THE INFLUENCE OF THE ACOUSTO-OPTIC EFFECT ON LDV MEASUREMENTS OF UNDERWATER TRANSDUCER VIBRATION AND RESULTANT FIELD PREDICTIONS

VF Humphrey Institute of Sound & Vibration Research, University of Southampton, SO17 1BJ, UK
M Cooling Institute of Sound & Vibration Research, University of Southampton, SO17 1BJ, UK
P Theobald National Physical Laboratory, Teddington, Middlesex, TW11 0LW, UK
S Robinson National Physical Laboratory, Teddington, Middlesex, TW11 0LW, UK

1 INTRODUCTION

Higher frequency sonar transducers are conventionally characterised by making measurements with hydrophones. For large aperture devices this may require a significant experimental facility in order to reach the far-field, and even then the measurements may not be made at the operational range. One approach is to use a hydrophone to scan a plane (or cylindrical surface) in the near-field of the transducer and propagate this data numerically to predict the far-field behaviour; this has already been demonstrated for high frequency sonar transducers [1, 2] and high frequency ultrasound transducers [3, 4]. Such scanning techniques can take a long time for large devices at high frequencies.

However, the availability of optical measurement systems, such as Laser Doppler Vibrometers (LDVs), make it possible to consider alternative optical techniques of characterising fields by measuring the movement of a thin membrane (pellicle) in the field [5] or by means of the acousto-optic effect [6]. Alternatively, the velocity of the transducer front face may be measured directly, and the 2-D data propagated numerically to predict the acoustic field [2]. In principle this approach enables devices with large near-field regions to be calibrated in small laboratory tanks.

The use of an LDV to measure surface velocities in water is, however, complicated by the acousto-optic effect as a result of the pressure wave generated in water. The acoustic wave modifies the apparent optical path length via the acousto-optic effect; the LDV will interpret this as an additional component of surface velocity. This effect can be significant, especially for edge waves which propagate across the face of the transducer with their wavefronts parallel to the optical beam, enabling the integrated effect to build up. This has been noted [7, 8] and means that the LDV output will not necessarily be an accurate representation of the surface velocity underwater. However, the nature of the additional apparent components generated by the edge waves (which appear to propagate across the surface with a phase velocity equal to that of water) means that they will not tend to radiate strongly in the axial direction. The extent to which the additional components are significant is the subject of this study; they may not be important if the real and acousto-optic contributions can be resolved in *k*-space. Model predictions are used to explore the effects on field predictions derived from LDV measurements of transducer surface velocity. The results of numerically propagating LDV surface measurements are also presented.

2 THEORY

Consider a Laser Doppler Vibrometer (LDV) arranged outside of a water tank so that its laser beam is incident normally on to the surface of the transducer (see Figure 1). As a result of the acousto-optic effect the LDV will register an apparent velocity v_{app} where

$$v_{\text{app}}(t) = n_w(t) - \gamma \frac{d}{dt}\int_0^L p(z,t)dz \quad \text{with} \quad \gamma = \left(\frac{\partial n}{\partial p}\right)_S.$$

Here γ is the adiabatic piezo-optic coefficient and n_w is the refractive index of water under ambient conditions. The piezo-optic coefficient describes the changes in optical refractive index with acoustic pressure.

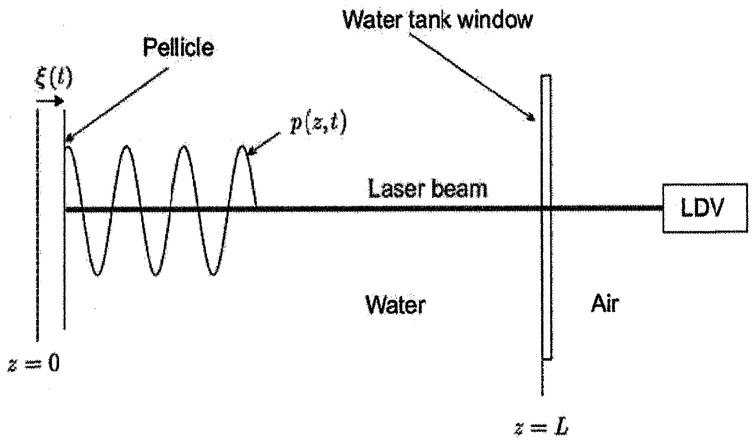

Figure 1. Basic LDV geometry, showing an acoustic pulse having travelled part way to the tank boundary.

The special case where the acoustic field is a plane wave that has not propagated as far as the tank window is now considered. Consider the transducer to be stationary at time zero, and then to instantaneously start to move with a perfect sinusoidal velocity

$$v(t) = \begin{cases} v_0 \sin(\omega_0 t), & t \geq 0, \\ 0, & t < 0. \end{cases} \tag{3}$$

This results in a pressure

$$p(z,t) = \begin{cases} p_0 \sin(\omega_0 t - kz), & t \geq 0 \; and \; z \leq c_0 t, \\ 0, & t < 0. \end{cases} \tag{4}$$

Here ω_0 is the acoustic angular frequency, k is the acoustic wavenumber in water and $p_0 = \rho_0 c_0 v_0$. For this plane wave case it can be shown [9] that $v_{app}(t) = n_{eff}.v(t)$ where

$$n_{eff} = n_w - \gamma \rho_0 c_0^2 = 1.009. \tag{5}$$

For a real transducer the wavefield will not be planar in nature. In addition it is essential to consider the source being driven with a tone-burst so that measurements are still made under free-field conditions such that the acoustic field hasn't reached the optical window. For this reason it is necessary to model the acousto-optic effect for a time dependant field radiated by a transducer.

In order to investigate the effects of the acousto-optic effect on LDV measurements a numerical model was set up to simulate a circular transducer driven with a tone burst signal. The first step in the calculation process involved calculating the time dependent pressure field $p(r, z, t)$ of a circular transducer, of radius a, through which the laser beam passes. This was achieved using a method described by Stepanishen [10] which expresses the velocity potential at a point in space as a convolution of the transducer impulse response with the source velocity time history. This was used to calculate the wavefield as a function of time at each spatial co-ordinate (r, z).

These results were then used to calculate the apparent velocity of the transducer using Equation (1) by numerically integrating along the laser path at a constant radial coordinate r. The calculated values were numerically differentiated to give the temporal derivative of the integrated pressure, again as a function of time. From this the effective transducer velocity, as would be seen by a LDV, was calculated.

The fundamental signal measured by an LDV is the time-dependent apparent velocity considered thus far. Commercial LDVs are, however, often designed to measure steady-state surface vibration. This is achieved by taking the Fourier transform of an appropriately time-gated section of the raw velocity signal, resulting in a measured velocity spectrum. Data at individual frequency components are then typically assessed by viewing 2D amplitude and phase distributions over the moving surface. For underwater transducer measurement, it will be the velocity spectrum component at the driving frequency that is of interest. Such steady-state measurements have been simulated by processing the apparent velocity signals predicted by the numerical model in exactly the same way. The time window was selected to simulate that typically used in experimental measurements.

3 MODEL SIMULATIONS

Model predictions were run for a small device (31.75 mm in diameter) at 500 kHz. Figure 2 shows the magnitude and phase of the apparent velocity, as a function of the radial coordinate, according to the model. The magnitude is normalised by the true velocity, which is also shown for comparison. This shows clear deviations from the true velocity over the transducer surface with a particularly large deviation on the acoustic axis. For $r > a$, i.e. over the baffle surrounding the piston, the apparent velocity is not zero, and only falls off slowly with r. The phase variation indicates that the apparent velocity looks like a wave that travels over the surface of the baffle with the speed of sound in water.

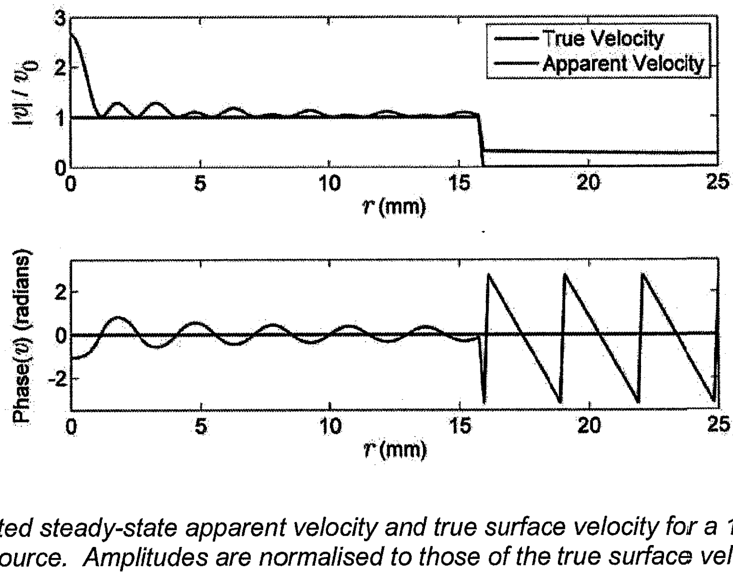

Figure 2. Simulated steady-state apparent velocity and true surface velocity for a 15.9 mm radius circular piston source. Amplitudes are normalised to those of the true surface velocity over the radiating area.

In order to understand this behaviour it is possible to subtract the expected velocity from the apparent velocity to obtain the optical artefact in the velocity. Figure 3 shows the normalised magnitude and phase of this artefact velocity, again as a function of the radial coordinate. Over the transducer area the artefact has the appearance of a standing wave in a system with circular symmetry; the acousto-optic artefact appears to be dominated by the effect of the edge wave propagating over the surface of the transducer. This is because in this region the wavefronts and the laser beam are parallel so the effect of the acousto-optic effect can build up constructively.

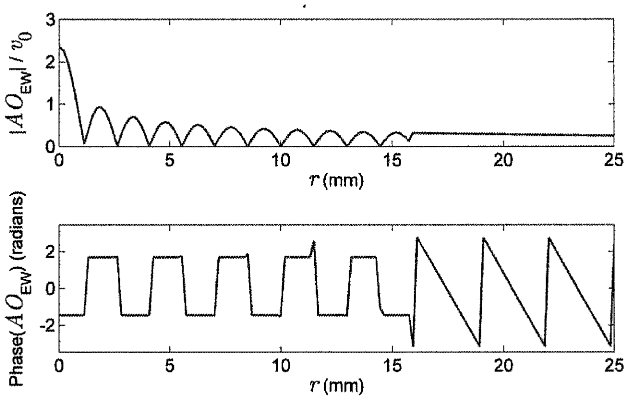

Figure 3: Velocity artefact (apparent velocity – true velocity) for the results presented in Figure 2. All amplitudes and phases are expressed relative to those of the true surface velocity over the radiating area.

These results indicate how the acousto-optic effect will make it difficult to analyse transducer surface vibration underwater using LDV techniques. However, it is possible to use the simulated LDV data as input to a propagation routine to predict the far-field beam pattern. The resulting normalised directivity is shown in Figure 4, with the true directivity of a circular piston for comparison. This shows that the beam pattern is very well reproduced for angles up to 30°, with only the nulls between the sidelobes not well reproduced. However the directivity predictions above 50° show significant deviations from the true directivity, especially as the angle approaches 90°.

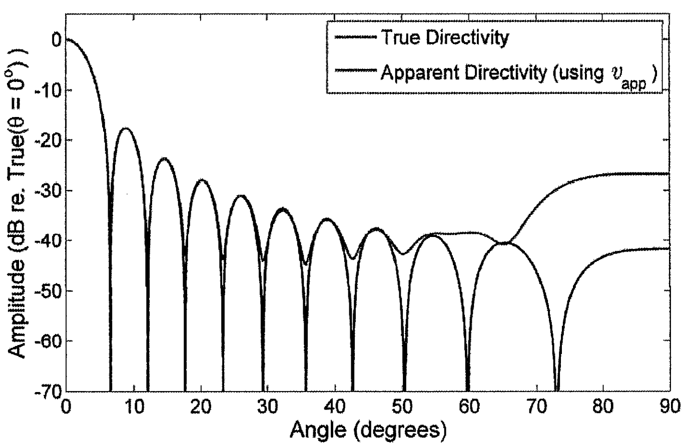

Figure 4: Predicted far-field directivities calculated from the simulated apparent velocity distribution for a 15.9 mm radius, 500 kHz circular piston transducer. The true directivity is shown for comparison.

4 EXPERIMENTAL MEASUREMENTS

Results that show the potential of the LDV technique will be considered in this section. The measurements reported here were performed on two circular transducers, 31.8 mm and 200 mm in diameter, at a frequency of 500 kHz. The transducers were each driven with a tone-burst, derived from an arbitrary waveform generator and amplified by an ENI 240L power amplifier. The 'far-field' measurements were made in a test tank or a larger reservoir facility as appropriate.

Optical scans of the transducer were undertaken using a Polytec PSV-400 scanning vibrometer, consisting of an OFV 505 scanning head and a PSV-E-400-M2-20 control unit. The vibrometer scanned the laser beam over a grid of user defined positions on a surface and measured the normal component of the surface velocity by measuring the Doppler shift of the reflected laser light.

Figure 5 shows the results of the LDV scan on the smaller 31.8 mm diameter device when mounted in aluminium baffle. The amplitude results show clear evidence of fluctuations across the surface of the transducer similar to those shown in Figure 2. The periodic phase variation over the surface of the baffle indicates that this is related to the acousto-optic artefact due to the travelling edge wave.

The results shown in Figure 5 have been used to estimate the far-field directivity of the source by linear propagation [1]. The resulting directivity is compared with direct hydrophone measurements of the directivity at a range of 1.25 m in Fig 6(a). The agreement between the predicted and directly measured directivity patterns for the three main lobes is excellent. At higher angles the differences become increasingly significant, especially beyond about 70° where the acousto-optic artefact contribution becomes dominant. It should be noted that the hydrophone measurement of directivity has its own uncertainties, the primary ones being whether the experimental setup has the centre of rotation correctly positioned and whether the hydrophone was correctly aligned.

In Figure 6(b) corresponding directivity results are presented for the larger 200 mm transducer; hydrophone measurements, made at a range of 24.4 m, are compared with predictions from the LDV optical measurements. Again excellent agreement is obtained for the main lobe and first few sidelobes although some larger deviations are observed above 15°. These can be attributed, in part, to the fact that the transducer had to be transferred to a reservoir facility to make the far-field measurements, making it difficult to ensure consistency of vertical alignment between the measurements. Overall, Figure 6 presents a convincing validation that accurate far-field directivity data can be obtained at modest angles from optically measured surface velocity data – despite the presence of an acousto-optic artefact.

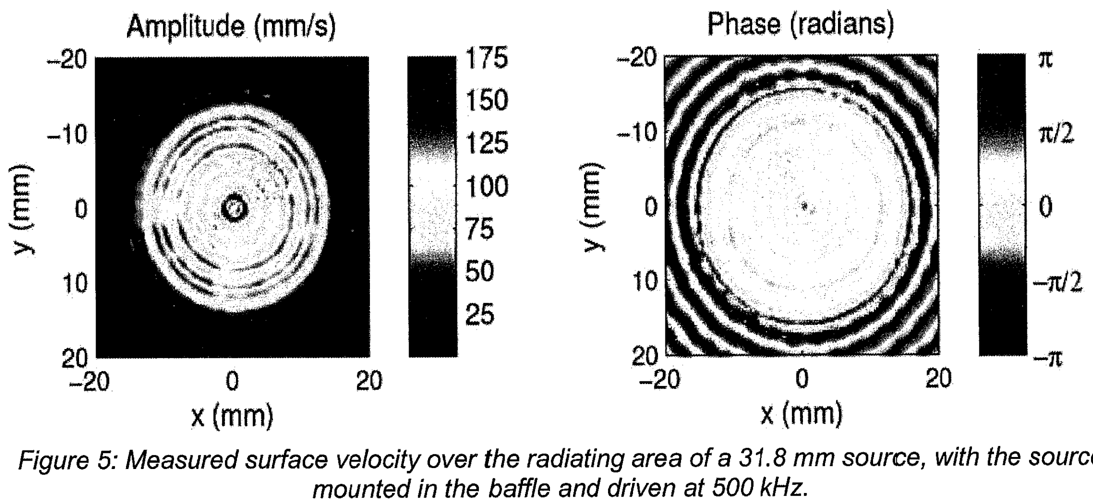

Figure 5: Measured surface velocity over the radiating area of a 31.8 mm source, with the source mounted in the baffle and driven at 500 kHz.

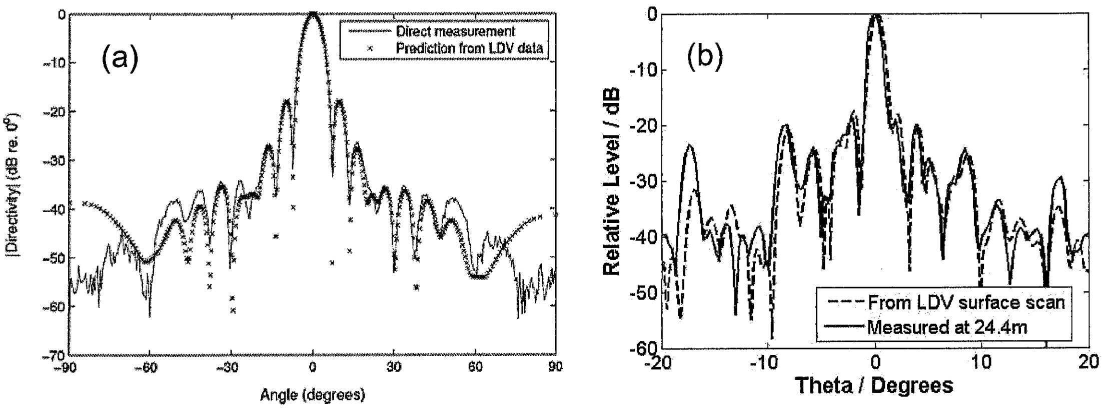

Figure 6: Amplitude of the far-field directivity for (a) the 31.8 mm diameter source measured at 1.25 m and (b) the 200 mm source at 24.4 m. The hydrophone results are compared with predictions obtained from the LDV measurements of the transducer surface velocity. The frequency used was 500 kHz in each case.

5 DISCUSSION AND CONCLUSIONS

The field radiated by a transducer underwater has the potential to create extra phase shifts in the optical path (via the acousto-optic effect) which complicate the measurement of transducer surface velocity using an LDV. This is because the LDV interprets these additional phase changes as an additional apparent velocity of the surface. Model simulations show that this velocity artefact can be comparable with the true velocity, and is mainly associated with the edge waves that travel across the surface of the transducer and surrounding baffle. Clearly this makes the interpretation of LDV data for a transducer in water difficult, especially as the effects may resemble what might be expected from standing waves on the transducer surface.

Simulated LDV data for a small transducer, 31.8 mm in diameter, have been used to calculate the far-field directivity from the apparent surface velocity. This shows that the effect of the artefact on the propagated field directivity is small for angles up to 30°. This has been confirmed by experimental observations that indicate that it is possible to estimate far-field directivities for small angles from LDV scan data. Experimental results for both a 31.8 mm and larger 200 mm diameter transducer show very good agreement between the propagated LDV data and hydrophone measurements for angles near the acoustic axis. The optical approach has the potential advantages over hydrophone scans of being non-perturbing, higher resolution and faster. The LDV data can be also used as an input to nonlinear propagation algorithms if required.

Further detailed calculations have been used to investigate the acousto-optic effect for tone bursts and the factors affecting LDV measurements of ultrasonic transducer surface velocities underwater. Numerical modelling indicates that there can be a benefit in using the LDV to measure the velocity of a thin gold coated polymer membrane (pellicle), offset from the transducer face, rather than the velocity of the transducer face directly. This has the effect of reducing the significance of the acousto-optic artefact due to the fact that the wavefronts of the edge waves are no longer parallel to the laser beam at the pellicle surface.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the Acoustics and Ionising Radiation Programme at the National Physical Laboratory (part of the Department for Business, Innovation and Skills National Measurement System).

REFERENCES

1. V.F. Humphrey, S.P. Robinson, P.D. Theobald, G. Hayman, P.N. Gélat and A.D. Thompson, Comparison of optical and hydrophone-based near-field techniques for full characterisation of high frequency sonar, Proceedings of Underwater Acoustic Measurements, Heraklion, Crete, Greece, pp. 457-464, 2005.
2. V.F. Humphrey, G. Hayman, S.P. Robinson and P.N. Gélat, Forward and back propagation of wavefields generated by large aperture transducers, Proceedings of the Seventh European Conference on Underwater Acoustics, ECUA 2004, Delft, The Netherlands, pp. 1045-1050, 2004.
3. M.E. Schafer and P.A. Lewin, Transducer characterisation using the angular spectrum method, J. Acoust. Soc. Am. 85, pp. 2202-2214, 1989.
4. P.R. Stepanishen and K.C. Benjamin, Forward and backward projection of acoustic fields using FFT methods, J. Acoust. Soc. Am. 71, pp. 1158-1164, 1982.
5. P.D. Theobald, S.P. Robinson, A.D. Thompson, R.C. Preston, P.A. Lepper and Y.B. Wang, Technique for the calibration of hydrophones in the frequency range 10 to 600 kHz using a heterodyne interferometer and an acoustically compliant membrane, J. Acoust. Soc. Am. 118, pp. 3110-3116, 2005.
6. A.R.Harland, J.N. Petzing and J.R. Tyrer, Non-perturbing measurements of spatially distributed underwater acoustic fields using a scanning laser vibrometer, J. Acoust. Soc. Am. 115, pp. 187-195, 2004.
7. O.A. Sapozhnikov and A.V. Morozov, Piezoelectric transducer surface vibration characterisation using acoustic holography and laser vibrometry, 2004 IEEE International Ultrasonics, ferroelectrics and Frequency Control Joint 50th Anniversary Conference, 2004.
8. D. Certon, G. Ferin, O. Bou Matar, J. Guyonvarch, J.P. Remenieras and F. Patat, Influence of acousto-optic interactions on the determination of the diffracted field by an array obtained from displacement measurements, Ultrasonics 42, pp. 465-471, 2004.
9. C.B. Scruby and L.E. Drain, Laser Ultrasonics, Adam Hilger, Bristol, 1990.
10. P.R. Stepanishen, Transient radiation from pistons in an infinite planar baffle, J. Acoust. Soc. Am. 49, pp. 1629-1638, 1971.