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LETTERS TO THE EDITOR

NON-INVASIVE MEASUREMENTS OF UNDERWATER PRESSURE FIELDS USING LASER DOPPLER VELOCIMETRY

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1. INTRODUCTION

The propagation of mechanical sound waves in dense media such as water is central to many communication and imaging techniques used in naval and medical environments. Knowledge of the spatial and temporal pressure variation within the acoustic field is of significant importance for many users and many techniques have been developed to facilitate this need. Work has been done in attempting to theoretically predict the acoustic field generated by a specific source at a given frequency by such techniques as finite element modelling. Data generated from these predictions have been used for feedback into the design loop with a view to refining the quality and efficiency of the transducer. Other theoretical tools include the "angular plane wave spectrum method", where a plane of measured pressure data is used to predict the pressure amplitude and phase at a point elsewhere in the field [1, 2]. Despite recent advances in these theories, the most reliable means of characterizing the field remains taking pressure measurements directly from the field.

The traditional method of measuring the pressure variation at a point within an acoustic field is the use of a hydrophone device which will output a voltage proportional to the integral of the pressure across its active element. However, there are certain drawbacks to measurements made by such devices. Firstly, the scaled output is assumed to represent the pressure at a point, whereas in reality the active element will have a finite dimension over which the pressure is integrated. The position of this point will move within the volume of the hydrophone depending on the acoustic frequency, appearing close to the perimeter for wavelengths smaller than the dimensions of the element. Secondly, the devices typically have frequency responses characterized by resonant spikes and non-responsive regions. Consequently, scaling the voltages into values of pressure will be subject to uncertainties. It is also well documented that such things as temperature and hydrostatic pressure have a detrimental effect on the stability of a hydrophone sensitivity [3].

Where more refinement is required, such as in calibration standard techniques, optical interferometric techniques have been developed. The NPL laser interferometer measures the displacement of a thin (typically 5 μm), gold-coated Mylar pellicle suspended in the acoustic field, from which the pressure can then be derived [4], as depicted in Figure 1. The properties of Mylar are such that it is assumed to appear transparent and thus non-perturbing to the acoustic field.

The primary restricting factor in applying this technique is the limited time window in which the motion of a point at the centre of the pellicle represents the true acoustic

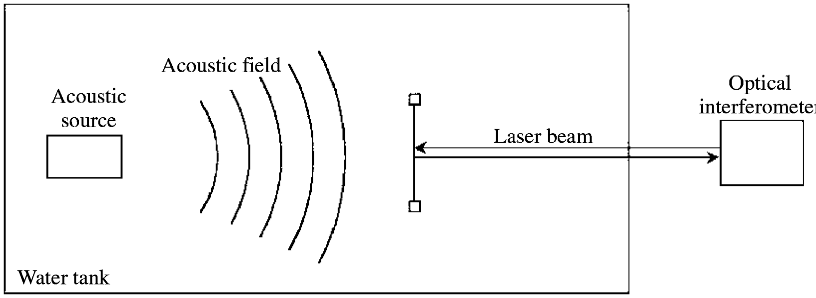


Figure 1. Geometry used for taking optical interferometric measurements from a pellicle.

displacement within the field before the motion becomes contaminated by acoustic signals reflected from the perimeter mounting of the pellicle. This, combined with the fact that a sample length of 10 uncontaminated cycles of the acoustic waveform are required to achieve desirable confidence levels, results in the technique having a lower frequency limit of approximately 200 kHz. Although a path length compensating Pockel's cell is included in the reference arm of the interferometer, it is extremely difficult to eliminate all unwanted vibrations from the measurement. The random uncertainty of this technique is typically 1% and the systematic uncertainty varies from 2·3 to 6·6% in the frequency range of 500 kHz to 15 MHz.

Work done recently by Wang Yeubing and Huang Yongjun at Hangzhou Applied Acoustics Research Institute has suggested the use of heterodyne interferometry as a means of measuring the velocity of a point on the surface of a pellicle [5]. By using a 0·7 m long strip of 30 mm wide Mylar held at each end, and requiring a sample of only one complete cycle, the lower frequency limit can be reduced to 5 kHz. The upper frequency limit is given as 200 kHz, determined by the response of the instrument. Uncertainty values for this technique ranged between 2·7 and 5·3%. The insensitivity of this type of interferometer to environmental disturbances, and capability to measure high velocities over a wide frequency range gives measurements from a heterodyne interferometer a favourable advantage over those from a Michelson interferometer.

This paper investigates taking acoustic velocity measurements from a pellicle using a standard heterodyne interferometer, referred to as a vibrometer, and continues to detail a novel method of making non-perturbing measurements of integrated pressure with distance from acoustic fields, using the same device. Essentially, when the beam is passed through the field, perpendicular to the acoustic axis, as shown in Figure 2, path length variations caused by the pressure-induced refractive index changes are measured as velocities by the vibrometer.

2. THEORETICAL ANALYSIS

Laser Doppler velocimetry or "vibrometry" is a well-established technique for the measurement of solid surface vibrations. The principle of operation is that of the detection of the Doppler shift in the frequency of light scattered from the vibrating surface:

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

where ω is the laser light frequency, E_T and φ_T are the respective amplitude and phase of the light incident at the detector with the target in its central position and a_v and ω_v are the

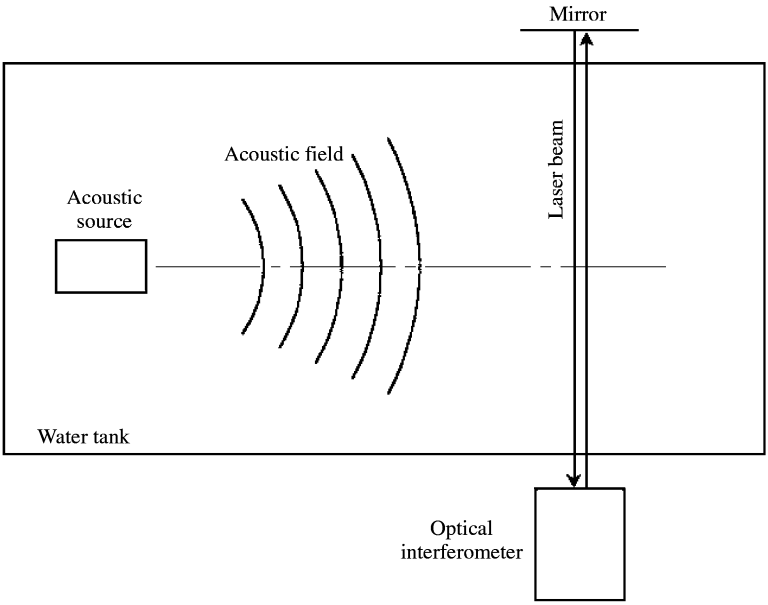


Figure 2. Geometry used for taking LDV measurements directly from the field.

respective amplitude and frequency of the target vibration. The signal processing electronics then output an analogue voltage proportional to the velocity of the vibrating surface.

For the majority of airborne surface vibration measurements, this explanation is sufficient, since the primary influence in the vibrometer output signal is the target velocity. However, where the beam is passed through a more dense media, other effects such as dynamic pressure fields cause optical path length changes which can be interpreted as target velocities. For this reason, it is crucial to consider the vibrometer measurements in terms of the overall optical path length change.

The pressure variation, $p(t)$, at a point, z, during a stable period of an acoustic burst along the line section is given as

$$P(t)_z = P_{0z} \sin(2\pi f t + \varphi_z) \tag{2}$$

where p_{0z} is the pressure amplitude at point z, f is the acoustic frequency, and φ_z is the acoustic phase at the point z. From this the refractive index, n, at a point, z, can be shown to vary as

$$n(t)_z = (\partial n/\partial p)_T \, p(t)_z, \tag{3}$$

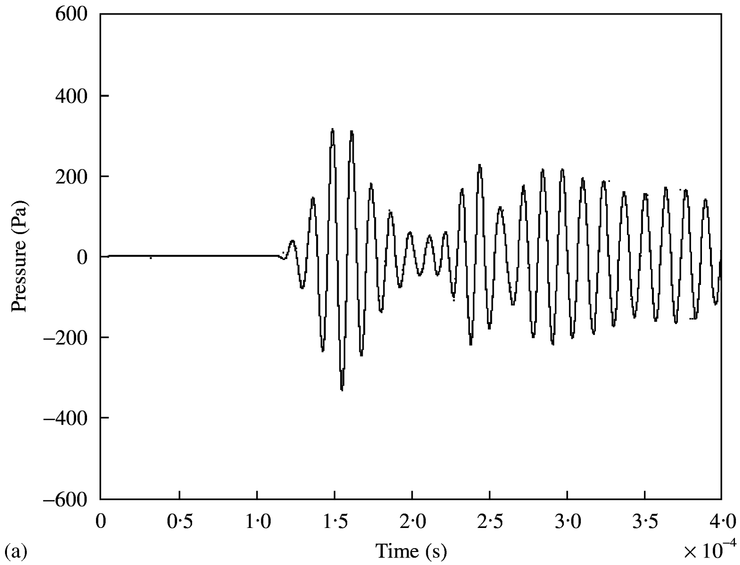
where $(\partial n/\partial p)_T$ is the piezo-optic coefficient at temperature, T [6].

The optical path length, L, along a path Z, can be derived as

$$L = \int_0^z n(t)\,\mathrm{d}z. \tag{4}$$

The final velocity output from the vibrometer is equivalent to twice the rate of change of the path length, due to the double pass of the optical beam through the media, as depicted in Figure 2:

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



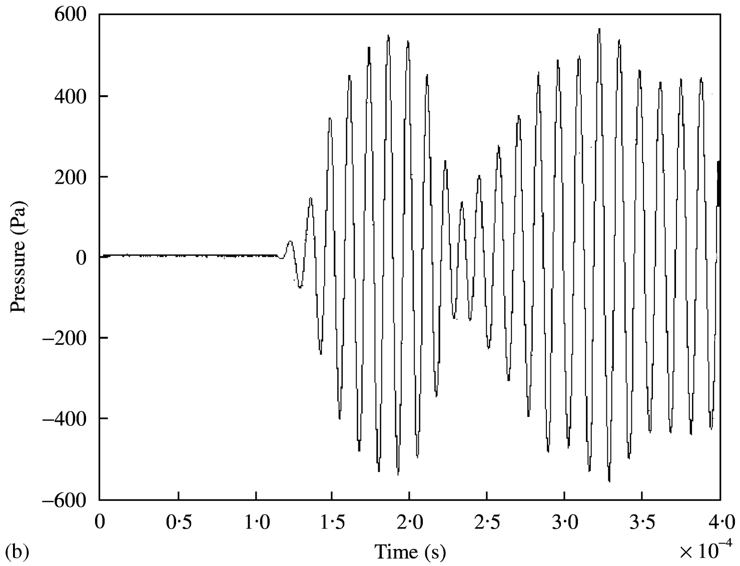


Figure 3. (a) Hydrophone measurement of a two cycle tone burst; (b) hydrophone measurement of a six cycle tone burst.

3. EXPERIMENTAL ANALYSIS

A repeated 80 kHz tone burst acoustic field was generated in a tank and an average of 100 tone burst repetitions were measured in two ways. Each tone burst consisted of two cycles in (a) and six cycles in (b). Figure 3 shows these results from a 25 mm diameter ball hydrophone, Figure 4 shows the vibrometer beam traversing the field (set-up as depicted in Figure 2). In this arrangement, the target is placed outside of the changing media and is consequently assumed to remain stationary throughout the duration of the tone burst.

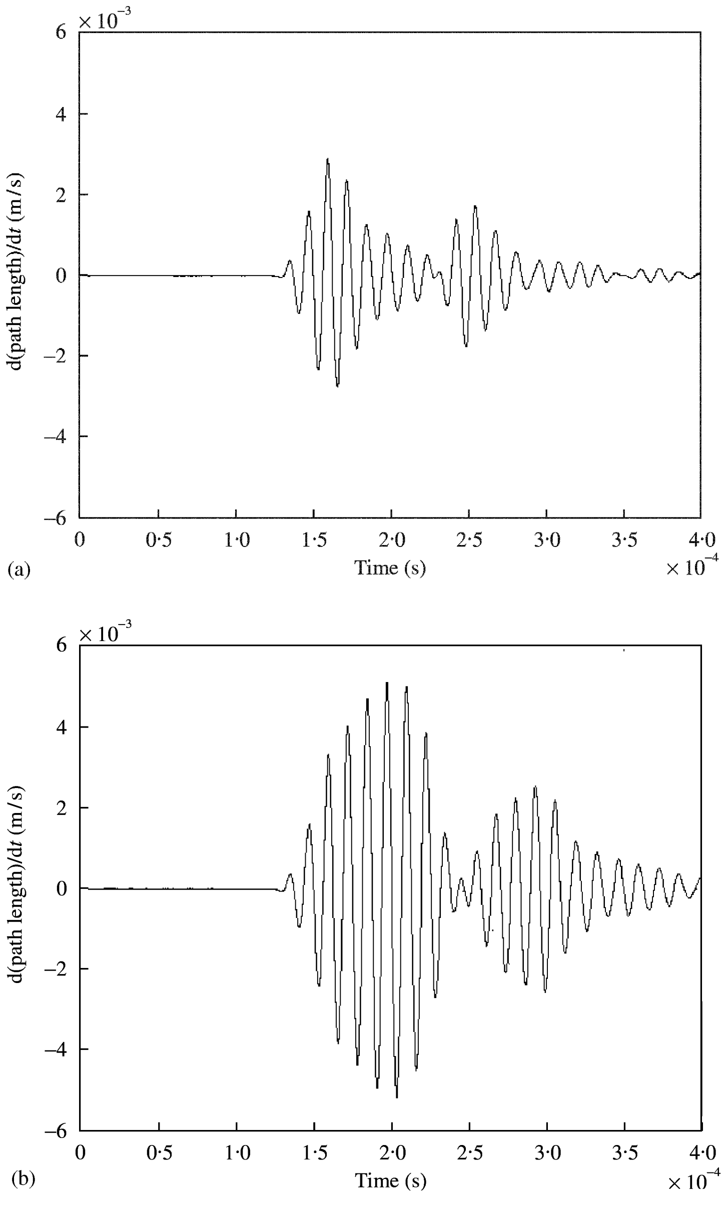
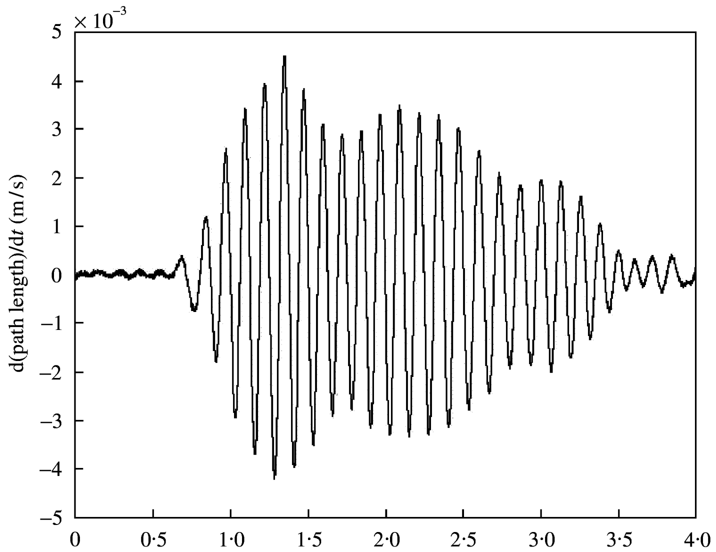
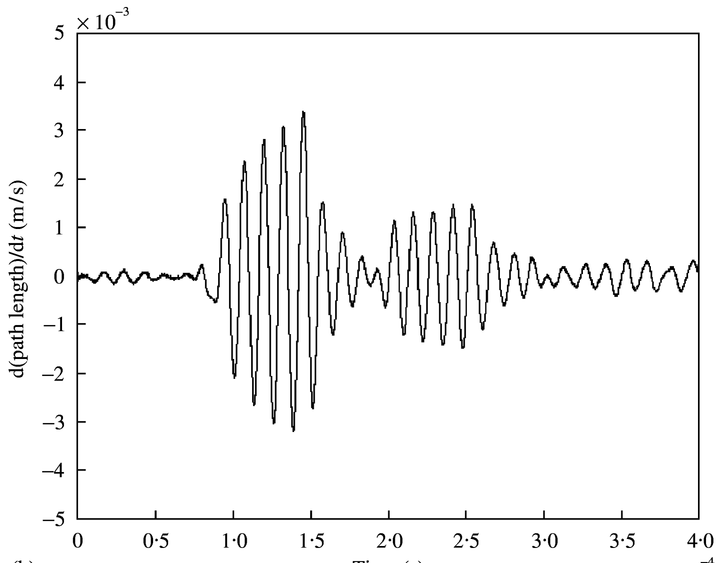


Figure 4. (a) LDV measurement of a two cycle tone burst; (b) LDV measurement of a six cycle tone burst.

It can be seen that both techniques offer a method of identifying the presence and temporal and spatial position of an acoustic tone burst. Interference caused by reflections from the tank walls becomes a significant hindrance in identifying the response of each measurement technique, although each can be seen to replicate the 80 kHz signal present during the original tone burst. A compromise had to be reached when considering the duration of the acoustic burst, since it should be sufficiently long to allow the hydrophone to reach a steady state response, but short enough such that the initial pulse had passed the measurement transducer before the first reflections arrived. The signal level versus time traces from the hydrophone and the vibrometer measuring directly from the field can be



(a)



(b)

Figure 5. (a) Rate of change of optical path length derived from hydrophone measurements of a line section; (b) rate of change of optical path length measured from an LDV signal for the same line section as in (a).

seen to be contained within "envelopes" similar in shape with the initial signal, followed by the first reflections (from side walls, floor and water–air surface interface) and then subsequent reflections. The amplitude of the reflected signal is significantly greater when measured with the hydrophone than with the vibrometer.

A source was then used to generate a tone burst acoustic field of five cycles at 80 kHz. Eleven known positions along a line section through the field, perpendicular to the acoustic axis, were then interrogated using a calibrated ball hydrophone and a recording of the average of 100 sweeps of pressure with time was taken at each point. This vector was then

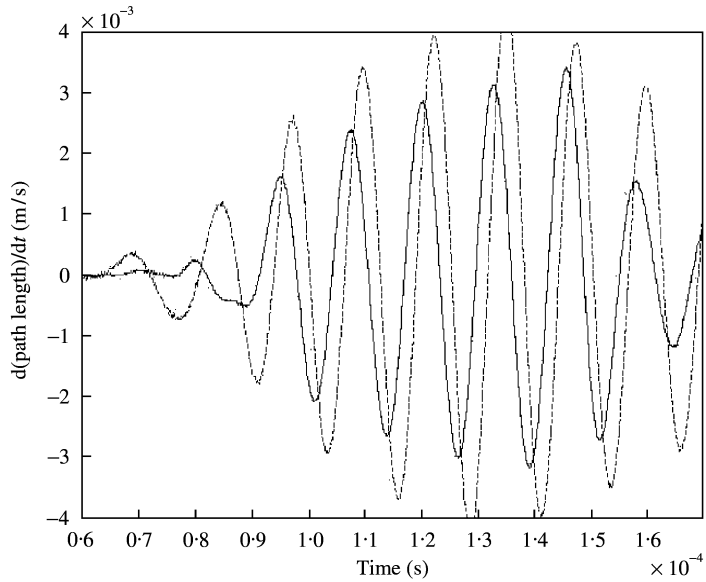


Figure 6. Detection of the arrival of the acoustic signal by hydrophone (– – –) and LDV (——).

converted to refractive index using the piezo-optic coefficient, integrated with distance across the field and then differentiated with respect to time to give the rate of change of path length (using equations (3)–(5)). The vibrometer was then passed along this same line section and the resultant average of 100 repetitions of the velocity signal with time was recorded.

A comparison of the two signals, as shown in Figure 5, demonstrates the different characteristics of each measurement technique. Since a significant feature of each individual hydrophone measurement is the response at the beginning and end of the tone burst, this effect is prevalent once the signal has been integrated with distance. Consequently, it is difficult to identify as to which is the original five cycle tone burst and where the first reflections arrive to contaminate the signal. Calculations taking into account the dimensions of the tank suggest that the first reflection should arrive at the centre of the laser beam, where the hydrophone was situated, from the side wall after approximately 2×10^{-4} s. Despite giving an apparently noisier signal, the response of the vibrometer is such that the original tone burst signal can be distinguished from the first reflection, which arrives, as predicted, after approximately 2×10^{-4} s. The RMS of the amplitude of a complete number of cycles within the original tone burst period for each measurement shows agreement to within 25%.

A more detailed look at the initial detection of the acoustic signal by the two devices, as depicted in Figure 6, shows that the hydrophone measurement precedes that of the vibrometer by $10{\cdot}4 \times 10^{-6}$ s. Given that the speed of sound at a depth of 150 mm in freshwater at 16·5°C is 1471·1 m/s [7], this corresponds to a distance travelled of 15·3 mm.

The diameter of the hydrophone ball was nominally 25 mm and the beam of the vibrometer measurement passed approximately through the centreline of the ball position. If the beam were positioned exactly perpendicular to the acoustic axis and passed exactly through the centre of the ball position, the acoustic wave would be incident at the edge of the ball $8{\cdot}3 \times 10^{-6}$ s before reaching the centre. Taking into account errors and uncertainties, this might correspond with the theory that the apparent centre of the hydrophone approaches the perimeter when the acoustic wavelength is short in comparison

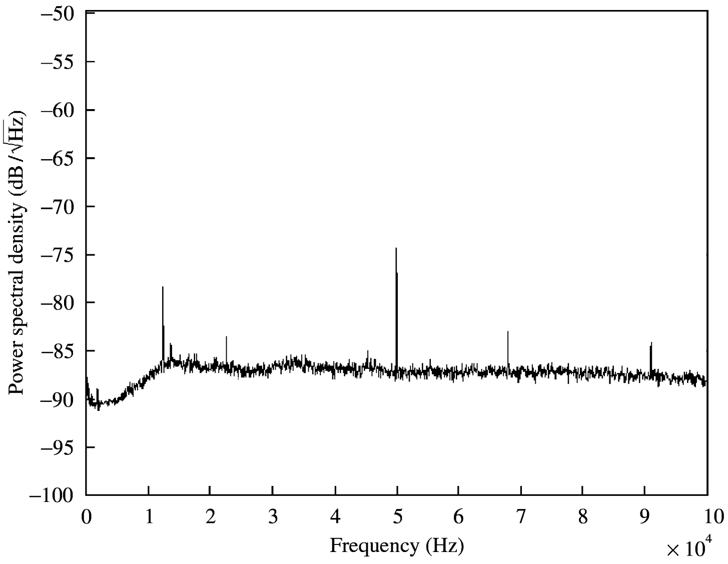


Figure 7. Noise floor from LDV beam passed through a tank with no acoustic field.

to the dimensions of the hydrophone. It can also be seen that the rise time of the vibrometer signal is faster than that of the hydrophone, in that the amplitude of the first detected cycle is approximately 50% of the maximum amplitude, compared to 30% for the hydrophone.

When assessing the sensitivity of the vibrometry technique for measuring the rate of change of path length, it is important to consider the noise floor of the instrument. The noise floor of a vibrometer is dependent on both the hardware and processing electronics of the instrument as well as the reflecting target and the media through which the laser beam travels. The vibrometer was set up as in Figure 2, but without an acoustic field present. Figure 7 represents the power spectrum of an average of 100 Fast Fourier Transforms (FFT) of time-resolved velocity traces recorded by the vibrometer.

At 80 kHz, the noise floor is measured to be -88 ± 1 dBm. The minimum sensitivity of a vibrometer system is typically described as a signal 3 dBm greater than the noise floor in the power density spectrum, which in this case is the equivalent of a velocity amplitude of 15×10^{-6} m/s. Taking into account the double pass of the vibrometer beam through the media, this relates to a product of pressure and distance of 128×10^{-3} Pa m $\pm$ 4·2%

4. CONCLUSIONS

The beam of a vibrometer has been shown to offer a non-perturbing method of measuring the pressure within an acoustic field. The shapes of the resultant velocity–time signals from a line integral through a tone burst acoustic waveform show strong similarities with the pressure–time signal generated by a hydrophone placed centrally within the acoustic field.

The rise and fall time of the vibrometer is significantly shorter than that of the hydrophone. This is demonstrated by the fact that when the pressure measurements are converted into refractive index and integrated to provide path length information, it becomes very difficult to distinguish between the original signal and the reflections from the tank walls. The vibrometer signal, however, shows the original signal to be clearly isolated from the arrival of the reflected signal.

The signal from the hydrophone is shown to precede that of the vibrometer by a duration corresponding to a distance travelled by sound in water of approximately 15 mm, when the beam is passed through a position at the centre of the hydrophone ball. This raises questions as to whether the hydrophone measurement should be interpreted as representing the pressure at a point at the centre of the hydrophone.

The minimum detectable signal level must be quoted as a product of the pressure distribution and the distance travelled by the optical beam through the field. The noise floor of the vibrometry system is not only determined in part by the hardware and processing electronics of the vibrometer, but also by the reflecting target and the media under interrogation. In the arrangement described in this work, the noise floor at 80 kHz was found to be -88 ± 1 dBm. The minimum detectable signal is described as a signal level 3 dB greater than the noise floor, which in this case corresponds to a value for the product of the pressure distribution and the distance travelled by the beam of 128×10^{-3} Pa m, assuming the beam is passed through the field twice.

More detailed theoretical and experimental analyses concerning one-, two- and three-dimensional measurements will be reported shortly.

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