The application of scanning vibrometer in mapping ultrasound fields

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1. Introduction

Optical interferometry has been used for calibrating hydrophones at frequencies greater than 500 kHz[1] for many years with very small uncertainties. Optical method have been found to be an effective non-perturbing method for detecting ultrasound fields with very fine spatial and temporal resolution; ultrasound fields can be mapped using a membrane and a scanning vibrometer[2], and two-dimensional fields can be imaged [3],[4] when the optical beam from a Laser Doppler Vibrometer (LDV) is aligned normal to the axis of the sound beam from an arbitrarily shaped projector.

This paper presents a theoretical analyses for using a LDV system to detect ultrasound fields and further presents the result of some initial optical scan measurements performed using an LDV system. Results are presented of the particle velocity distributions produced by a focused ultrasound projector measured using a scanning LDV on an acoustically compliant, optically reflective membrane using a scanning LDV. Further measurement results are also presented of two-dimensional field maps obtained by positioning the laser beam perpendicular to the acoustic axis of a projector and detecting the line-integral acousto-optic effect. Visual maps of the acoustic waves radiating from the projector and the reflected and scattered propagating field by objects in water were obtained using this method and are presented in this paper.

2. Theoretical consideration

For the arrangement depicted in figure 1, where the laser beam enters a water tank through an optical window, both the acoustic wave and the laser beam propagate along the same axis (x...
axis). If a thin reflective membrane is placed at the plane \( x = l_0 \) and the wave front is at the position \( x = l_1 \) at time \( t \), then the optical path length \( q(t) \) can be expressed as\(^1\):

\[
q(t) = -2n_0 a(t) + \frac{2n_1}{\rho c^2} \int_{l_0}^{l_1} p(x,t) \, dx
\]

(1)

Where \( a(t) \) is the particle displacement of the acoustic wave, \( n_0 \) is the refractive index of water, \( \rho \) is the density of water, \( c \) is the speed of sound in water, \( n_1 \) is the elasto-optic coefficient of the water medium and \( p(x,t) \) is the acoustic pressure.

Equation (1) shows that both the displacement of the membrane due to the acoustic displacement and the acoustic pressure variation along the optical path will contribute to the optical path length.

For plane waves, (1) can be written as:

\[
v(t) = -2(n_0 - n_1)u(l_0,t)
\]

(2)

Where \( v \) is the velocity detected by the vibrometer and \( u \) is the particle velocity on the membrane.

For the laser wavelength \( \lambda = 632.8 \text{nm} \), under normal ambient temperature and atmospheric pressure, \( n_0 \) is approximately 1.33, and \( n_1 \) is approximately 0.32. Therefore, (2) indicates that the velocity of the membrane is the major contributor to the measured velocity.

An ideal plane wave does not exist in practice as acoustic waves will diverge after propagating a specific distance in the medium and eventually evolve into spherical waves. For a spherical wave transmitted from a projector placed at position \( x = 0 \), then (2) can be written as

\[
v(t) = -2u(x,t)[n_0 - n_1 \left( \frac{kl_1}{kl_0} \right)^2 \exp^{\text{jk}l_0} \left( \frac{\exp^{\text{jk}l_0}}{kl_1} + \int_{l_0}^{l_1} \frac{\exp^{\text{jk}x}}{x} \, dx \right)]
\]

(3)

Although (3) is in a complex form, numerical calculation shows that if the distance between the projector and the membrane is larger than three wavelengths \( (l_0 > 3\lambda) \), then (2) can be used.
in place of (3) with negligible difference.

When an angular scanning LDV is used to measure the distributed acoustic field at the membrane, the laser beam will deflect from the x axis by an angle $\theta$. In this case, the acousto-optic effect will become more significant and (2) should be expressed as:

$$v(t) = -2(n_0 - n_1)u(l_0, t)/\cos \theta$$  \hspace{1cm} (4)

Equation (4) shows that for the case where the laser beam is not parallel to the acoustic beam, the velocity perceived by the scanning LDV will become larger than the normal value. This effect can be minimized by positioning the scanning head farther away from the membrane, thus reducing the total range of the incident scan angles.

For the arrangement depicted in figure 2, where the laser beam traverses the acoustic field twice following reflection from a mirror external to the tank, the voltage output from the LDV will be proportional to the rate of change of acoustic pressure along the laser beam:

$$v(t) = 2n_1 \int_{y_1}^{y_2} \hat{p}(y, t)dy$$  \hspace{1cm} (5)

Where $\hat{p}(y, t)$ is the rate of change of acoustic pressure along the axis of the laser beam at time $t$, $y_1$ and $y_2$ represent the positions at the beginning and the end of the acousto-optic interaction region.

**Figure 2.** Measurement arrangement of optical method using a still reflector.

Equations (2) and (5) indicate that whilst the particle velocity on the membrane can be measured directly with the arrangement depicted in figure 1, the arrangement depicted in figure 2 can be applied to detect the ‘average’ rate of change of acoustic pressure along the
optical beam. The advantage of this is that it allows the spatial distribution of acoustic fields on the plane perpendicularly to the laser beam to be imaged with the use of a scanning LDV. Though the quantitative analysis cannot be performed with this measurement arrangement, the technique is truly non-invasive and can provide two-dimensional or even three-dimensional information about the acoustic field.

3. Experiment results

Experiments for acoustic field mapping were performed using a Polytec PSV300 system with a 1 MHz measurement bandwidth, where the built-in software was used to re-construct the images in terms of the rate of path length change along the optical axis. The measurement arrangements depicted both in figure 1 and in figure 2 were carried out in a glass water tank with a dimensions 0.3×0.3×1.2 m. The experimental setup shown in figure 1 used a strip pellicle of Mylar with a width of 10 cm and a thickness of 23 µm coated on one side with 40 nm of aluminum was used as the reflective membrane. For the experimental arrangement depicted in figure 2, the reflector was constructed from a rigid plate covered with a layer of retro-reflective material.

3.1. Measurements for the distribution of particle velocity

The distribution of particle velocity was measured in the focal field region produced by a Panametrics V3438 transducer at a number of frequencies using the configuration shown in figure 1. The projector was driven with a 16 V tone from a HP8111A function generator, the scanning area was circular in shape with a diameter of 32 mm. Figure 3 and 4 show the measurement results for the 500 kHz and 1MHz fields respectively.

![Figure 3. The distributions on the focus of a projector at 500kHz.](image)

![Figure 4. The distributions on the focus of a projector at 1MHz.](image)

3.2. The mapping of acoustic fields

The images obtained using the configuration shown in figure 2 from the 200 kHz and 400 kHz excitation of a plane-piston projector with a diameter of 18 mm are shown in figures 5 and 6.
respectively. Both the waveform and the distribution of acoustic pressure around the radiating surface of the projector are mapped. These images show that even though the acoustic pressures in the near field have a complex distribution, the ‘average’ line integral effect measured by the LDV system clearly show the expected behavior of a piston projector.

Figure 5. Ultrasound wave from a piston transducer at 200kHz.  

Figure 6. Ultrasound wave from a transducer at 400kHz.

The distribution of acoustic pressure around the focal region of the Panametrics V3438 projector was also measured using the acousto-optic method shown in figure 2. The field map of the instantaneous acoustic pressure is plotted in figure 7, which clearly shows an increase in amplitude around the focal region and also shows the waveform within the focal region behaves similar to a plane wave.

Figure 7. Acoustic pressures of a projector around its focus at 600kHz.

In addition to the mapping of transducer fields, scans were also performed with scattering objects position in the acoustic field. One example of this was the insertion of a glass sheet into a 500 kHz acoustic field. The interaction region was scanned as shown in figure 8 and the field map obtained of instantaneous acoustic pressure was plotted as shown in figure 9. The incident acoustic field can be seen propagating from the top left before reflection from the
glass sheet at which point interference occurs with the incident acoustic field. A small amount of transmission can also be seen on the right of the glass sheet.

**Figure 8.** Setup for scanning reflection field from a glass sheet.

**Figure 9.** The image from LDV for a glass sheet in a 500kHz acoustic field.

Another scan was performed to map the scattering from a small diameter rod positioning in a 600 kHz acoustic field. The interaction region was scanned as shown in figure 10. Figure 11 shows the plotted map of the acoustic wave propagating from the top left with interference patterns produced following scattering from the rod. Whilst the scattered wave dominates the fan-region from the top of the rod to the top right of the scanning area, the incident wave can still be seen on the bottom right region of the scanning area in figure 11.

**Figure 10.** Setup for scanning scattering field from a rod.

**Figure 11.** The image from LDV for a rod in a 600kHz acoustic field.

4. Conclusions
The use of a Laser Doppler Vibrommeter has been demonstrated for measurement of acoustic
fields using two different methodologies. The first shows how acoustic fields can be mapped in a single one-dimensional plan using an acoustically compliant, optically reflective thin membrane which allows an absolute measure of acoustic velocity/pressure with the appropriate correction for acoustic-optic interactions. The second method exploited the acousto-optic interaction to map the acoustic field in two-dimensions by traversing the optically scanned beam across the acoustic beam. The acousto-optic study presented in this paper has demonstrated that it is possible to characterise acoustic fields in a rapid and non-perturbing way, with resolutions that exceed those possible with conventional hydrophone scans. In addition, the technique offers considerable potential for use in measuring the high intensity focused and highly non-linear fields encountered in lithotripsy and high intensity focused ultrasonic (HIFU) applications of ultrasound. In such applications, traditional hydrophone sensors can be damaged by the intense acoustic fields, and always perturb the field to some extent by their presence. A non-perturbing optical technique would offer significant advantages.

Acknowledgements
We gratefully acknowledge the financial support of the UK Department of Trade & Industry (National Measurement System Directorate).

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