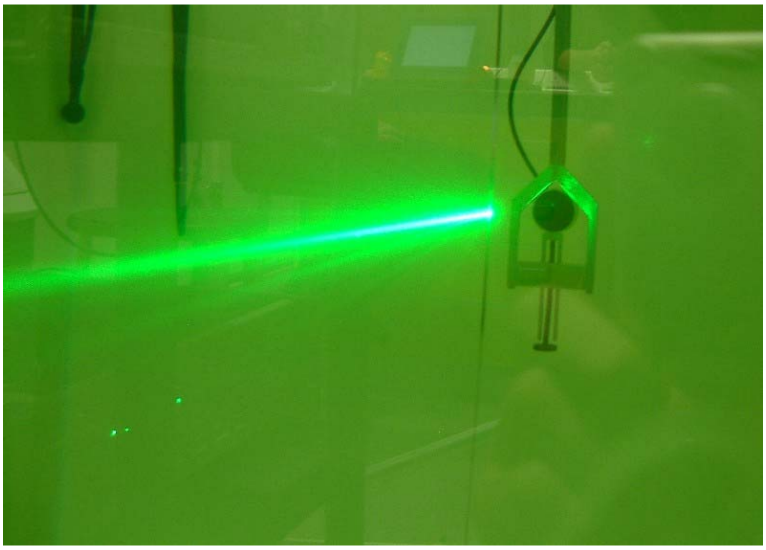

Figure 2. Photograph showing LOE interferometer beam incident on a 2 mm strip membrane in the NPL small test tank.

Figure 3 shows the acoustic velocity signals measured from each for a 10 kHz and a 60 kHz acoustic tone-burst. The results show that at certain frequencies the signal-to-noise ratio of the LOE interferometer is approaching that of a high performance hydrophone and that at higher frequencies, the signal-to-noise ratio of the LOE interferometer is better than that of a high specification bulk-optic commercial vibrometer. During a calibration the acoustic velocities used could be significantly higher than this.

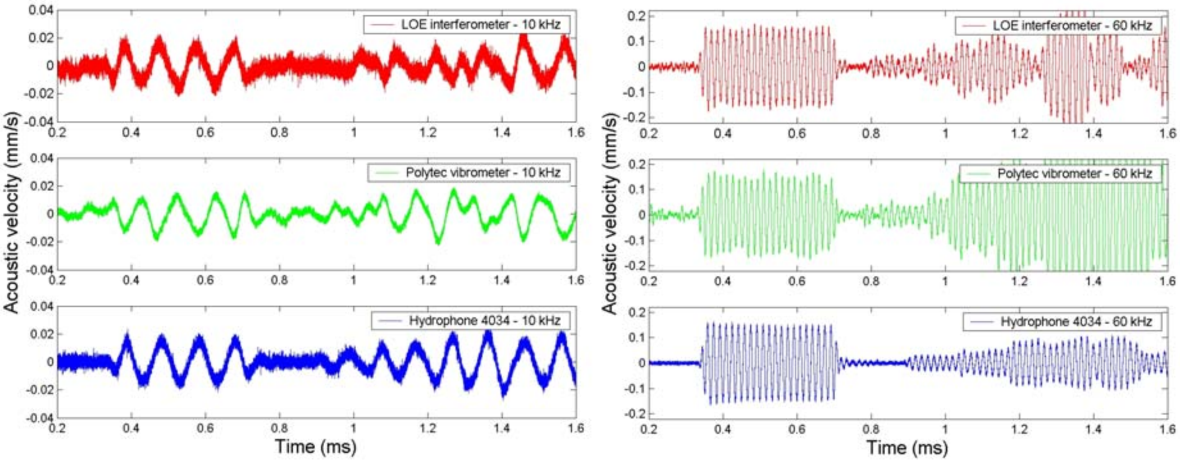

Figure 3. Acoustic velocity comparison using a 4034 reference hydrophone, a Polytec vibrometer and the LOE all-fibre interferometer.

Figure 4 shows the hydrophone calibration results obtained using the optical method with both the LOE interferometer and the Polytec vibrometer compared with the reciprocity reference sensitivity data for the hydrophone. Overall, both optical methods show good agreement with the reciprocity data given that the uncertainty on the reciprocity data is around 0.5 dB for a 95% confidence level. However, the LOE interferometer shows disagreement at higher frequencies. The LOE interferometer was calibrated by injection of a reference electronic FM signal into the post photo-diode stage. Initial testing indicated that the noise difference between the calibration FM signal and the photodiode FM signal causes a response difference at the PLL. Work has recently been underway to adjust the slew rate of the PLL stage to increase the useable bandwidth to over 500 kHz and will be corrected within the scope of the project.

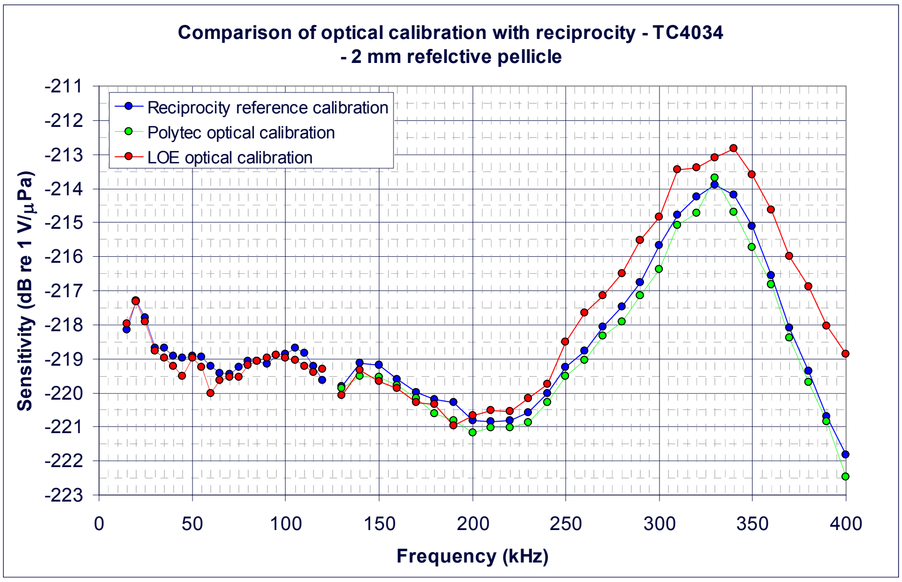

Figure 4. Hydrophone calibration results using optical method compared with reference reciprocity data.

2.4 Discussion

Overall, the use of a strip type reflective membrane has proved suitable for measurements from a few kilohertz to 600 kHz [6] and the LOE all-fibre interferometer has proved capable of bettering the signal-to-noise ratio performance of a high specification commercial device by a specific design criteria targeted at underwater acoustic measurement. In addition to this, the working characteristics and the signal processing are completely understood and the complete transfer function of the Doppler decoding electronics can be obtained to provide true traceability to the wavelength of light. The sound in water design criteria has also led to a very robust fibre implementation which will make it suitable for measurement in more hostile environmental conditions than a bulk optic device and will further allow delivery of the optical beam directly into the water via a submerged delivery head.

The sound in water aspect of the project has generated scientific output in two application areas, each of which should feed directly in to the 2004-2007 NMS Acoustics Programme. The development of a pilot system for measurement of point acoustic velocity will progress within the NMS Unit Programme as a primary standard development project and the initial work on acoustic field mapping should feed into a broader Unit Programme project on three-dimensional mapping of acoustic fields using optical methods.

3 SOUND IN AIR

3.1 Introduction

For sound in air, measurement standards are realised through the free-field calibration of laboratory standard microphones. Current practice is to use the reciprocity calibration method to yield the sensitivities of the microphones under test. The free-field sensitivity determined is therefore related to the particular sound pressure developed during the calibration, which is governed by practicalities of the calibration procedure rather than the application to which the microphone is put. The microphone when used as a sound source is capable of producing relatively low free-field sound pressure level of 0 dB - 20 dB (20 μPa - 200 μPa) at the receiver microphone position. However, in common practice, microphones tend to be used at much higher levels, from approximately 40 dB up to 140 dB. Special applications might extend this range at both ends by some 30 dB. In most cases the microphones are simply assumed to function linearly and the sensitivity derived in the calibration is extrapolated to these higher levels. The efficiency of the microphone to act as a transmitter of sound also reduces with frequency and places a lower limit on free-field calibration methods of 1 kHz - 2 kHz. Below this limit the free-field response is assumed to be equivalent to the pressure response (measured in a small closed cavity), but this assumption is difficult to validate in practice. Practical measurements will often be concerned with frequencies down to 30 Hz or below.

Free-field standards are established up to 20 kHz. The uncertainty in the primary standard for microphone calibration is between 1.5% and 3.5% at the 95% confidence level. This current capability is approximately twice the uncertainty of the most demanding industrial user. In future, there will be increasing interest in the calibration of smaller microphones and microphone arrays, devices that are often not well suited to being calibrated using reciprocity techniques. Looking at the options for improving the reciprocity technique, the rewards from its further development are getting ever smaller. The method is made difficult in a free field due to the very low acoustic level that can be produced by a transmitting microphone. Signal-to-noise problems and cross-talk from the electrical signal driving the transmitting microphone place fundamental limits on what can be achieved, hence making it difficult to calibrate smaller and novel devices. Consequently, increasing the accuracy of microphone calibration requires a new initiative.

Optical techniques provide an absolute measurement capability, which are generally traceable to the wavelength of light. Furthermore, optical methods provide very high spatial resolution, are not generally limited in bandwidth and do not perturb the acoustic field being measured. Many of the limitations of current calibration methods could potentially be overcome by employing optical methods to provide a direct calibration of the microphone.

For sound in air, the ultimate aim for the future is to develop a measurement system capable of measuring in a free-field chamber with a spatial resolution of 0.3 mm over a frequency range of 30 Hz to 50 kHz where the local sound pressure level is typically 40 dB to 100 dB, with a measurement uncertainty of around 0.3% at lower frequencies increasing to 0.5% at 10 kHz and above. This project has worked towards developing a foundation from which to continue this work in future Unit Programmes. The literature survey undertaken as part of Phase One [1] of the project identified Laser Doppler Anemometry (LDA) using the photon-correlation signal processing technique as the most likely method to provide the required capability and performance. Much of the work undertaken in Phase Two and Three of the project has been reported in publications by Schlicke et al [7] and Theobald et al [8], and is discussed further in section 3.2.

3.2 Laser Doppler anemometry

Laser Doppler Anemometry is a non-intrusive, optical technique for measuring fluid flow. The frequency of a photon scattered by a particle is shifted by an amount directly proportional to the particle's velocity. The technique of LDA is based on the fact that by measuring this frequency shift, the velocity can be determined. If it assumed that the particle faithfully follows the flow, then the measured velocity is equal to the flow velocity. For typical flow velocities, the frequency shift is very small in comparison with the frequency itself and therefore difficult to measure accurately. In practice, therefore, this shift is not measured directly. Instead, an optical fringe pattern is established over a volume of space by the interference of two laser beams. As particles traverse the interference fringes, the emitted light is modulated at a frequency dependent on its velocity normal to the fringes and the fringe spacing. By analyzing the optical signal, the flow velocity normal to the fringes can be established.

There are a number of possible optical configurations [9] for an LDA measurement system. After a systematic review of alternative methods, the dual-beam mode was chosen as the most appropriate, where the measuring volume consists of interference fringes formed by intersecting laser beams. This configuration interferes a split laser beam at the focal point of a converging lens. A photomultiplier tube (PMT) is positioned such that the fringe volume, which is in the acoustic field, is imaged at the entrance to the detector. The output of the PMT, the LDA signal, is then correlated with itself using either hardware or software. From the auto-correlation function (ACF), the velocity component in the direction perpendicular to the fringes can be determined. This LDA configuration is shown in Figure 5, where Figure 6 shows a close-up of the interference fringes [10].

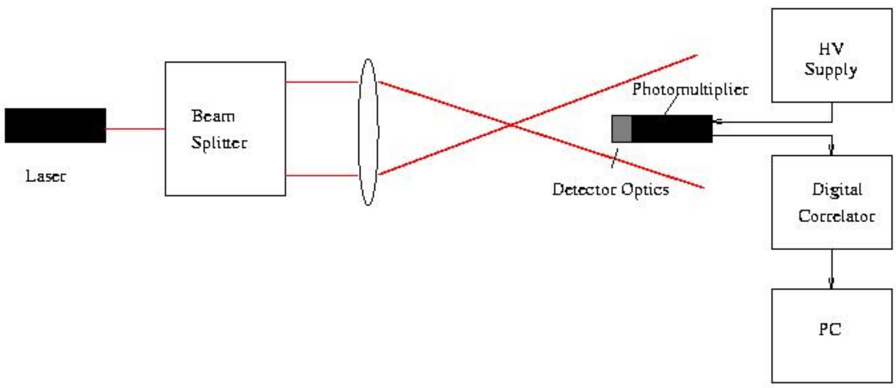

Figure 5. Optical configuration of LDA system.

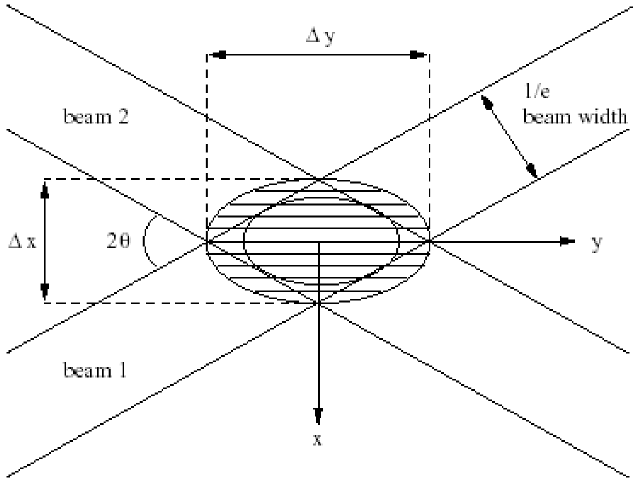

Figure 6. Measurement cross-section of interfering optical beams.

The laser beam has a wavelength λ and is assumed to have a Guassian profile of $\frac{1}{e^2}$ with a diameter *d*. The half-angle of the beam intersection is *θ*. The measurement volume has dimensions $\Delta x = \frac{d}{\cos\theta}$, $\Delta y = \frac{d}{\sin\theta}$ and $\Delta z = d$; these values are typically fractions of a millimetre, so LDA can be described as a point measurement technique. Each of the two beams is assumed to be of equal intensity, and the spacing between consecutive fringes is $\frac{\lambda}{2\sin\theta}$.

Small particles suspended in the fluid scatter some of this light. The number of photons scattered depends on a variety of factors, such as the number and size of the particles, the intensity of the laser beam and their position within the interference pattern, and this number changes as the particles follow the fluid motion. A photomultiplier records some of this scattered light; if its intensity is sufficiently small, corresponding to an average of less than 40 million photons per second, individual photons can be counted.

The particle velocity can be obtained from the photomultiplier in a number of ways. If the optical signal is continuous, it can be Fourier Transformed to obtain the Spectral Density Function from which the velocity can be extracted from the frequency spectra by analyzing the location and heights of the peaks and sidebands. Alternatively, the signal can be de-modulated in the time-domain to yield the instantaneous frequency and hence velocity. For a discrete optical signal which can be considered to be a series of individual photon events, the signal can be auto-correlated to determine the velocity. The choice of analysis method therefore depends on the smoothness of the optical signal, which depends on the sample rate and the number of photons detected.

In a free-field environment, the seeding (natural particles) density is relatively low and the distribution is variable. The auto-correlation analysis method was therefore chosen as the most appropriate method of decoding the particle velocity. The sensitivity of this technique is such that natural impurities in the fluid are frequently sufficient to produce an adequate signal. The photon count and thus the signal to noise can be improved by the addition of seeding particles which faithfully follow the mean and acoustic flow. The photon count could also be increased by the use of a more power laser and thus negate the need for seeding particles.

The scattering particles are assumed to follow the flow faithfully, and have an instantaneous velocity, u, of the form [7]

$$u(t) = u_m + u_a \sin(\omega_a t) \tag{4}$$

where u_m is the mean flow velocity or DC term, u_a is the acoustic velocity amplitude or AC term and ω_a is the acoustic angular frequency. The fluid motion is therefore considered to be a superposition of a mean flow and an acoustic oscillation.

Normally, the auto-correlated photomultiplier signal detected in the presence of a sound field would result in an ACF that is time-averaged over the entire acoustic cycle. In practice, a gating technique is used where short bursts of the photomultiplier signal are auto-correlated at regular intervals. This restricts the range of velocities contributing to the ACF. If the duty cycle of the gating signal is small, the acoustic velocity is approximately uniform during the period of time when the gating signal is high. The ACF of the photomultiplier signal when the fluid velocity is uniform is simply a damped cosine for which an example is shown in Figure 7.

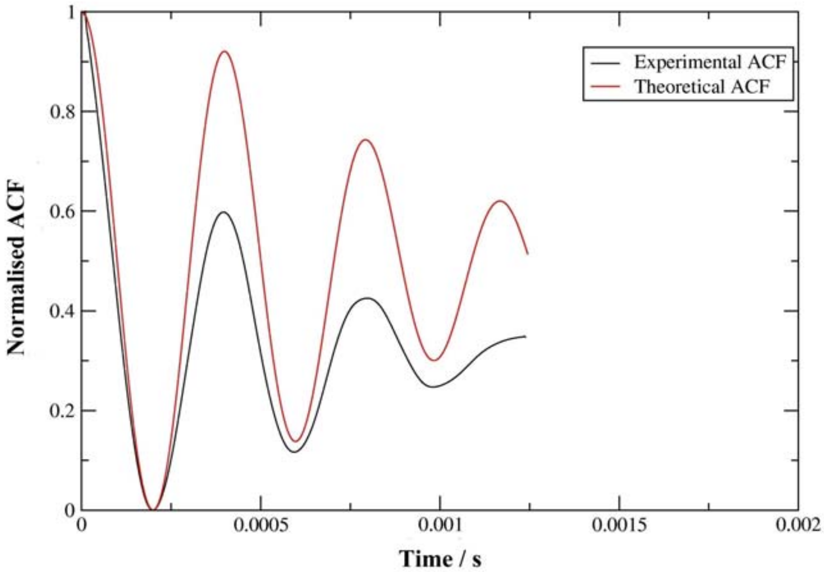

Figure 7. Auto-correlation function produced for a 200 Hz standing wave.

The measured ACF in Figure 7 appears more damped than that predicted theoretically. This was possibly due to the optical beams not being optimally balanced during the measurement.

The time to the first minimum is inversely related to the instantaneous velocity given in equation (4). In the case of the absence of an acoustic field, the mean flow velocity u_m, is given by:

$$u_m = \frac{\pi}{D\tau_{\min}} \tag{5}$$

For the case where there is no mean flow, the acoustic velocity u_a, is given by:

$$u_a = \frac{3.832}{D\tau_{\min}} \tag{6}$$

where $\tau_{\min}$ is the time to the first minimum in the ACF for both equation (5) and (6). In each case, D is the optical component related to the fringe spacing and given by,

$$D = \frac{4\pi \sin\theta}{\lambda} \tag{7}$$

where θ is the half angle of the intersecting optical beams and λ is the optical wavelength. It is equation (7) that provides the traceability to the wavelength of light.

If a number of ACF's are produced at different phase offsets then the time to the first minimum can be plotted as a function of phase offset. This type of plot is shown in Figure 8, where a series of 360 ACF's were obtained at step phase offsets for a 200 Hz acoustic signal in a 1 m long glass standing wave tube. Such a plot provides a means of calculating the mean and acoustic velocities separately.

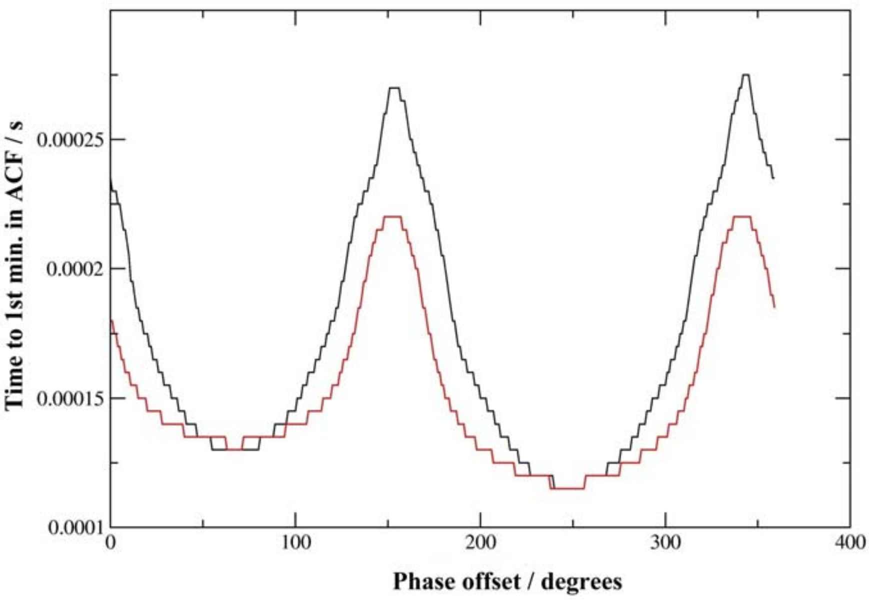

Figure 8. $\tau_{\min}$ as a function of phase offset for a 200 Hz acoustic signal – experimental data in black, theoretical data in red.

The plot shown in Figure 8 is periodic with two distinct peaks and troughs. Since the instantaneous velocity is inversely related to the time to the first minimum of each ACF (see equations (5) and (6)), the peaks in the graph correspond to sections of the acoustic cycle where the instantaneous velocity was lowest and the troughs correspond to the gated ACF's for which the instantaneous velocities were greatest. If there were no mean flow present, the troughs would be positioned at the same value of $\tau_{\min}$. The different values of $\tau_{\min}$ for each trough presented in Figure 8 indicate the presence of a mean flow component. For this example, the mean flow velocity u_m was found to be 1.34 ms^{-1} and the peak acoustic velocity u_a was found to be 0.05 ms^{-1}. The fact that the higher trough occurs first indicates that the mean flow and the maximum acoustic velocity are in different directions.

The agreement between the experimental ACF data (black) and the theoretical $\tau_{\min}$ data (red) obtained was worse at the lower velocities (peaks) than at the higher velocities. One possibility for this was that the sound field may not have been exactly sinusoidal. There were in fact some small harmonics present due to non-linearity in the speaker. This was not of concern as only the maximum velocities are of interest and the acoustic source could easily be replaced with a linear unit.

3.3 Discussion

Although some initial pseudo free-field measurements were performed within the project, the results yielded insufficient signal-to-noise ratio using the existing optical arrangement and the use of a higher laser power, although providing sufficient photon count, yielded inaccurate results due to laser instability. It was not possible to source a stable high power laser (>200mW) within the scope of the project and therefore the work was limited to the 20 mW HeNe laser used for the standing wave tube measurements. Free-field measurements with a stable high power laser should now be taken forward in the 2004-2007 NMS Acoustics Programme. The use of extra seeding in the free-field is both undesirable and impractical due to induced flow during seeding injection. Initial measurements have considered acoustic fields of up to 1 kHz. Future work would intend to extend this to above 20 kHz.

Optical techniques such as LDA also offer a potential solution to other sound measurement areas that are not suited to measurement with a standard microphone. One example of this is the measurement of fan noise using a microphone where the flow in the vicinity of the microphone introduces an additional and undesirable source of noise. The ability of LDA with photon-correlation to separate the AC and DC components would enable an accurate acoustic measurement independent of the adverse effects of flow.

4 CONCLUSIONS

4.1 Sound in water

A method has been established to enable the acoustic velocity to be measured optically in the small NPL test tank which employed a commercial Doppler interferometer and an optically reflective, acoustic compliant membrane. The use of an acoustic compliant membrane in the water has been investigated using scanning vibrometry and modelling techniques resulting in the use of a 1 mm to 2 mm wide strip pellicle. In parallel, an all-fibre Doppler interferometer was developed for the specific application of underwater acoustic measurement in the frequency range 1 kHz - 500 kHz for a dynamic range of 5 mm/s. The main advantage of the developed all-fibre system over a commercial system is that it can be fully characterised at each signal processing stage allowing a transfer function to be established. This ability to calibrate the signal processing/decoding stage allows traceability to the wavelength of light to be achieved. The all-fibre system also employs a 532 nm wavelength laser for better transmission through water; the fibre design adds to the overall ruggedness of the device and allows the optical head to be positioned within the propagation medium (water). The developed all-fibre vibrometer has been tested in a three-way comparison with a reference hydrophone and a commercial vibrometer. The results showed the noise floor of the all-fibre interferometer to be better than that of a commercial device across much of its frequency range. The agreement has also been shown to be excellent between a few kilohertz and around 250 kHz. Similar agreement will be obtained to 500 kHz and above once some phase lock loop calibration issues have been resolved. It is intended that this work will feed directly into the 2004-2007 NMS Acoustics Programme to further develop and fully test the overall equipment and methodology for future implementation as an accredited calibration facility and primary standard.

Other optical techniques were also investigated for measurement and mapping of acoustic fields in water. These were surface scanning vibrometry which has been shown to produce excellent near-field results, and the acousto-optic effect which has been employed for mapping complex wave fields. The acousto-optic effect is particularly important as it allows true non-invasive measurement of whole fields and can be used to measure very high field intensities which would normally damage or even destroy a conventional type hydrophone.

The initial objectives and deliverable of the sound in water aspect of the project have on the whole been met with the delivery of a all-fibre interferometer with a RMS velocity equivalent noise floor better than 30 $\mu m\ s^{-1}$ in a 200 kHz bandwidth, 500 kHz bandwidth and a spatial resolution better than 0.3 mm. In addition to the NPL reports published for each stage of the project, the sound in water aspect of the project has also delivered two conference papers with three peer-reviewed journal paper to be submitted with in a month of the end of the project.

4.2 Sound in air

An initial measurement system has been developed and tested based on laser Doppler anemometry using photon-correlation signal processing techniques that is capable of acoustic particle velocity measurement with a high spatial resolution of less than 1 mm. The adopted method allows the separation of the mean flow velocity and the acoustic particle velocity without the need for any secondary measurement system. The ability to isolate these two components is essential to measurement in free-field environments where mean air-flow will inevitably exist.

It was only possible within the scope of the project to perform measurements around the low kilohertz range so future work would aim to extend this both down to around 30 Hz and upwards to 20 kHz. It is planned to feed the outputs of this project directly into the 2004-2007 NMS Acoustics Programme to further develop the operational frequency range in a free-field environment and fully tests its performance over both its frequency range and dynamic range. Many of the measurements performed within this project were in the 10-100 mPa range. The ability to calibrate microphones at this level or higher would be very significant as this would be much closer to the operational pressures used when performing measurements with the microphones. Current reciprocity methods are limited by the pressure that a microphone can generate. Future work in the NMS Unit Programmes should aim to develop the LDA technique using photon-correlation signal processing to provide a viable alternative to reciprocity by reducing measurement uncertainties, and more importantly, provide direct realisation of the acoustic pascal.

Moving away from the restrictions imposed by reciprocity methods and improving dynamic range for free-field calibration methods will become increasingly important in the future as MEMS based acoustical measuring instruments are developed. The development of these instruments in the future, which will require free-field calibration but will not be compatible with existing methods, highlight the importance of developing an optical primary standard with improved dynamic range and excellent spatial resolution.

The sound in air aspect of the project has delivered two conference paper with one peer-reviewed journal paper drafted for submission.

5 ACKNOWLEDGEMENTS

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