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Acousto-optic tomography for mapping of high-frequency sonar fields

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This paper presents an acousto-optic method for tomographic mapping of acoustic fields generated by high-frequency sonar array transducers. The method uses a laser interferometer to measure the integrated refractive index change across the propagating acoustic wave generated by the transducer. An interferometer, being a displacement or velocity measuring device, interprets this rate of change of optical path length as a displacement or velocity. Obtaining a series of these projections by scanning the laser beam or the transducer for a number of rotation angles of the transducer allows a two-dimensional plane of the acoustic field to be reconstructed using the techniques commonly used in X-ray Computed Tomography. Acousto-optic tomographic measurement results are presented for a 95 by 95 mm, 400 kHz 1-3 composite, 4-element sonar array transducer and are compared to conventional planar hydrophone scans obtained using a 1.5 mm probe hydrophone. The optical method allows measurement of the acoustic field without perturbing the field being measured, which can occur when using the planar hydrophone scanning method. Different tomographic geometries are considered, including parallel beam and fan-beam methods, with the advantages and disadvantages of each being discussed.

1 Introduction

Field measurements for sonar transducers should ideally be performed in the far-field region where the field characteristics (pressure, phase and profile) are of most interest. However, the near-field region for high-frequency devices of this type can often extend several metres, beyond the bounds of typical underwater acoustic tanks. However, it is possible to characterize these devices in the far-field region by performing planar scanned measurements in the near-field and propagating the field out to the required far-field distance. This method has been successfully demonstrated by Humphrey *et al* using the angular spectrum method, comparing forward propagated near-field scan data to measurements performed in the far-field[1]. However, the planar scanning of a hydrophone for measurement of large area sonar transducers can take an extended period of time. In addition to the costly nature of this, the time period it takes to complete a scan often can make it difficult to maintain stable environmental conditions and increases the likelihood of response changes in the sonar transducer and hydrophone due to temperature fluctuations and the potential of bubble formation etc. In addition to this, the hydrophone can also have a perturbing effect on the acoustic field being measured and although a needle hydrophone is often used, the proximity of the hydrophone to the sonar transducer could introduce errors due to reflections between the hydrophone and the surface of the sonar transducer.

Optical measurement methods have the potential to over come many of the limitations inherent in the conventional planar hydrophone scan. Optical interferometry can provide non-invasive measurement of absolute displacement or velocity with an extremely small measurement cross-section. Interferometry has been used in underwater acoustic measurement for the calibration of hydrophones using an optically-reflective and acoustically-compliant membrane [2-6]. A heterodyne interferometric method has also been proposed for the surface scanning of high-frequency sonar transducers and offers an extremely rapid approach to profiling the surface velocity of large area sonar transducers [1]. Whilst this method is very well suited to mapping the surface vibration of multi-element sonar transducers, and thus is able to identify faulty or miss-firing elements, absolute determination of surface velocity can be compromised by the interaction of the laser beam with acoustic field in front of the transducer [7,8]. Whilst this effect can be large due to the edge wave generated by the transducer crossing the optical beam at a high angle(where this acousto-optic effect is strongest), in-practice, for 1-3 composite type, non-uniform sonar transducers, the edge wave effect is quite small and does not restrict array pattern identification [9].

Alternative optical methods exploit this acousto-optic effect by traversing the optical beam across the acoustic field to measure the change in optical path length resulting from the local changes in the refractive index as the acoustic wave propagates. Examples of this include, light diffraction tomography at megahertz frequencies [10], Schlieren [11], acoustic pressure mapping by measurement of the phase variation across the optical wave-front caused by refractive index variation in water [12] and the use of laser Doppler vibrometry to measure the spatial pressure distribution in an acoustic field [13,14]. This paper describes a method based on the acousto-optic effect which is used to reconstruct the field generated by a high-frequency (480 kHz) sonar array transducer using a tomographic reconstruction technique following both parallel and fan beam acousto-optic scans. One-dimensional scanning across the axis in front of the transducer allows a two-dimensional planar slice of the acoustic field in front of the sonar transducer to be reconstructed.

2 Piezo-optic measurement

Laser interferometry is conventionally used to measure the displacement or velocity of a moving target. This is achieved by measuring the change in optical path length of a measurement arm (reflected from the target) relative to a reference beam which is forced to travel a fixed optical path length. The optical path length is defined as the product of the refractive index and the geometrical distance travelled by an optical beam. Therefore, if the geometrical distance is fixed in the measurement arm, an optical interferometer can be used to measure the change in refractive index of a medium. An acoustic field results in changes in the local refractive index of the medium of propagation due to localised density fluctuations resulting from the passage of an acoustic pressure wave [15].

A laser Doppler interferometer conventionally measures the velocity of a target but in this case, with a stationary target mirror, it will detect the rate of change of optical path length [14]. If the case is considered for an acoustic field of a single frequency, f, with the optical beam intersecting the acoustic field in a direction parallel to the wave fronts, the acoustic pressure, P, at a distance, x, along the optical beam and at time, t, may be written as

$$P(x,t) = P_0(x)\sin(2\pi f t + \phi(x)) \qquad (1)$$

where $P_0(x)$ and $\phi(x)$ are the unknown amplitude and phase distributions along the line [13]. The refractive index at a point along the line, $n(x,t)$, is related to the pressure variation by

$$n(x,t) = n_0 + \left(\frac{\partial n}{\partial P}\right)_S P(x,t) \qquad (2)$$

where n_0 is the ambient unperturbed refractive index of the water medium and $(\partial n/\partial P)_S$ is the adiabatic piezo-optic coefficient [15]. From this, the optical path length, $L(t)$, is

$$L(t) = L_0 + 2\int_0^x n(x,t)\,\mathrm{d}x \qquad (3)$$

where L_0 is the ambient unperturbed optical path through the media. The rate of change of optical path length is then:

$$\frac{\mathrm{d}L(t)}{\mathrm{d}t} = \frac{\mathrm{d}(2\int_0^x n(x,t)\,\mathrm{d}x)}{\mathrm{d}t}. \qquad (4)$$

Therefore, the variation in pressure amplitude and phase along the line of the optical beam can be shown to influence the rate of change of optical path as follows [13]:

$$\frac{\mathrm{d}L(t)}{\mathrm{d}t} = \frac{\mathrm{d}(2\int_0^x ((\partial n/\partial P)_S\, P_0(x)\sin(2\pi f t + \phi(x)))\,\mathrm{d}x)}{\mathrm{d}t} \qquad (5)$$

This provides a line integral of pressure through the measurement medium along the interaction region of the optical beam and the acoustic field, where the greatest sensitivity is achieved when the optical beam is parallel to planar wave-fronts. If the optical beam crosses the acoustic field at an angle and intersects several wave-fronts, phase cancellation will occur, reducing the signal measured by the interferometer and making reconstruction of the field more difficult. The integrated effect of the acousto-optic interaction will essentially reduce to zero for the case of the optical beam intersecting a perfect plane-wave in a direction perpendicular to the wave-fronts (head-on into a plane-wave) [16]. For real transducers, the wave-fronts are not generally planar and, in particular, the spreading of the acoustic field due to diffraction will give rise to some phase cancellation [13,14]. However, for the transducer tested here, this did not pose a severe problem. The method described does not rely on diffraction of the optical beam by the acoustic field, unlike techniques such as light diffraction tomography [10, 17]. For these measurements, the acoustic frequency and amplitude are low enough such that the bending of the light beam is negligible and the method only considers the rate of path length change of the zeroth diffraction order.

Unfortunately, the technique cannot be easily used to measure an acoustic field parameter at a point as a result of the line integral through the acoustic field, although the measurement method may be combined with tomographic techniques to map the spatial distribution of the acoustic field.

3 Tomographic reconstruction

Acousto-optic measurements may be combined with tomography techniques, similar to those used in medical imaging for X-ray computed tomography [18], to map the spatial distribution of the acoustic field. Fig. 1 and Fig. 2 show diagrams illustrating the projection scan principle for parallel and fan beam scanning configurations. In order to cover a planar slice of the acoustic field, a number of line integrals should be measured across the entire width of the acoustic field. This was achieved by moving the transducer under test and keeping the optical beam and mirror fixed for the parallel beam scan and by scanning the optical beam across the width of the acoustic field in front of a retro-reflective panel for the fan beam scan. To undertake a tomographic reconstruction, this process must be repeated at a series of angular intervals over a ±90° range for the parallel beam scan and over a ±180° range for the fan beam scan as the -90° and +90° are not equivalent projections for the fan beam scan (they are for the parallel beam scan configuration). For each angle, θ, the measured data for the line integrals form an estimate of the projection of the acoustic field at that angle, termed the Radon transform, R_θ, which for a general function of Cartesian coordinates, $f(x,y)$, is given by:

$$R_\theta(x') = \int_{-\infty}^{+\infty} f(x'\cos\theta - y'\sin\theta,\, x'\sin\theta + y'\cos\theta)\,\mathrm{d}y' \qquad (6)$$

where

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \qquad (7)$$

and x and y are arbitrarily chosen orthogonal reference axes, and x' and y' are the axes after transformation by a rotation of angle θ.

Having measured the projections at a series of angles, the data is then inverted to form the reconstructed image by performing an inverse Radon transform. This numerical computation is accomplished by a filtered back projection algorithm, the filter being designed in the frequency domain and multiplied by the fast Fourier transforms of the projections. The image formed is a numerical estimation of the field with the estimation accuracy improving with greater number of projections (greater number of angles). The inverse transform used here was implemented using the Matlab® programming language [19]. It should be noted that for the fan beam configuration, the projections were corrected to replicate the equivalent parallel beam projection before performing the filtered back projection to reconstruct the field.

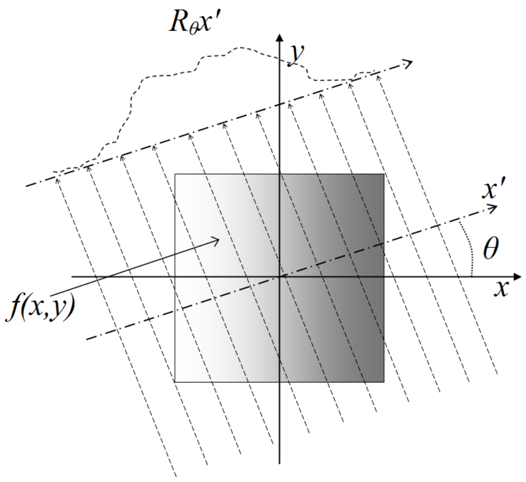

Fig.1 Parallel beam scan configuration through some acousto-optic distribution $f(x,y)$ at an angle θ, producing the Radon transform $R_\theta(x')$.

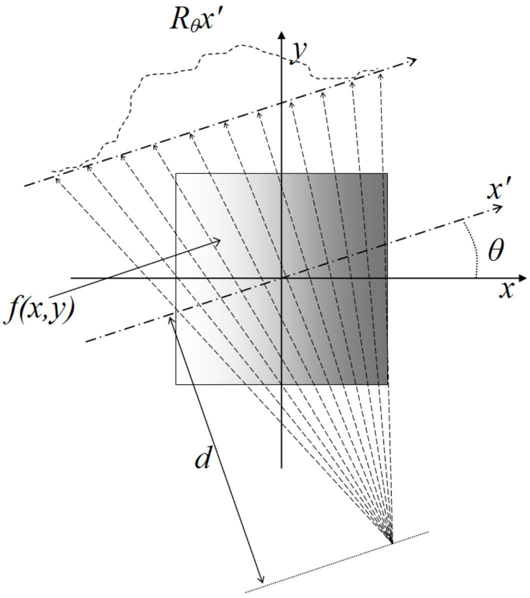

Fig.2 Fan beam scan configuration through some acousto-optic distribution $f(x,y)$ at an angle θ, producing the Radon transform $R_\theta(x')$.

4 Measurement methodology

The scans were performed in the NPL small open tank facility, a 2.0 x 1.5 x 1.5 m test tank with a two-carriage precision positioning system, featuring a glass window to allow optical interrogation of the acoustic field. The transducer was mounted to the rotary stage of one carriage with the radiating face pointing downward. For the parallel beam scan, a mirror was fixed to the other carriage in a position outside the acoustic field. The scans were undertaken by translating the transducer across the laser beam and measuring the signal recorded by the vibrometer at discrete intervals. The line scan was undertaken over a 160 mm range at intervals of 0.5 mm. Such a line scan was repeated for a series of discrete angles, with measurements made over a 180° range at 0.5° intervals. For the fan beam scans, the transducer was centralized on the mount such the laser beam intersected the axis of centre of rotation of the transducer. A line scan was then performed for each 0.5° of rotation between 0° and 360°. A line scan was performed with a spatial resolution of less than 0.5 mm over a ±80 mm range, resulting in a maximum line scan angle of around 1.8° for the vibrometer stand-off distance of 2.5 m. A retro-reflective panel was used to provide sufficient optical reflection over all angles of the line scan. The Polytec PSV-400 used for the measurements provided a measurement bandwidth of 1.5 MHz. Employing the scanning capability of the vibrometer for the fan beam scan provided a much more rapid scan time and allowed for 10 time averages to be used for each measurement point along the scan line. The laser beam was aligned through the optical access window to be parallel to the transducer face and passed at a distance of 16 mm in front of the face. The transducer chosen was a flat faced, 1-3 composite quad array of approximately 95 mm by 95 mm and was driven in turn at frequencies of 480 kHz with a tone-burst, derived from a HP33120A arbitrary waveform generator and amplified through an ENI 240L power amplifier. The amplitude and phase of the received signal was measured at each discrete point, the received signals being analyzed using a HP 89410A vector signal analyzer. The tone-burst length, analysis window length and window start time were selected with great care to ensure that complete information about the transducer surface vibration was obtained at all points on the measurement scan without acoustic reflections from the optical reflector or tank boundaries. For comparison, a planar hydrophone scan was performed 16 mm from the face of the transducer with a spatial resolution of 0.5 mm over a 130 mm by 130 mm plane using a Reson TC4035 probe hydrophone with a 1.5 mm active element diameter.

5 Results and discussion

The results of the reconstructed scans for the PCT quad transducer at 480 kHz with the upper left and lower right elements firing are shown in Figs. 3, 4 and 5 for the parallel beam acousto-optic, fan beam acousto-optic and planar hydrophone scans respectively.

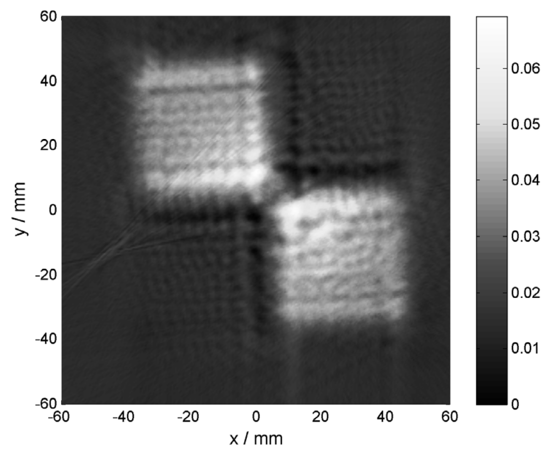

Fig.3 Parallel beam acousto-optic scan and reconstruction of PCT quad array.

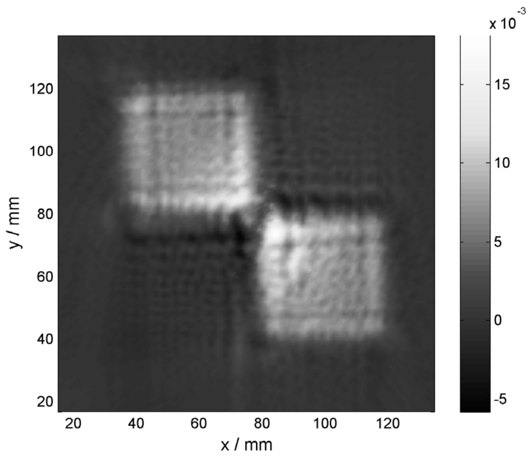

Fig.4 Fan beam acousto-optic scan and reconstruction of PCT quad array.

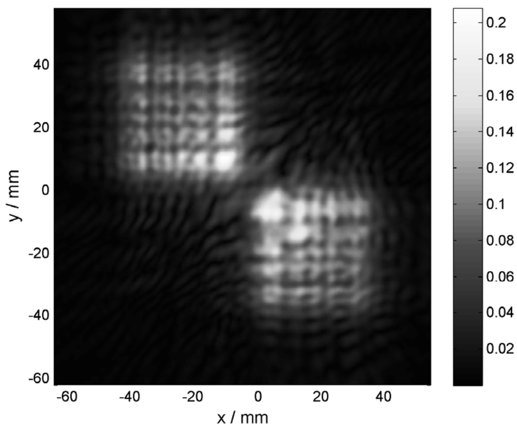

Fig.5 Planar hydrophone scan of PCT quad array.

A relatively good comparison is obtained between the two optical scanning configurations which were performed with comparable scan spatial and rotational resolutions. The parallel beam scan shown in Fig. 3 does exhibit some line artefacts across the transducer which were caused by optical dropout during the scan. Optical dropout results in a very poor signal-to-noise ratio for a particular measurement point or points. In general, the fan beam scan suffers from a lower light return than the parallel beam scan due to the necessity of a retro-reflecting panel in place of a mirror. However, due to the fact that the fan beam scan utilizes the scanning capability of the vibrometer and not the transverse scanning of the transducer, the fan beam scan is at least an order of magnitude faster than the equivalent parallel beam scanning and is therefore able to employ time averaging without a compromise on scan time. In Fig. 4, it can be seen that the 10 time averages used have reduced the artifacts due to optical dropout along with other smudging artifacts which were present in the parallel beam scan. This is not to say that the fan beam tomography method provides a better reconstruction than an equivalent parallel beam tomographic scan. The greater speed of the fan beam scan enables greater averaging which would be prohibitively costly in time using the parallel beam configuration. Without the time averaging, the fan beam reconstruction is noticeably worse than the parallel beam reconstruction due to the lower light return levels for the fan beam configuration. Both the acousto-optic tomographic scans compare well, on a relative level, with the planar hydrophone scan although the hydrophone scan shows a more substantial effect from the interference from the edge waves than the two acousto-optic scans. This could be related to the directivity of the hydrophone. It should also be remembered that the hydrophone has an element diameter of 1.5 mm. For this particular transducer, which is a relatively small device, the parallel beam tomographic scan took significantly longer than the hydrophone scan, around 84 hours compared with 48 hours respectively. However, the hydrophone scan time will increase with the square of the lateral dimensions of the transducer where the acousto-optical scan will only increase linearly. The fan beam acousto-optic tomographic scan took around 80 hours, with 10 time averages, compared with the equivalent 84 hour scan using the parallel beam configuration with no time averaging.

6 Conclusion

An acousto-optic tomography technique has been presented employing both parallel and fan beam configurations, demonstrating the non-invasive two-dimensional imaging of an acoustic field generated by a high frequency sonar array. The technique exploits the interaction between the laser beam of an interferometer and the acoustic field produced by the sonar array. The resulting change in refractive index of the water due to the acoustic field is detected by the interferometer and is interpreted as a velocity line integral. Combining a scan of these line integral velocities across the transducer face with rotation of the transducer allows a tomographic technique to be used to reconstruct a slice of the field. The technique is similar to that commonly used in X-ray based CT scanning. A comparison of parallel and fan beam configurations shows that the fan beam scan is the most suitable, offering more rapid scans times or higher quality scans with the use of averaging with no time penalty over the parallel beam scan. The results of the acousto-optic tomographic scans are compared relatively to a conventional planar hydrophone scan at 480 kHz in the near-field of a high frequency sonar array and show good qualitative agreement for the spatial distribution of the acoustic pressure field.

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