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A comparison of hydrophone near-field scans and optical techniques for characterising high frequency sonar transducers

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Two potential methods of fully characterising the response of high frequency sonar transducers and arrays operating in the frequency range 100 kHz to 500 kHz are compared. In the first approach two-dimensional planar scans, with a spatial resolution of better than half a wavelength, are performed in the acoustic near-field using a small probe hydrophone. The measured two-dimensional data are propagated numerically using a Fourier Transform method to predict the far-field response. Alternatively the data can be back-propagated to re-construct the pressure distribution at the source, a powerful diagnostic technique which can identify defects in transducers and array elements. The second approach uses a scanning laser vibrometer to measure the velocity of the transducer surface; with the resulting velocity data also being used to predict the far-field response by numerical propagation. Comparison of the propagated hydrophone near-field scan data with direct measurements at these ranges shows very good agreement, indicating the usefulness of the method for deriving far-field transducer responses from near-field measurements in laboratory tanks. The potential limitations introduced to the optical approach by the acousto-optic effect are discussed.

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 nearfield of the transducer and propagate this data numerically to predict the far-field behaviour. The propagation of hydrophone pressure scans has already been successfully demonstrated high frequency sonar transducers [1, 2] and high frequency ultrasound transducers [3, 4]. If required the finite amplitude propagation effects can be accounted for in the propagation step. Such scanning techniques can, however, take a long time for large devices at high frequencies.

However, the development and availability of optical measurement systems, such as Laser Doppler Vibrometers (LDVs), make it possible to consider alternative optical techniques of characterising the fields. For example, an LDV can be used to measure the movement of a thin membrane (pellicle) in the field [5] or used to measure the field 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]. This approach, using surface velocity measurement and numerical propagation, enables devices with large near-field regions to be calibrated in small laboratory tanks in principle.

The use of an LDV (or other optical technique) to measure surface displacements 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 change in path length as an additional component of surface velocity. This 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 still the subject of study; they may not be important for large devices if the real and acousto-optic contributions can be resolved in *k*-space. Results are presented here for the numerical propagation of surface velocity measurements made on large devices, and are confined to small angles from the acoustic axis.

2 Theory

The first approach uses the angular spectrum method to propagate the acoustic pressure field from one plane to another. This requires the complex pressure $p(x, y, z_0)$ to be measured over the xy plane at a range z_0 from the transducer (see Fig. 1).

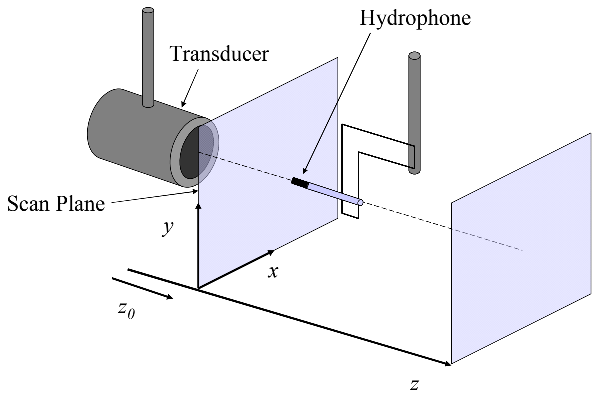


Fig. 1. Experimental arrangement for making 2-D scans in near-field of transducer.

The plane-wave spectrum of the field $P(k_x, k_y)$ can then be calculated by taking the 2-D Fourier transform of the complex pressure [9]:

$$P(k_x, k_y) \quad = \quad \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} p(x, y, z_0)\, e^{-i(k_x x + k_y y)}\, dxdy \qquad (1)$$

where k_x and k_y are the components of the wavenumber k along the x and y axes respectively. The pressure distribution in another plane at a different range z can then be calculated by propagating each plane wave component from the measurement plane to the observation plane (by multiplying by an appropriate phase factor) and then performing the inverse 2-D Fourier transform to give the resulting pressure:

$$p(x, y, z) \quad = \quad \left(\frac{1}{4\pi^2}\right)\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} P(k_x, k_y) e^{ik_z(z - z_0)}\, e^{i(k_x x + k_y y)}\, dk_x dk_y \qquad (2)$$

Alternatively, if the transducer is planar and lies in the source plane $r'(x', y', 0)$ and has a normal velocity $\dot{w}(x', y', 0)$ over its face then the pressure $p(x, y, z)$ at a field point $r(x, y, z)$ can be calculated, assuming linear propagation, using the Rayleigh integral:

$$p(x,y,z) = \frac{-i\rho_0 ck}{2\pi} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \dot{w}(x',y',0) \frac{e^{ik|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|} dx'dy' \quad (3)$$

where ρ_0 is the water density and c is the speed of sound in the water. An alternative approach is to take the 2-D Fourier transform of the normal velocity to obtain the velocity spectrum in the source plane:

$$\dot{W}(k_x,k_y,0) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \dot{w}(x',y',0) \exp\left(-i(k_x x' + k_y y')\right) dx'dy' \cdot \quad (4)$$

Then the Fourier transform of the pressure in the observation plane at z is given by [9]:

$$P(k_x,k_y,z) = \frac{\rho_0 ck}{k_z} \dot{W}(k_x,k_y,0) \exp(ik_z z) \quad (5)$$

where

$$k_z = \sqrt{k^2 - k_x^2 - k_y^2} \cdot \quad (6)$$

Hence the pressure p can be obtained via the inverse Fourier transform:

$$p(x,y,z) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} P(k_x,k_y,z) \exp\left(i(k_x x + k_y y)\right) dk_x dk_y \cdot \quad (7)$$

For transducers with dimensions much larger than a wavelength the velocity spectrum will be narrow in k space so that for all k values of significance $k_z \approx k$ simplifying the calculations.

In practice, the pressure distribution or surface velocity is only measured over a limited region of the appropriate *xy*-plane. This can introduce significant errors unless care is taken to ensure that the pressure/velocity levels are insignificant at the edges of the sampled region. In addition, when performing the forward propagation it is necessary to increase the matrix size by zero padding the measured data to reduce the interference effect resulting from the use of a finite aperture. The use of an FFT results in the measurement aperture being effectively replicated in both the x and y directions; the high angle plane wave components from the replicated apertures can then interfere with the low angle components from the central aperture to give erroneous results. Zero padding the data before taking the 2-D FFT reduces this effect although, in practice, this limits the range achievable by the use of Eq. (2) or Eq. (7). The far-field behaviour can alternatively be obtained from the plane wave spectrum itself (Eq. (1) or Eq. (4)) [9].

3 Experiment

The measurements reported here were performed on the transducers described in Table 1. These were chosen because their near-field regions extended to significant distances; however, their near-field to far-field transitions were still accessible within the 5.5 m diameter large open tank at NPL in order to validate the predictions.

The transducers were driven at the frequencies given in Table 1 with a tone-burst, derived from a HP33120A arbitrary waveform generator and amplified through an ENI 240L power amplifier. The near-field scans were performed in a small open tank facility, a 2 m x 1.5 m x 1.5 m GRP test tank with a two-carriage positioning system (*XYZ* and *θZ* motion with 10 µm resolution). This also features a glass window to allow optical interrogation of the acoustic field. The 'far-field' measurements were made in a large open, wooden test tank, 5.5 m in diameter and 5 m deep and at a larger reservoir facility.

The near-field hydrophone scans were undertaken by scanning a Reson TC4035 hydrophone over a planar surface in the acoustic near-field, with the amplitude and phase of the signal being measured at discrete points and the received signals analysed using a HP89410A vector signal analyser with on-board spectral analysis. The tone burst length, analysis window length and window start time were selected with care to ensure that complete information about the transducer surface vibration was obtained at all points on the measurement scan. Scans were automated, enabling them to be left overnight to complete. Step sizes were chosen to be λ/2 or smaller to ensure that the Nyquist sampling criterion was satisfied and the scan width was chosen to ensure that the signal amplitude was at least 20 dB lower at the scan edges than that at the beam centre.

The need for phase stability put very stringent requirements on the temperature variations allowed over the measurement period. In practice this did not appear to be a significant problem with the temperature typically being stable to within 0.15 ºC over a 24-hour period (the maximum observed variation was 0.3 ºC).

Name	Diameter [mm]	Frequency [kHz]	Description
A	200	500	Circular 1-3 composite array
B	150	320	Circular single element piston

Table 1 Transducers characterised during the work described in this paper.

Optical scans of the transducer were undertaken using a Polytec PSV-300 scanning vibrometer, consisting of an OFV 056 scanning head and a PSV-Z-040-F control unit. The vibrometer scans the laser beam over a grid of user defined positions on a surface and measures the normal component of the surface velocity by measuring the Doppler shift of the reflected laser light. The scanning process is achieved within the LDV by mirrors that are aligned by the use of computer-controlled stepper motors.

The vibrometer was positioned 0.834 m outside a small open tank (2 m x 1.5 m x 1.5 m), with the optical beam entering the tank via a glass window (see Fig. 2). The transducer was positioned 0.58 m from the window, providing a total optical stand-off distance of around 1.6 m assuming a refractive index of 1.33 for water. The vibrometer provided a measurement range of ±250 mm s-1 and a measurement bandwidth of 1.5 MHz.

The vibrometer scan was synchronised with the function generator with 5 averages being performed for each scan point. The output of the vibrometer was then band-pass filtered to isolate the frequency of interest. A spatial scan resolution of approximately 1 mm was used and the total scan angle never exceeded 7.5°.

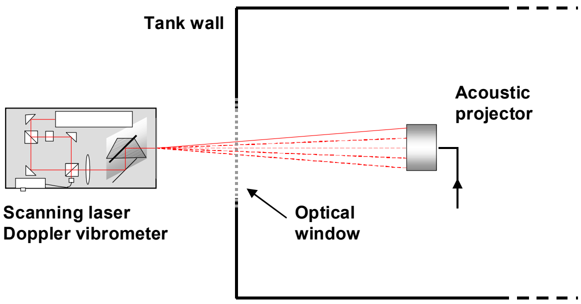


Fig. 2. Experimental arrangement for making 2-D scans of transducer using LDV.

In interpreting the LDV output it is necessary to consider the effect of the acoustic wavefield, through which the laser beam propagates, on the phase of the optical beam via the acousto-optic effect. For the case of an acoustic plane wave propagating parallel to the laser beam it can be shown that the effect can be accounted for by replacing the refractive index of water with an effective refractive index [10]. A more extensive analysis [11] indicates how this can effect can be allowed for in general although for transducer fields the effects can be much more complicated [7].

4 Results

4.1 Hydrophone scans

Fig. 3 shows the experimental results for the pressure amplitude measured at a range of 10 mm for Transducer A operating at 500 kHz. The plots show a region 120 mm by 120 mm in size and are colour-mapped to represent amplitude (linear scale). The plotting routine uses the MATLAB smooth function to remove the spatial sampling quantisation. The results show circular symmetry, with evidence of an inner and outer ring in the array (with different vibration amplitudes). Departures from uniform response are seen in the amplitude in the inner ring.

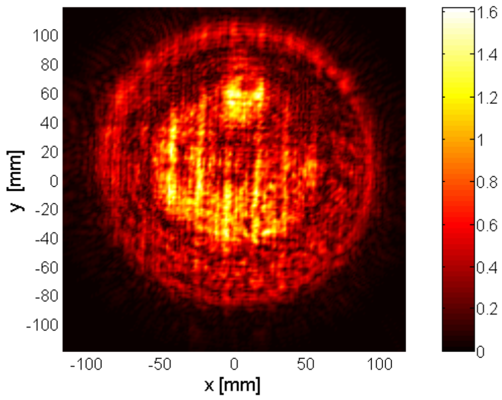


Fig. 3. Results for Transducer A at a range of 10 mm at 500 kHz showing measured pressure amplitude on a linear scale.

(a)

(b)

(c)

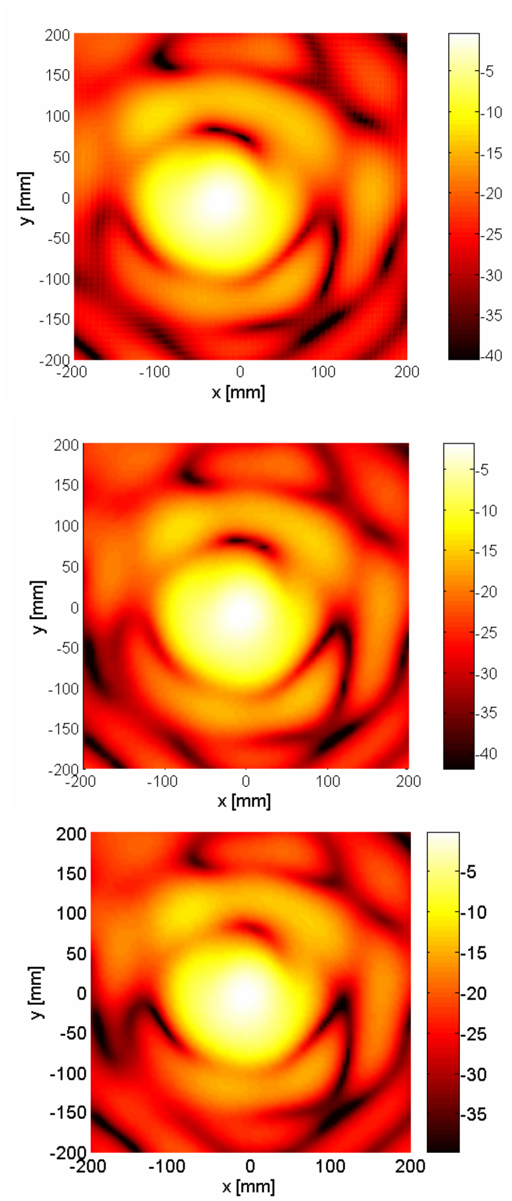


Fig. 4. Normalised pressure amplitude results (in dB) in the *xy* plane for Transducer A at 3.34 m and 500 kHz showing: (a) forward-propagated pressure field from 10 mm, (b) direct measurement at 3.34 m, and (c) forward-propagated optical LDV surface velocity measurements.

The result of forward propagating this field to 3.34 m, in the near-field/far-field transition region, is shown in Fig. 4(a). This clearly shows departures from perfect circular symmetry. For comparison, the measured field in the *xy* plane at 3.34 m is shown in Fig. 4(b). The excellent agreement in the form of the beam profile should be noted, with all of the deviations from perfect circular symmetry clearly reproduced. Fig. 5 shows a quantitative comparison of the propagated and measured beam-plots in the $y = 0$ plane for Transducer A at 3.34 m. Good agreement is shown between the measured beam profile and the predicted profile generated by forward propagating the scan data from 10 mm. The main lobe is reproduced very well, but some departures are evident in the side lobes. These can be attributed, in part, to the fact that the transducer and hydrophone had to be transferred to the larger tank to make the 3.34 m measurements, making it difficult to ensure consistency of vertical alignment between the measurements in different tanks.

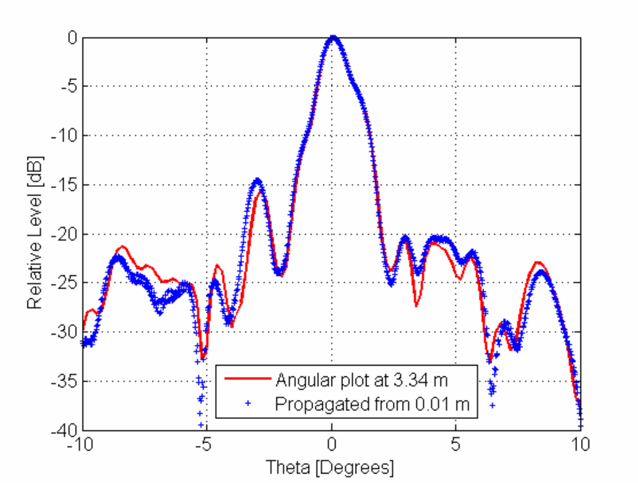
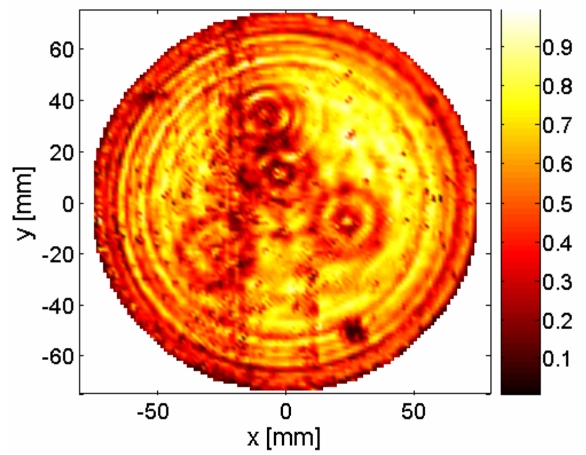


Fig. 5. Measured beam plot for Transducer A at 3.34 m predicted from scan at 10 mm (line) compared with experimental measurements at 3.34 m (+).

An additional application of the nearfield scanning approach is that the pressure data can be propagated back to the transducer to investigate the surface vibration of the transducer face [2, 4, 7]. In contrast the acousto-optic effect may mean that LDV measurements don't necessarily give an accurate measurement of the surface velocity.

4.2 LDV scans

(a)



(b)

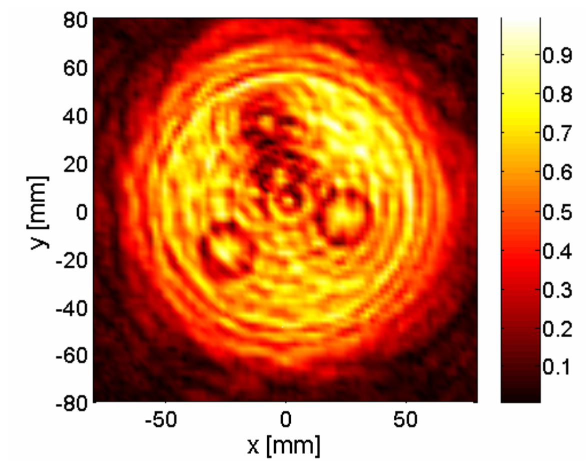
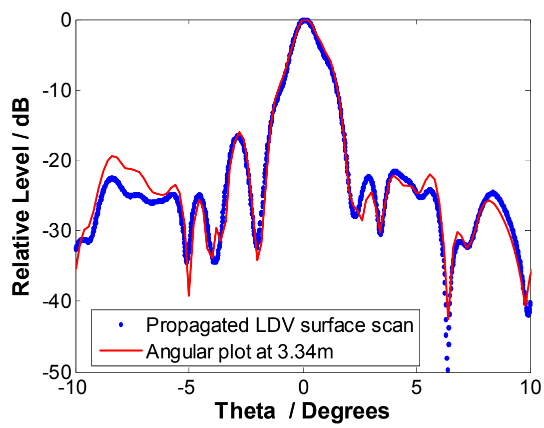


Fig. 6. Results for transducer B showing: (a) direct measurement of the surface velocity amplitude using scanning laser vibrometry (linear scale) and (b) pressure amplitude measured at 10 mm from the transducer face.

An idea of the capability of the LDV system can be obtained by comparing the optically measured data with that obtained by conventional near-field scanning with a small (Reson TC4035) hydrophone. Fig. 6(a) shows the normalised magnitude of the surface velocity measurements obtained for transducer B. These are compared with a scan made at 10 mm from the transducer face by scanning the hydrophone under computer control (Fig. 6(b)). In both cases the plots are scaled to the maximum amplitude. The transducer has four circular "defects" about 20 mm in diameter that can be identified in both plots. The general agreement between the measured optical and acoustic data is apparent, especially in terms of the size and position of the defects. However, other data, on more well behaved transducers, clearly shows additional velocity contributions due to the acousto-optic effect, as described in [7]. It should be noted that the optical data takes significantly less time to obtain than the hydrophone scan data. In addition the LDV measures the relative phase of the surface velocity as function of position as is required to calculate the velocity spectrum (Eq. (4)).

The result of propagating LDV data by taking the velocity spectrum, calculating the pressure spectrum at a distance and then calculating the pressure distribution using the inverse FFT is shown in Fig. 4(c) for transducer A. This shows the magnitude of the field in the transverse *xy*-plane at a range of z = 3.34 m on a dB scale, normalised to the maximum value. For comparison Fig. 4(b) shows hydrophone data obtained conventionally at 3.34 m on the same 0 to -40 dB range. The excellent agreement should be noted.

(a)



(b)

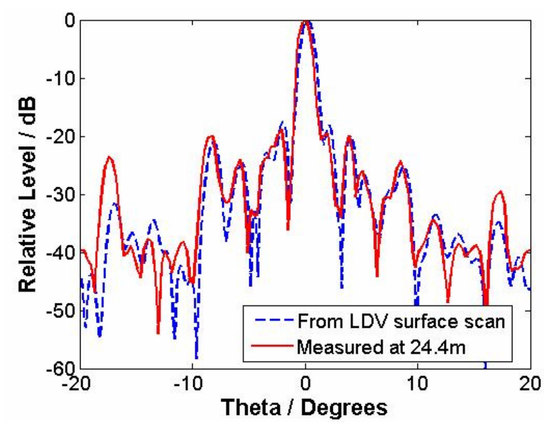


Fig. 7. Measured beam plots for Transducer A at 500 kHz: (a) at 3.34 m and (b) 24.4 m. Measurements are compared with the results predicted by linear propagation of the LDV scan data.

Fig. 7(a) shows a quantitative comparison of the numerically propagated and measured beam-plots in the $y = 0$ plane for Transducer A at 3.34 m. Good agreement is shown between the measured beam profile and the predicted profile generated by forward propagating the optical data. The main lobe is reproduced very well, but some departures are evident in the side lobes. These can be attributed, in part, to the fact that the transducer had to be transferred to the larger tank to make the 3.34 m measurements, making it difficult to ensure consistency of vertical alignment between the measurements in different tanks. A similar comparison for a range of 24.4 metres is shown in Fig 7(b). Again the agreement for angles up to 10º is very good, although that for higher order sidelobes is not as good. The extent to which this is a result of alignment issues is not clear.

5 Conclusion

The results presented show that near-field 2D planar scanning with a small hydrophone is a powerful technique for characterising large sonar transducers. The use of numerical propagation enables a prediction of the field at any distance to be made, including the far-field response. The use of finite amplitude propagation codes would, in principle, enable high amplitude fields to be characterised in a similar way. The near-field data can also be back propagated to determine the transducer behaviour [2, 4, 7]. Near-field hydrophone scans are, however, relatively time consuming due to fine resolution required and can place significant constraints on the test tank temperature stability. The approach does provide a means for predicting far-field response using measurements in relatively small facilities.

In principle an LDV system can be used to obtain equivalent 2D scans of surface velocity that may also be used as the input to a linear propagation model to derive the pressure field at other distances. The optical approach has the potential advantages over hydrophone scans of being non-perturbing, higher resolution and faster. However, the radiated field has the potential to create extra phase shifts via the acousto-optic effect which the LDV interprets as an additional apparent velocity of the surface [7, 8]. Clearly this makes the interpretation of LDV data for transducer surface velocity in water difficult. The effect on the results for the propagated field, such as that performed here, are still under investigation. The results demonstrate good agreement for a large transducer near to the acoustic axis when compared with acoustic measurements. Detailed calculations are currently being used to investigate the acousto-optic effect for tone bursts and its effect on the propagation of LDV measurements of transducer surface velocity.

Acknowledgments

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