

REPORT

Fundamental standards for acoustics based on optical methods - First stage report

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FUNDAMENTAL STANDARDS FOR ACOUSTICS BASED ON OPTICAL METHODS - FIRST STAGE REPORT

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ABSTRACT

This report documents the results of a literature survey into optical methods for the measurement of acoustic parameters in air and water. The report reviews existing methods for the measurement of sound in air and water in order to establish the requirements for metrology-based optical methods for sound measurement. The favoured approach for developing fundamental standards for acoustics based on optical methods are laser Doppler anemometry (LDA) using photon correlation for air, and laser Doppler vibrometry (LDV) using a reflecting membrane in the acoustic field for water.

A review of current progress on the project is also presented with recommendations made for the direction of work to be undertaken in the second phase of the project. This report is the Deliverable for the Phase One Work Package for Project 3.6 of the NMS Quantum Metrology Programme of the UK Department of Trade and Industry. The project is being undertaken by a consortium of the National Physical Laboratory, Loughborough University and Edinburgh University, with Laser Optical Engineering Ltd and QinetiQ as sub-contractors.

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Approved on behalf of the Managing Director, NPL
by Dr R C Preston, authorised by Head of
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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. The project entitled ‘Fundamental standards for acoustics based on optical methods’ is Project 3.6 of the National Measurement System (NMS) Quantum Metrology Programme of the UK Department of Trade and Industry. This report details the review of optical techniques undertaken during the first six months of the project.

For over 40 years, primary standards for sound pressure in air have been based on the reciprocity calibration of laboratory standard microphones. For a similar period industry has used reciprocity for the calibration of hydrophones used in underwater acoustics in the kilohertz frequency range, techniques which have also been established as national measurement standards. Despite the tremendous progress that has been made in this type of acoustical metrology, there are fundamental limitations of the reciprocity technique that make improvements in accuracy increasingly difficult to achieve. At megahertz frequencies these limitations have been overcome using optical interferometric techniques, and the aim of this project is to explore fully the application of optical techniques for absolute acoustical calibration at lower frequencies in both sound in water and sound in air.

1.2 *Background*

1.2.1 *Current measurement standards for acoustics*

For sound in air, measurement standards are realised through the calibration of laboratory standard microphones. Current practice is to use the reciprocity calibration method to yield the sensitivities of the microphones under test. The sensitivity determined is therefore related to the particular sound pressure developed during the calibration, which is governed by practicalities of the reciprocity method rather than the application to which the microphone is put. The microphone when used as a sound source is capable of producing free-field sound pressure levels of just 0 dB - 20 dB (20 μ Pa - 200 μ Pa) at the receiver microphone position. In common practice, microphones tend to be used at much higher levels, from approximately 40 dB up to 140 dB. Special applications will 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 and in special applications, frequencies below 1 Hz are important. Optical methods have the potential to overcome these difficulties and provide a direct calibration of the microphone. Most methods however do not yield the sound pressure, but the particle displacement or velocity. The relationship between these parameters, that is the acoustical impedance of the air, therefore needs to be established.

For sound in water, the main acoustic sensor used as a transfer standard device is the hydrophone. A hydrophone is an acoustic receiver which develops an electrical voltage across its terminals in response to the acoustic pressure sensed over the surface of the active element. A wide range of different types of hydrophone is commercially available. Sizes vary

depending on the frequency range and acoustic output requirements. For the most accurate measurements, measurement hydrophones are used which have relatively small active elements compared with the acoustic wavelength and whose response is determined by calibration.

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. Instead of a direct measurement of the free-field acoustic pressure, a measurement of another field parameter may be made and the pressure calculated from this parameter. Optical methods offer a method to measure either the acoustic particle velocity, v , or acoustic particle displacement, a . For a plane-wave acoustic field, these parameters are related to the acoustic pressure by:

$$p = \rho c v = \rho c \omega a$$

where ρ is the density of the medium, c is the speed of sound in the medium and ω is the angular frequency. Although a plane-wave is an idealised field geometry, plane wave conditions may be approximated with sufficient accuracy for small hydrophones at large enough distances away from a source of spherical waves.

The typical values of the acoustic field parameters that are encountered in calibration work in water vary with frequency. At frequencies of hundreds of kilohertz where directional acoustic sources are more commonly used, acoustic pressures of typically about 2 kPa may be observed. This is equivalent to acoustic particle velocities of about 1.4 mm s^{-1} . At low kilohertz frequencies during free-field reciprocity calibrations and where omnidirectional sources are commonly used, acoustic pressures of 50 Pa or lower may be observed, equivalent to only $30 \text{ } \mu\text{m s}^{-1}$ in terms of acoustic particle velocity. However, with the use of a range of suitable source transducers, it should be possible to keep the acoustic pressure at a minimum of 300 Pa (equivalent to 0.2 mm s^{-1}).

Clearly, the noise floor of the optical system must be low enough to be able to measure the above signals with an acceptable signal-to-noise ratio. With a suitably designed system implemented in a manner designed to minimise environmental vibration, it is envisaged that an RMS noise equivalent velocity of $10 \text{ } \mu\text{m s}^{-1}$ should be achievable in a 200 kHz bandwidth. Suitable signal processing (e.g. signal averaging) may be required to improve the signal-to-noise ratio. The target for this project will be to aim to achieve a noise equivalent pressure of 1 Pa or better, i.e. a velocity less than $1 \text{ } \mu\text{m s}^{-1}$.

As can be seen from the above equation, for a given acoustic pressure the acoustic particle displacement is inversely proportional to the frequency of the acoustic wave. This means that the acoustic particle displacement can be very small and difficult to measure at high frequencies. For example, 300 Pa corresponds to acoustic displacements of about 6 nm at 5 kHz, 0.6 nm at 50 kHz, and 0.06 nm at 500 kHz.

1.2.2 Needs for improvement

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.

For sound in air, free-field standards are established up to 20 kHz. The NMS primary standard uncertainty 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.

For sound in water, the current primary standard calibration method for hydrophones used in underwater acoustics is the three-transducer spherical-wave reciprocity method [1]. Although this method is long established and widely used, in terms of metrology 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 1-2%.
- The method depends on an assumption about the geometry of the acoustic field, i.e. that it is spherically spreading. To achieve a field which is spherically spreading to a close approximation requires larger separation distances than is sometimes practical in a laboratory tank.
- The method does not directly establish the SI unit of acoustic pressure.

- The limited echo-free time of finite sized laboratory tanks in reciprocity calibration causes problems with lack of steady state conditions when gated tone-burst signals are used.

The above issues contribute uncertainties to the reciprocity method and lead to overall uncertainties of no better than $\pm 6\%$ (expressed for a coverage factor of $k=2$). Whilst this level of accuracy meets the needs of many current industrial customers, there is industrial pressure on the NMS to improve the absolute accuracy by a factor of over two. Furthermore, there is no 'headroom' between existing primary standards and the accuracy sought by the majority of users.

For sound in both air and water, the various sources of uncertainty in the existing primary acoustical calibration methods based on reciprocity represent fundamental limitations to their further development. Developing a new range of primary acoustical standards based on optical techniques is therefore of great strategic importance to the UK National Measurement System.

1.2.3 Proposed methods

It is clear that one of the fundamental limitations of reciprocity is that an assumption has to be made about the acoustic pressure at a point of interest. 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 techniques for sound measurement rely primarily on the detection of light scattered from small objects or particles (either single or multiple) suspended in the flow. These could be natural particles in air or water, specially seeded particles or a thin membrane or pellicle. On the passage of a sound field, the particles will oscillate with the motions of the fluid. However, the observed oscillations on the detector surface may be very much greater or less than the actual ones, due to the acousto-optic effect i.e. the effect of the refractive index variations in the fluid caused by the passage of the sound wave. For air, the acousto-optic effect is very small. For water, or other liquids, the acousto-optic effect will usually dominate for beam path lengths greater than just a few centimetres, dependent on the geometry and the acoustic frequency.

For measurements in small tubes, the acousto-optic effect is small but for free-field measurements in water tanks it is usually dominant. This raises the question of spatial resolution of the system, since the acousto-optic effect is an integrated effect along the beam paths. Thus for measurements in water it will probably be important to devise techniques for localising the measurements. Use of a pellicle in special optical configurations designed to minimise the acousto-optic effect may be used and also tomography offers a possible solution i.e. the images of the particles are observed simultaneously from more than one direction and the signals are combined in a manner that eliminates the signal components not common to the two beams. This approach has been used in the study of turbulent flows e.g. the cross-beam correlation technique.

It should be noted that the acousto-optic interaction often plays the crucial role in enabling coupling between the acoustic field and the optical beam, such as in methods based on the Raman-Nath parameter where the absolute knowledge of this interaction parameter is essential. However, in other techniques, the acousto-optic interaction represents a

perturbation for which a correction must be applied. The latter methods are preferable because of the inherent uncertainty in knowing the absolute value of the interaction parameters.

It is also attractive to consider other interaction mechanisms between the optical beam and the acoustic field. For instance, fluorescence may be a possible method of determining an acoustical quantity at a point without interaction along the laser beam path. Methods based on a two-laser interaction system are other possibilities. Of course, there needs to be coupling between the physical acoustic field and the optical effect if it is to be used as a means of detecting an acoustic disturbance.

1.2.4 Review of techniques

At this stage it is fair to say that previous work, and in particular the recently completed PhD by Andrew Harland at Loughborough University on “The Application of Laser Doppler Velocimetry to the Measurement of Underwater Acoustic Pressure Fields”, suggests that refractive index measurement techniques and transducer surface velocity measurements are strong candidates to form the basis of new acoustical standards in water. For sound in air, it is likely that laser Doppler anemometry is still the main contender for research investigation.

However, a critical review of the current literature has been performed to ensure likely candidate techniques are not overlooked. Primarily, this review has been performed to ensure that the techniques chosen for the measurement of sound in air and water are ultimately the most likely to achieve the target specifications for this project. The review considers the majority of optical methods that are employed for the measurement of acoustics in air and water, and assesses their potential to meet the criteria laid out for this project. This criteria places demands on both the acoustical performance, with specifications for sound in air and water discussed below, and on the logistics of implementing the technique in the measurement environment.

The review also allows techniques to be highlighted that show potential for future development in acoustic measurement.

1.3 Technical challenges

To apply optics to acoustical metrology, a number of issues have to be addressed at the outset, the main ones being:

- to determine the acoustical quantities of interest, the frequency range of interest, the magnitude of the quantity and the target accuracies;
- to consider the physical constraints. For instance, it is essential to be able to determine an acoustical quantity at the centre of a large (roughly 3 m cube) free-field chamber and at the centre of a 5.5 m diameter 5 m deep water tank for sound in air and water respectively;
- to consider the logistics of the acoustic and optical systems including location of the optical source, optical components, optical beam delivery, etc.;
- to consider environmental issues. For instance, vibration will contaminate the measurements and there will be thermal disturbances and steady flow in the test facilities that will perturb optical fields.

Thus the review in Chapter 2 considers a number of techniques in relation to their ability to address the issues and challenges highlighted above. Furthermore, the review also aims to analyse the methods in relation to their inherent acoustic capability such as sensitivity, spatial resolution, linearity, bandwidth and the influence of important perturbing effects such as acousto-optic interactions.

In addition to the challenges stated above, it would be advantageous, for both sound in air and water to use an optical technique that is not reliant on additional seeding to obtain the required sensitivity. This will be particularly difficult for the sound in air system and so any seeding would have to be well controlled and chosen such that it would not contaminate the equipment or the measurement chamber. Further to this, the seeding would have to comply with the acoustic field and not alter the acoustic parameters of the field in any way.

1.4 Target specifications

For sound in air, the target requirements for an optical calibration method are:

- Capable of measuring magnitude and phase of the acoustic particle velocity enabling the sound pressure in a freely propagating spherical or plane wave to be determined;
- Measurement is required of an acoustic field parameter where the local sound pressure level is typically 60 dB to 100 dB - a microphone source can produce only 0 dB to 20 dB ($0.05 \mu\text{m s}^{-1}$ to $0.5 \mu\text{m s}^{-1}$);
- Frequency range of 1 kHz to 20 kHz - minimum requirement, ideally a wider range covering 30 Hz to 50 kHz should be possible;
- Resolution of 0.3 mm to 0.5 mm should also be possible;
- Measurement uncertainty of 0.3% at low frequencies increasing to around 0.5% above 10 kHz;
- Ideally the system should operate with no seeding (or with natural seeding);
- No perturbation to the acoustic field;
- System capable of being integrated into the free-field chamber used for reciprocity calibration at NPL.

For sound in water, the target specification is:

- 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;
- Acoustic pressures used during calibration should be around 300 Pa (equivalent to 0.2 mm s^{-1}), although lower pressures may also be encountered, potentially as low as 50 Pa (equivalent to $30 \mu\text{m s}^{-1}$);
- RMS noise equivalent velocity of $10 \mu\text{m s}^{-1}$ is required in a 200 kHz bandwidth;
- Accuracy required is such that the overall uncertainty is of the order of $\pm 2.5\%$ expressed for a 95% confidence level;
- Reproducibility should be such that the Type A (random) standard uncertainty is better than $\pm 0.5\%$;

- 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.

These specifications represent the long-term technical objectives for applying optical techniques to acoustical calibration.

2 REVIEW OF OPTICAL TECHNIQUES

2.1 *Sound in air*

There are essentially three optical techniques that have been used successfully for sound measurement in air: laser Doppler anemometry (LDA), particle image velocimetry (PIV) and light diffraction tomography. However, out of these three LDA appears to have by far the greatest potential for application to the calibration of microphones.

2.1.1 **Laser Doppler anemometry**

The use of LDA as applied to sound in air has been investigated widely at Edinburgh University and also at the Université du Maine in Le Mans. The use of two crossing, interfering beams, mean that a small remote volume of an acoustic field can be analysed. The acoustic particle velocity is generally obtained from the frequency shift of scattered light from the particles as they oscillate in the interfering focal point of the two beams. The use of seeding is often used to increase the photon count scattered from the particles in the acoustic field, and thus increase the measurement sensitivity. However, in some cases, the sensitivity is good enough that no artificial seeding is necessary [2].

Université du Maine, Le Mans, France [3] has used LDA for the measurement of acoustic velocity in an enclosed tube, with an aerosol seeding based on water condensation with a particle size of approximately 1 μm . Velocities equivalent to sound pressure levels between 60 dB and 120 dB have been validated at frequencies between 50 Hz and 500 Hz. The uncertainties associated with this measurement range have not been stated. The work has however, considered LDA in free-field applications by employing a fibre delivery system.

Edinburgh University (EU) has much experience in the use of LDA and has investigated many aspects of using LDA for acoustic measurement in air. Investigations into seeding and its affect on periodic and random amplitude modulation [4] have shown that for higher seeding density, periodic amplitude modulation is replaced by random amplitude modulation. Random amplitude modulation is favourable if averaging over several acoustic periods is possible. Two different seeding particles of smoke and water were used for the investigation.

In LDA, there are in essence two different techniques for detecting and analysing the Doppler signal: continuous detection, followed by spectral analysis or frequency tracking, and photon correlation. The latter method can only be used for time-averaged signals but has the advantage that it can be applied to very low seeding levels. The LDA work at Edinburgh University [2] has employed photon correlation spectroscopy to demonstrate velocity and direct phase measurement for sound levels from 110 dB to 120 dB. The sensitivity was sufficient enough that no extra seeding was needed to make acoustic measurements of a 1 kHz sine wave source in a tube, in the absence of a standing wave, with a measurement uncertainty of around $\pm 10\%$. This work was followed up at EU [5] by further improvements to the optical arrangement.

Other work has been performed at EU [6] employing LDA photon correlation to measure a velocity field in which sinusoidal fluctuations generated acoustically are superimposed on a steady flow. The ability to measure the acoustic parameters in the presence of flow is potentially very important, as velocity flow would become unavoidable in an open environment for free-field measurement. LDA photon correlation has also been used for measurement of acoustic impedance [7] and the LDA photon correlation has also been

modelled [8] to establish the limitations on the lower measurement limit. To maximise the measurement sensitivity, a short wavelength laser is required, and the intersections angle of the two beams must be as large as is possible with the optical equipment. It must also be remembered that seeding density/size is a major factor in determining the achievable measurement sensitivity.

LDA using photon correlation analysis shows potential for small point volume measurement of particle velocity in an acoustic field. Although currently it has only been demonstrated in enclosed tubes, it should be possible to adapt the technique for free field measurement. Ideally, further work performed in this project would push LDA photon correlation towards use in a free-field environment and investigate measurement sensitivity in a free-field environment with natural seeding or a controlled additional seeding. The acousto-optic effect is considered to be too small in air to contribute to the acoustic measurement of the acoustic field using LDA and should only be an issue when using LDA techniques in water [9] [10].

2.1.2 Particle image velocimetry

PIV is a velocity measurement technique that can ‘instantaneously’ record velocities over a whole field by photographing small particles contained in a flowing medium. The laser light source used can be pulsed to obtain successive images (or snapshots in time) of light scattered off the particles at an optical receiver, from which velocity information can be obtained by analysis of the separation between the particle images.

PIV has been used [11] to image the acoustic Rayleigh streaming present in an enclosed acoustic field. The work described has limitations on the dynamic range which is determined by the ability to resolve fringes on the measurement slide, which translates to a minimum distance between particles. The technique is applied only to acoustic streaming and application to an acoustic field measurement would be severely limited because of the particle image distances, which is determined by the pulse separation.

EU [12] has also used PIV for the measurement of acoustic streaming and considered it for the measurement of acoustic oscillation. Although PIV allows full field measurement, it can only be applied at relatively high sound intensity levels and has very limited temporal resolution. The temporal resolution of the technique limits its use at anything other than low frequency.

2.1.3 Light diffraction tomography

Light diffraction can be used to measure the acoustic field by virtue of the acousto-optic effect, where a laser beam crossing the acoustic field is diffracted due to the change in refractive index caused by the pressure variation across the acoustic field. By changing the orientation of the optical beam relative to the acoustic beam axis, it is possible to construct a tomographic image of the acoustic field. This is particularly useful for three-dimensional mapping of acoustic fields.

Almqvist et al [13] has used light diffraction tomography to measure air-coupled transducers in the frequency range 40 kHz to 2 MHz. The uncertainty of the measurements was estimated to be 13% and the absolute measurements were compared at 40 kHz and 100 kHz with calibrated B&K type 4138 (one eighth of an inch) microphones within the uncertainty stated. The pressures used in this work, which make the use of light diffraction possible, are up to 300 Pa (144 dB), beyond the practical range of sound pressure aimed for in this project.

TV-holography has been investigated [14] as a technique for tomographic reconstruction of the near field pressure at a loudspeaker. Imaging was performed by the interference pattern produced by passing the optical beam through and back the acoustic near field normal to its direction of travel. The tomographic image was constructed with a 1.5 degree resolution. Comparisons with microphone measurements were done at peaks of 35 Pa, a lower limit of 0.4 Pa for beam propagation distance of 1 m through the acoustic field. Poor signal to noise makes averaging over many measurements essential.

Light diffraction tomography has mainly been used for mapping of the acoustic field. The need to integrate around the beam to extract a point measurement leads to relatively large uncertainties that make it unsuitable for calibration purposes. Implementation at lower pressure levels also gives poor signal-to-noise.

2.1.4 Summary

There are potentially, three optical techniques suited to the measurement of acoustic fields in air: laser Doppler anemometry, particle image velocimetry and light diffraction tomography. PIV, although a possible future technique, is currently only suitable for low frequency and velocity measurements due to its poor temporal resolution. Light diffraction techniques, similar to that used for sound in water have been applied to sound in air. The disadvantage of this technique is the need to integrate around the beam to extract a point measurement, resulting in potentially large uncertainties. It is also unsuitable for the work in this project due to the high acoustic pressures needed to bring about sufficient change in refractive index. LDA was selected as the low-risk solution at the outset of this project. No techniques have been identified to challenge the view that this is the most suitable technique to pursue. LDA is capable of interrogating the acoustic field at a well-defined point, and generally has good sensitivity. The measurement uncertainty is calculable and the method provides scope to minimise this with careful design. The potential to execute the method without the need for deliberate seeding adds to its attraction. A major difficulty will be adapting the technique for free-field measurement, since it is known to be sensitive to air flow caused by thermal gradients for example, although work at EU has demonstrated the ability to measure an acoustic field in the presence of steady flow. Demonstrating that the particles follow the acoustic displacements will also be crucial.

2.2 Sound in water

Potentially there are a number of optical techniques that provide outputs in response to an acoustic field, detecting either the local changes in pressure or the movement of particles within acoustic field. These potential techniques are listed below, where many of them have in some form been applied to the measurement of acoustic fields in water or liquid.

Many of the techniques suggested are subject to or reliant on acousto-optic interactions in the fluid. When using interferometric or vibrometry techniques that rely on a pellicle in the acoustic path, where the optical beam traverses the length of the acoustic path, the acousto-optic effect then represents a perturbation for which a correction must be applied. The pressure variation along the acoustic path causes local refractive index changes in the fluid and is therefore interpreted by the interferometer as an effective path length change. At high frequency, a correction for this effective path length change can be determined based on using the elasto-optic coefficient [15]. The acousto-optic effect is also a major problem for LDA measurements of acoustic fields in water, manifesting itself as unwanted movement in the interference fringes. The refractive index changes that result from the presence of an

acoustic field in water are much larger than the resultant changes in air due to water having a density approximately 1000 times that of air. In water it is therefore possible to use techniques that measure light characteristics, which are related to the refractive index or pressure change in the acoustic field.

Potential optical techniques include:

- Schlieren
- Electronic speckle pattern interferometry (ESPI)
- Particle image velocimetry (PIV)
- Laser Induced Fluorescence and Coherent Anti-Stokes Raman Spectroscopy
- Light diffraction tomography
- Homodyne interferometry
- Laser Doppler anemometry (LDA)
- Laser Doppler velocimetry

These techniques are discussed below based on the review of the literature performed as part of phase one of the project and also on material provided by Andrew Harland of Loughborough University (LU).

2.2.1 Schlieren

The Schlieren technique uses the principle of refraction caused by local density changes produced by the pressure variation in the acoustic field. An arrangement of optical elements are used to create a diffraction pattern from the light from a pin hole light source passing through a fluid in the presence of an acoustic field [16]. By considering the side orders of the diffraction pattern produced as a result of the acoustic field, information can be obtained about the pressure variation in the acoustic field. The difficulty in quantitatively relating the optical information to parameters in the acoustic field, make the technique particularly difficult to implement as a metrology tool.

2.2.2 Electronic speckle pattern interferometry (ESPI)

ESPI or TV holography has been well established as a technique for mapping surface displacements. It has also been used for acoustic measurement in water [17] [18] and for mapping small surface vibrations of underwater acoustic transducers [17]. Generally the technique is limited by resolution if a video camera is used to receive the speckle pattern.

2.2.3 Particle image velocimetry (PIV)

PIV has been discussed in section 2.1.2 for sound in air measurement, and although it could be implemented for sound measurement in water, it has not been done so in the literature. Temporal resolution would be a major limitation of PIV for sound in water measurement. However, its full field measurement ability and its insensitivity to acousto-optic effects make it an interesting technique. A disadvantage of the technique is the need to seed the water with particles.

2.2.4 Laser Induced Fluorescence and Coherent Anti-Stokes Raman Spectroscopy

Coherent Raman Spectroscopy uses two laser fields of different frequencies to stimulate a sample which is consequently made to vibrate at the frequency difference of the two lasers. The vibrating molecules then modulate the dielectric constant, which alters the frequency, intensity or polarisation of the incident beam, to form a coherent Raman signal amplitude.

The technique has not been applied to acoustic measurement, although studies at LU, investigating light in water, have uncovered some interesting points with regard to the fluorescent activity of the water itself. It has been found that it is a highly non-linear process, which is also dependent on temperature. If a dependence on acoustic pressure were demonstrated then this technique may have potential for further work.

2.2.5 Light diffraction methods

Light diffraction methods use the periodic refractive index change of the water in the presence of an acoustic field, and mostly employ tomographic techniques for reconstruction of the acoustic field. Generally the technique is used within the limits of the weak acousto-optic interaction. If the intensity of the acoustic field is sufficiently low, the diffraction effect is small and the light suffers only phase variations. This is known as Raman-Nath diffraction.

Light diffraction methods have been one of the measurement techniques pursued by LU. Harland [19] [20] [21] has used LDV techniques to measure the acoustic field both in line with the acoustic beam using a pellicle suspended in the water and traversing the beam using the acousto-optic interaction. The advantage of traversing the acoustic beam and reflecting off a surface that is removed from the acoustic medium is that the acoustic field is absolutely unperturbed. Harland relates the LDV measurement to the change of path length for a line integral through the acoustic field. Other work done by LU [19] considers an integral around the acoustic beam to re-construct a three-dimensional image of the acoustic field. The investigations by LU have generally been performed around the 100 kHz region with sufficient sensitivity to measure particle velocities as low $15 \mu\text{m s}^{-1}$.

Other work [22] has used a tomographic technique to optically map ultra-sonic fields using diffraction caused by acousto-optical interactions at frequencies around 15 MHz, beyond the limits of weak acousto-optic interactions. The effect was observed normal to the acoustic field with pressure and phase information obtained in the region of 10 kPa. When compared with a calibrated PVDF hydrophone, the technique was shown to have an uncertainty of 20 % or more. Uncertainties associated with light-diffraction tomography in the Raman-Nath regime and in an extended regime for weak to strong acousto-optic interaction have been considered [23]. Using the Raman-Nath approach in the extended regime gave rise to errors up to 50%. Light diffraction methods have further been reported in the literature for measurements in the megahertz frequency range [24] [25] [26] [27].

Light diffraction is mainly used for mapping of acoustic fields and relatively large uncertainties in measurement make it unsuitable for calibration purposes. The major drawback of this technique is its inability to make a measurement of a true point. Integrating around the acoustic field to extract information from a single point in the acoustic field gives rise to large uncertainties. In many cases, the pressures required to induce the necessary sensitivity from the refractive index change are also higher than are needed with a pellicle directly in the acoustic field.

2.2.6 Homodyne interferometry

Optical measurement of sound in water is wide spread at high frequencies, with displacement interferometry being the primary standard at NPL for frequencies of 500 kHz to 60 MHz [28] [29]. The calibration accuracy achieved using this interferometer is typically $\pm 4\%$ at 0.5 MHz for a confidence level of 95% [30]. A similar approach for hydrophone calibration is considered in the literature [31] where the pellicle is placed on the surface of the water rather

than in the water, as with the NPL calibration facility. The calibration frequency range for this technique is 1 MHz – 50 MHz with an uncertainty less than $\pm 15\%$ and between 50 MHz and 70 MHz with an uncertainty greater than $\pm 15\%$. Baboux et al [32] also proposed a similar method, this time however, without the use of a reflective pellicle. The displacement is measured directly from the surface of the liquid. The ultrasonic source is positioned directly below the surface, on the bottom of the tank, with its acoustic beam in the vertical axis. Calibrations up to 20 MHz are demonstrated.

Other methods of ultrasound measurement are reviewed in the literature [33] [34] [35]. Fibre optic gradient hydrophones have also been developed [36] utilising Mach-Zehnder type interferometers.

The use of a displacement interferometer is limited at lower frequencies for a number of reasons: the pellicle used as the optical reflector limits the time window available before acoustical reflections arrive from its supporting structure, displacement interferometers are inherently more sensitive to low frequency vibration than heterodyne interferometers and implementation of a displacement interferometer into a larger tank for low frequency measurement would be difficult.

2.2.7 Laser Doppler anemometry (LDA)

LDA for sound in water is essentially the same as that applied to sound in air, where the Doppler shift is measured from the laser light scattered off particles oscillating in the acoustic field at the point of the interfering laser beams. Generally the use of LDA requires no seeding as tap water has enough particles to cause sufficient scattering. Early work [37] employing LDA in water demonstrated velocity measurement, using a tube arrangement with a standing wave, similar to that for sound in air. A similar arrangement by Vignola et al [38], showed spectral broadening due to Brownian motion to be small, and measurements of displacements of 5 nm over a 10 kHz bandwidth were achieved.

Crickmore [39] of QinetiQ suggested using either the particle motion or the acousto-optic pressure variation as a measurement technique. Work predicting and measuring the acousto-optic effect for various wavefronts [9] [40] [10] [41] showed that for long path lengths the acousto-optic effect would dominate in water. Although the effect can be predicted for a well-understood acoustic field, any other effects in the water that may cause a path length change in either of the beams will give rise to unknown errors. The moving fringe pattern due to independent path differences between the two beams is a major draw back of this technique, which would make it difficult to employ in this project.

As part of this project, two alternative methods using the LDA system have been studied theoretically by QinetiQ. Both are very similar to the LDV methods where the measurement beam is re-combined with a reference beam and therefore differs somewhat from the LDA techniques investigated at EU. It does however, differ from the LDV methods considered for this project as the QinetiQ approach uses the light scattered off particles suspended in the water rather than from a reflective pellicle. The proposed method is to pass the optical measurement beam along the acoustic beam to measure the acoustic oscillations in the water along the measurement beam. To overcome the problem of an averaged result along the optical beam and thus achieve the necessary spatial resolution, it is suggested that the optical beam be focussed from a large lens so that the optical focal point in the field would be most sensitive to the acoustic field. This combined with a pinhole at the receiver end to remove scattered light from either side of the focussed point would allow the spatial resolution

requirements to be achieved. Problems arising from the acousto-optic effect in two beam LDA systems are reduced and the fact that the measurement beam traverses the length of the acoustic beam allows corrections for the acousto-optic effect can be performed. The major drawback of this method is that measurements at a point are not possible without the use of a large lens, which if integrated into the measurement system would have to be outside the acoustic field so as not to cause any perturbation. There is also concern that the focussing of the optical beam could cause localised heating.

The second method proposed by QinetiQ is similar the first. However, the small measurement point is achieved not with a focussing lens, but by placing the receiving optics at an angle of less than 180° to the measurement beam with a narrow field of view so as to collect backscattered light from particles within a small region of the field. This technique, although able to make point measurements results in the measurement beam returning down a different path after scattering, which makes the acousto-optic effect very difficult to correct for.

With both techniques, the backscattered light is limited and the high density of seeding necessary to achieve the required sensitivity would be un-acceptably high.

2.2.8 Laser Doppler velocimetry

A heterodyne interferometer or vibrometer differs from a homodyne Michelson type interferometer in that the measured vibration results in a frequency difference between the measurement beam and the reference beam, and not a path length change. This makes them inherently less sensitive to external vibration. Monchalin [34] and Scruby and Drain [35] discuss heterodyne interferometry in more detail and consider the merits of both heterodyne and homodyne devices. The LDV system further differs from LDA in that it uses a single measurement beam that is re-combined with a reference beam to establish the Doppler frequency shift. Generally the LDA system as discussed, interferes the two measurement beams at the measurement point and the velocity of the particles in the field are found from the frequency of scattered light produced as it passes the interference fringe.

The use of an LDV system to measure particle velocity of an acoustic field in water has been demonstrated in the small NPL underwater tank with a standard pellicle design [20]. However, to allow the measurement of low frequency acoustic fields in the absence of reflections from the pellicle's supporting structure, a different design of pellicle would have to be considered. Yuebing and Yongjun [42] overcame this problem with the use of a reflective Mylar strip, demonstrating a test calibration facility for hydrophones in the frequency range 10 to 200 kHz by measurement of the particle velocity in the sound field. This interferometric calibration method achieves an overall uncertainty as low as about 0.5 dB.

A vibrometer was also used by Harland et al [20] for acoustic field mapping by light diffraction [19]. This may allow future work to employ LDV techniques for the mapping and visualisation of acoustic fields, particularly in water. Other applications for vibrometry are also considered in the literature [43] [44].

The work by Yuebing and Yongjun [42] is potentially the most practical approach for a low-risk solution to this project. An all fibre LDV system that could be used in an open water tank without perturbing the acoustic field would allow the low-risk solution to be realisable and allow further other solutions to be investigated.

2.2.9 Summary

For acoustic measurement in water, there are three potential techniques that have been employed widely in the literature: interferometric (homodyne and heterodyne) measurement, LDA and light diffraction methods. Light diffraction is mainly used for mapping acoustic fields and is not particularly suited to point velocity/pressure determination. Large uncertainties can be introduced in determining a point in the acoustic field due to the need to integrate around the acoustic beam. Techniques that rely on the acousto-optic interaction are generally difficult to employ to quantify acoustic parameters in absolute terms. LDA is a technique that is used widely in air and water for flow measurement and has been applied to acoustic field measurement successfully in air. In water however, the acousto-optic effect often dominates with movement of the fringe pattern. This can only be corrected if there is detailed knowledge of the acoustic field and there are no other effects present that could cause path length differences between the beams. Interferometric methods for point measurements in the acoustic field have been applied very successfully at higher frequencies and show similar potential at lower frequencies when employing heterodyne (LDV) methods. An LDV technique using a reflective compliant membrane in the acoustic field appears the most suitable approach for a low-risk solution to this project. A technical challenge with this approach as with all the other techniques described, is its application in an underwater free-field environment, although an enclosed fibre design would make this easier.

3 SUMMARY OF PROPOSED METHODS

3.1 *Sound in air*

Research at EU has so far concentrated on assessing the potential of optical techniques for acoustic measurement in closed tubes, with particular emphasis on the use of LDA for acoustic fields and flow. LDA has the advantage that it can measure absolutely the acoustic particle velocity at a defined point in an acoustic field, with no or little perturbation of the acoustic field. It is also possible that adequate sensitivity could be achieved in the absence of any artificial seeding in the chamber.

The literature review has presented no reasons as to why the direction of the current work at EU should be affected. The method favoured by EU is the use of forward scattering LDA using photon correlation analysis. This builds on much of their experience in the use of optical techniques for the measurement of sound in air and will also build on their collaboration with Université du Maine, Le Mans, France, for their experience of LDA in free-field environments. In addition to their collaboration with Université du Maine, EU also collaborate with Moscow University who are also actively involved in LDA techniques for sound in air measurement. Other non-optical collaborations include the University of Twente in Holland who have developed a Microflown sensor for detecting particle velocity.

Progress at EU has been centred on re-establishing the LDA photon correlation measurement system for measurement of a standing wave in an enclosed tube. Revisions were necessary for the autocorrelation function of a photon correlation signal in the presence of a mean flow and an acoustic oscillation, which were initially derived in earlier work at EU. The method used by EU is to gate the photomultiplier output to simplify the autocorrelation function; specifically the beating from the interaction between the Bessel function due to the acoustic oscillation and the mean flow (due to the thermal gradients etc) should be a mean flow from which the acoustic velocity amplitude can be extracted. Following this, preliminary tests have been performed with a semi-anechoic enclosure before attempting to test the LDA system for free-field measurement. The system shown for these preliminary tests is depicted in figure 1. From preliminary tests, it appears that less seeding is required when the gating circuit is incorporated into the circuit.

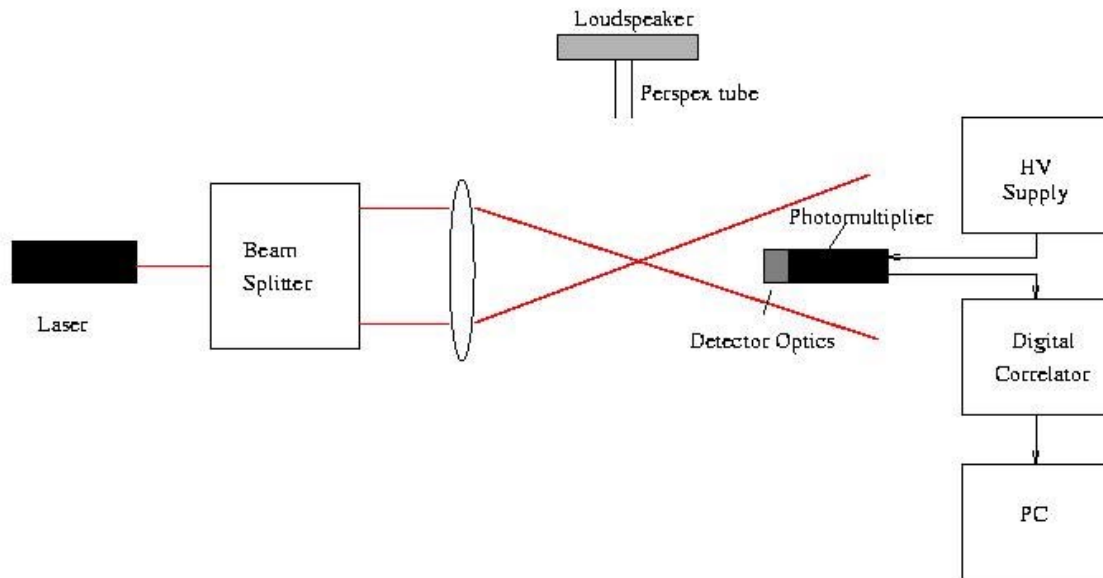


Figure 1: Photon correlation LDA system

Measurements and analysis performed by EU show that point measurement using a photon correlation LDA system is possible and has the potential to be used for microphone calibration. There are however, a number of fundamental problems that need to be addressed before it could be considered as a working solution. The main ones are:

- To date, all studies have been for sound propagation in closed tubes or environments. In reality, the techniques need to be applicable in free-field situations. This raises two problems of fundamental importance:
 - (a) The first problem relates to the seeding of the ambient air. In a free-field situation it is not practical to use high seeding levels as these will obscure the optical paths for both beam transmission and detection, and they may contaminate the free-field chamber. In addition, the speed of sound propagation will be artificially changed. Low seeding densities and small particle size reduces signal levels and hence the signal-to-noise ratio. On the other hand, if seeding particles are too large they will not faithfully follow the acoustic oscillations. Certain seeding conditions are also known to cause periodic loss of the Doppler signal.
 - (b) The second problem relates to mean flows induced within the chamber. Small density gradients will set up air circulations within the chamber, which will be in addition to any acoustic streaming induced by the acoustic oscillations. A mean flow will, for example, shift the positions of the peaks in the Doppler spectrum which could lead to spurious results.
- The signal detection and analysis techniques need to be optimised for the task in question, in order to obtain the maximum amount of information from the signal and hence gain the maximum accuracy of measurement. Calibration measurements are normally done with single frequency sound signals that will allow techniques such as phase-averaging to be applied. A comparison of photon correlation and frequency analysis should be considered.
- The optical configuration will need careful consideration, particularly as the size of the anechoic room will mean that the light transmission and collection lengths are necessarily long. Under these circumstances the standard dual beam LDA arrangement may not be the most appropriate. The possibility of using two spots of light, rather than a fringe pattern, within the measuring region should be considered.

- There also needs to be a comprehensive study to quantify the different sources of error in the measurement technique and to validate these by experiment.

The next stage of the project for sound in air is to continue the work on the LDA photon correlation system and make the transition from an enclosed environment to a free-field environment. Collaboration with Université du Maine, Le Mans, France will allow further testing of the photon correlation method in a free-field environment by comparison with their time-frequency analysis system. This will allow both a feel for the issues of free-field measurement and the performance benefits of using photon correlation as opposed to time-frequency analysis in a free field. It should also allow the autocorrelation function to be independently validated. Transition to a free-field environment at an early stage is vitally important as implementation into a free-field environment is clearly going to present further issues and technical challenges that will need to be considered. Used in an enclosed tube or indeed an enclosed semi-anechoic environment, the seeding has been relatively well controlled in its distribution, and further to this, the presence of thermally induced air circulation is limited. A large free-field chamber will pose more challenging.

3.2 Sound in water

Clearly, the safest approach to a low-risk solution for optical measurement of sound in water is to use a reflective, acoustically compliant membrane in the acoustic field, allowing a particle velocity to be measured using a heterodyne type interferometer or LDV. Although this is a similar approach to NPL's current methodology of high frequency hydrophone calibration, a number of fundamental problems need to be addressed. The main ones are:

- The use of a reflective membrane needs a supporting structure. Pellicles used at high frequencies cannot be used at lower frequencies because of acoustic reflections from the solid outer support interfering with the measurement. The use of a long narrow reflective strip should be considered. This needs to be designed such that it is rigidly suspended and does not suffer movement due to currents in the water.
- The measurement needs to be made in a water tank without the measuring instrument perturbing the acoustic field. This means that any measurement device that is placed in the water/acoustic field needs to be sufficiently small. A fibre optic approach is suggested that will allow the interferometry to be performed remotely from the acoustic field and therefore minimise the size of the optical head placed in the acoustic field.
- The acousto-optic interaction will need to be investigated. Techniques used for correction at high frequencies where the optical beam traverses several cycles of the acoustic beam may not provide an accurate correction at the lowest frequencies considered here.

Research at the Hangzhou Applied Acoustics Research Institute (HAARI), China has considered many of the issues with the optical measurement of low frequency acoustic fields in water. The initial measurements described below are intended to be similar to those described by Yuebing and Yongjun [42], to investigate the possibility of using a vibrometer with a strip type pellicle to measure the acoustic field. Contact with HAARI has already been established and an EPSRC Fellowship through LU will allow Wang Yuebing to work with LU and NPL. It is intended that this collaboration will allow the project to resolve many of the issues associated with the pellicle and the acousto-optic effect.

Initial measurements have been undertaken in the small test tank at NPL using a commercial Polytec vibrometer from LU and a reflective strip arrangement. The reflective membrane was a 600 mm long, 20 mm wide and 23 μm thick Mylar strip coated with 40 nm of aluminium.

The strip was held rigid using a 4 mm thick fibre glass U-shaped mount. For these measurements, the optical beam entered the water tank via a glass window in the side. The measurement arrangement is depicted in figure 2. The vibrometer was then used to measure the acoustic particle velocity over a range of frequencies from 4 kHz to 100 kHz.

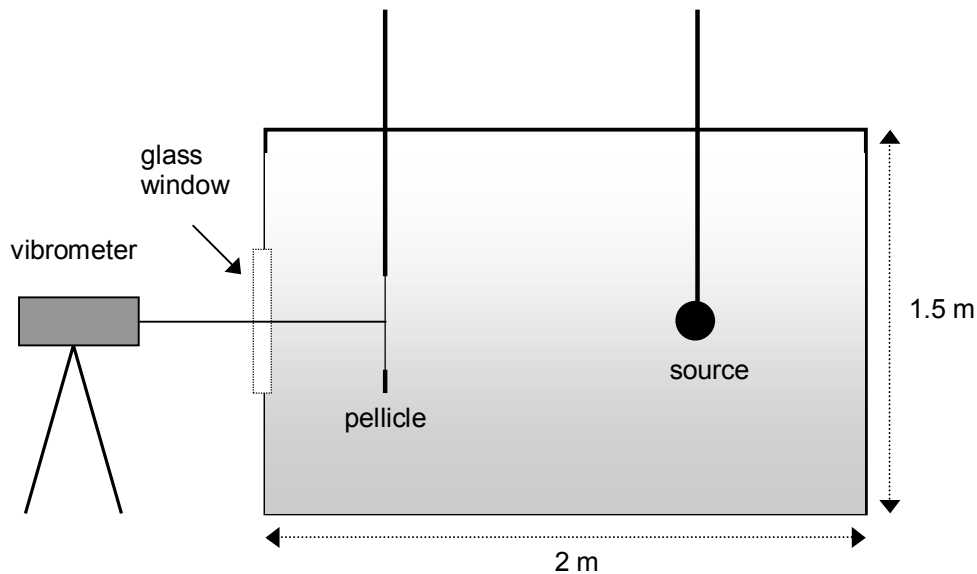


Figure 2: Vibrometer measurement arrangement in NPL's small underwater tank

A comparison of particle velocities measured using the vibrometer device with those using a set of reference (calibrated) hydrophones showed good agreement at lower frequencies. The following observations were made during these measurements:

- At higher frequencies, above 70 kHz, divergence in the comparison was evident due to roll-off in frequency response of the vibrometer.
- At lower frequencies, reflections from the U-shaped mount were present and caused interference in the measurement. These effects could be removed with tighter windowing.
- The measurements were sensitive to gentle movement of the pellicle, especially any twisting motion since the return beam would not then return through the receiving lens.

These initial measurements show that the measurement of particle velocity from a strip type pellicle using a vibrometer device is indeed possible. The limitations of the vibrometer, although a limiting factor in the measurements is not of primary concern as the vibrometer being constructed for use in this project will be produced to an improved specification, more focussed to the needs of this project. A key feature will be that it will be all fibre construction, designed to allow it to be inserted into the acoustic field with minimum perturbation. Using the fibre vibrometer, in principle the optical/measurement head could be placed in the tank as close to the pellicle as possible. One fibre would transmit the optical beam and another would receive the reflected optical beam.

It is clear that the pellicle mount needs to be designed to be more rigid in nature to stop it drifting with any currents present in the water. This will be especially true for implementation in NPL's large underwater tank.

Possible methods for removing the reliance on the pellicle have been considered. The use of seeding in a local area to achieve optical backscattering was dismissed because of a) gradual contamination of the water and b) control over injection of seeding. Another method of

coupling the optical beam with the acoustic beam is of course to use the acousto-optic effect as already discussed. The use of a fibre LDV device would enable the measurement arm (in the fibre) to form an open loop with the open segment placed in the acoustic field. To obtain good spatial resolution the open section (distance between fibre tips) would have to be short and thus the acousto-optic effect would be very small leading to poor sensitivity, although theory suggests that above acoustic pressures 300 Pa it should be sufficient. However, it is a method that should be considered further as part of a low-risk solution. It may also be possible to use the fibre as the reference arm by partial reflection off each of the fibre tips if the acoustic field also affected transmission in the fibres.

The lack of a suitable commercial vibrometer that meets the requirements of the consortium has meant that a specific system has been designed by Laser Optical Engineering Ltd (LOE). The vibrometer is being constructed entirely using fibre-optic technology and a frequency doubled Nd:YAG laser with a wavelength of 532 nm. The laser wavelength was chosen such that it suffers minimal absorption in water. The measurement arm of the vibrometer is comprised of two fibres, one to transmit the measurement beam and the other to receive the reflected optical beam. The reference arm is frequency shifted (80 MHz) using a Bragg cell to obtain directionality from the heterodyne frequency between the two arms. The vibrometer has been designed to meet a target specification of:

- A bandwidth from less than 1 kHz to greater than 500 kHz (with a “flat” frequency response)
- A response range greater than 5 mm s^{-1} with ideally an RMS noise equivalent velocity of $10 \text{ } \mu\text{m s}^{-1}$
- Minimum standoff distance of less than 1 mm and a maximum stand off distance of greater than 5 m

Initial testing of the vibrometer has recently been performed with a prototype demodulator circuit and further initial testing with the final demodulator will be performed before delivery to the consortium.

The next stage of the project for sound in water can be summarised as:

- Assess the performance of the LOE fibre vibrometer in the NPL small tank by comparison with a set of reference hydrophones. For this to be performed successfully the pellicle arrangement will need to be improved.
- Consider necessary acousto-optic corrections for the pellicle arrangement at low frequency.
- Investigate feasibility of removing reliance on the pellicle in the acoustic field. An open-loop fibre arrangement should be investigated for sensitivity.
- Implementation of low risk solution into NPL’s large underwater tank.
- Possibilities for three-dimensional mapping of acoustic field could be investigated.
- Other higher-risk options will also be considered. Stimulated Raman scattering for example, may be a possible method of determining an acoustical quantity. Consideration should be given to further investigation of this technique to assess its potential for future use.

The project should ideally deliver a working solution for sound in water, that is capable of the specified measurement in the large underwater tank at NPL, suited to hydrophone calibration at low frequency. In addition, the project should identify alternative methods which may show potential for further development in the future.

4 CONCLUSIONS

Several techniques have been used for the measurement of acoustic parameters in both sound and water. However, the techniques that are potentially able to meet the target specifications of point measurement, quantitative measurement and the required measurement uncertainty laid down at the outset of this project are limited. The review of the literature has presented no reason to believe that the current course of action for LDA measurement in air and LDV measurement in water should be changed.

The photon correlation LDA system chosen for sound in air has been investigated in the literature and has been developed further by EU as part of the initial work package for this project. It has been shown to be capable of accurate point measurement of acoustical particle velocity in a confined field, over a limited range of frequencies of interest, and shows further potential for implementation into a free-field environment.

For sound in water, the chosen measurement device for acoustical velocity is an LDV system or vibrometer. This type of system has several advantages in that it can determine absolute particle velocity, its sensitivity is not completely reliant on the intensity of the return light, it is less sensitive to external vibration, and most importantly, it can be implemented totally as an enclosed fibre instrument. This method for determination of the acoustic pascal is to measure the oscillation of a compliant reflective membrane positioned in the acoustic field. Different arrangements of the LDV are possible that could potentially determine the acoustic pascal without the use of a membrane. These options along with other potential more speculative techniques will be investigated during the course of the project.

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