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Optical probing of pulsed, focused ultrasonic fields using a heterodyne interferometer

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The pulsed acoustic field of a piezoelectric focused transducer transmitted in water has been investigated by using an optical heterodyne interferometer. The probe beam is reflected by a thin membrane that follows the motion of the fluid particle. Absolute measurements of the mechanical displacement have been performed in the frequency range 5–15 MHz with a spatial resolution better than 0.1 mm and a sensitivity of 0.1 nm with a 20 MHz detection bandwidth that corresponds to a minimum detectable acoustic energy density of 2 $\mu J/m^2$. The experimental results all agree quantitatively with diffraction theory predictions of impulse response at the focus of the transducer.

The ultrasonic pulse-echo technique is widely used in nondestructive testing (NDT) and medical imaging. The shape, dimensions, homogeneity of the transducer (usually piezoelectric), the backing, and the matching to the signal generator play a major role in the generation of the waves. Also, as the waves propagate in the fluid, their shape is changed by diffraction and absorption. It is thus useful to examine the acoustic field transmitted by piezoelectric transducers. In the frequency range 0.5–10 MHz, beam parameters are normally determined by scanning with a broadband miniature hydrophone[1] or with a reflective ball target.[2] However, optical methods have the advantage that they do not disturb the acoustic field. A common optical method uses light diffraction produced by the index modulation in the transmission medium (water) but yields the Raman–Nath parameter v that is not directly proportional to the acoustic pressure but instead is proportional to the integral of pressure along the light path, i.e., across the ultrasonic beam.[3,4] Such acousto-optic methods are also usually limited to narrow band measurements. Another optical technique has been used to probe continuous ultrasonic fields[5] and to calibrate hydrophones.[6] The technique consists of immersing a thin plastic membrane in front of the transducer and measuring the displacement of the membrane produced by the ultrasonic wave. The object of this letter is to report on experiments where a laser heterodyne interferometer is used to probe locally the mechanical displacement of the transient acoustic field launched by a NDT transducer and to compare some results with the impulse diffraction theory.

The experimental apparatus shown in Fig. 1 includes a thin plastic membrane or pellicle immersed in water to reflect the optical beam in a heterodyne interferometer arrangement. As previously described,[7] the interferometer consists of a reference beam (wavelength Λ) and of a probe beam with a frequency that is shifted by a Bragg cell (f_B=70 MHz). The probe beam is focused to a diameter less than 100 μm on a gold reflecting coating on the pellicle. The motion of the membrane induced by the acoustic pressure modulates the phase of the optical wave. The beating of the reference and probe beams is detected by a photodiode. The photocurrent at frequency f_B is phase modulated at the frequency f of the vibration of the membrane (amplitude u). The spectrum of this current contains components at frequencies $f_B \pm Nf$ that have for relative amplitudes the Bessel functions $J_N(\Delta\Phi)$ in which the argument is the optical phase-shift $\Delta\Phi$ given by

$$\Delta\Phi = \frac{4\pi}{\Lambda} u. \tag{1}$$

For $u < 20$ nm, only the components at f_B and $f_B \pm f$ are significant. The ratio $R = J_0/J_1$ between the carrier level $J_0(\Delta\Phi) \cong 1$ and the side component level $J_1(\Delta\Phi) \cong \Delta\Phi/2$ gives the absolute amplitude of the vibration independently of the amount of light reflected by the membrane. After phase demodulating the photocurrent with a broadband (10 kHz–20 MHz) electronics,[8] the signal is stored and processed by a waveform analyzer (DATA 6100). Absolute measurements of the mechanical displacement with 1 nm corresponding to 100 mV have been performed in air with an accuracy of 5% and a sensitivity of 0.1 nm.

To record the acoustic field, the transducer is moved along X and Y directions by stepping motors. As the heterodyne technique is not affected by thermal or mechanical disturbances, no special precaution is required during the experiments and the signal can be probed as the transducer is moving.

The pulse ultrasonic waves launched by a 7 MHz transducer of diameter 5 mm and focal length 23 mm has been investigated. The membrane of diameter 45 mm was made of a 15 μm thick Mylar film coated with an optically reflecting film of gold. The theoretical acoustic wave transmission coefficient of the pellicle is 97.7% at 7 MHz assuming 2.9×10^6 kg m^{-2} s^{-1} for the acoustic impedance and 2090 m/s for the ultrasound velocity of the Mylar film. The experimentally determined figure was 97.3%.

Absolute measurements of the mechanical displacement are affected by the refractive index variations of the column of water in between the membrane (located at $z=0$) and the internal side of the optical window ($z=L$), produced by the acoustic pressure $p(z,t)$. The relation may be written

$$n = n_0 + \mu p(z,t), \tag{2}$$

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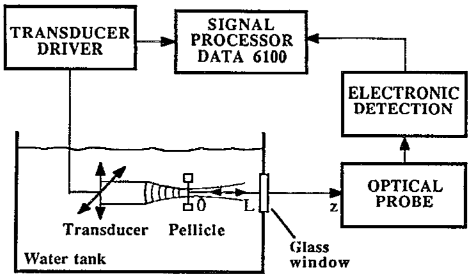

FIG. 1. Experimental arrangement.

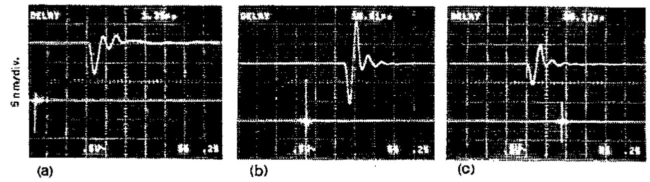

FIG. 2. Mechanical response of the membrane measured on the axis of the transducer at three distances: (a) 1 mm, (b) 23 mm (focal distance), (c) 40 mm. Horizontal scale; top: 0.2 μs/div., bottom: 5 μs/div.

where μ is the piezo-optic coefficient of water. At a given instant, the change in the phase shift of the optical beam reflected by the moving pellicle is[6]

$$\Delta\Phi=\frac{4\pi}{\Lambda_0}n_0a(t)-\frac{4\pi}{\Lambda_0}\mu\int_{a(t)}^{L}p(z,t)dz. \quad (3)$$

in which the mechanical displacement $a(t)$ of the membrane is assumed to be equal to the (Eulerian) displacement of the acoustic wave, i.e., $a(t)=u(z=0,t)$.

Since the spatial mean of the transient acoustic pressure is zero, the second term vanishes after the acoustic pulse passes through the membrane. The acousto-optic effect occurs at the same time that the transient displacement of the membrane. Assuming a plane wave, $p=-\rho_0c^2\partial u/\partial z$. Also assuming that the inside of the glass window does not move: $u(L,t)=0$, then Eq. (3) reduces to

$$\Delta\Phi=\frac{4\pi}{\Lambda_0}n_eu(0,t), \quad (4)$$

where

$$n_e=n_0-\mu\rho_0c^2. \quad (5)$$

In this one-dimensional model, the effect of the acousto-optic interaction is only to change the refractive index. Using the values $\mu=1.35\times10^{-10}$ Pa^{-1}, $n_0=1.329$ and $c=1480$ m/s for the piezo-optic coefficient,[9] the refractive index and the ultrasound velocity of water, respectively, gives an effective index $n_e=1.033$.

In order to confirm the validity of this model, the acoustic field was probed for different values of optical distance L on the axis of the transducer in the focal zone, where the wave fronts are planar rather than spherical. Experimental results show that the amplitude ($v_1=391$ mV) of the signal is nearly independent of the optical path length in water. The comparison with the value ($v_0=700$ mV), obtained in air, when the glass window has been replaced by the membrane, gives the effective index of water by the relation deduced from classical acoustics[10]

$$n_e=2\frac{v_1}{v_0}\left(\frac{1+[\frac{1}{2}(\alpha+\alpha^{-1})\tan kh]^2}{1+(\alpha\tan kh)^2}\right)^{1/2}, \quad (6)$$

where α is the ratio of the acoustic impedances of the polymer and of the fluid ($\alpha=1.96$), h is the thickness of the membrane and k the acoustic wave number in the membrane. The experimental result, $n_e=1.015$ is very close to the theoretical value of 1.033. Thus the calibration factor of the optical probe is nearly the same for measurements in water and for measurements in air.

Figure 2 shows the mechanical impulse response measured on the axis of the transducer. The membrane is placed at three different distances from the transducer: (a) very close (1 mm), (b) at the focal distance (23 mm), and (c) beyond the focal zone (40 mm). For these measurements, an electric pulse of 100 V having a duration of 30 ns was applied to the transducer. At the focus, the resulting peak value of the transient displacement is 10 nm. The noise level is 0.1 nm and corresponds to a minimum detectable acoustic energy density of 2 $\mu\text{J/m}^2$. This threshold can be improved by one or two orders of magnitude by averaging the signal. It clearly appears that the mechanical displacement (or the particle velocity) undergoes a time differentiation when passing through the focal point. Far away from this point, the waveform does not change, only the amplitude decreases regularly. These results are predicted by the convolution process embodied in the diffraction impulse theory.

From the classical theory of sound in a fluid, the acoustic pressure $p(\mathbf{r},t)$ and the particle velocity $v(\mathbf{r},t)$ in the ultrasonic field can be derived from the velocity potential $\phi(\mathbf{r},t)$. Using the Rayleigh integral formulation for the field transmitted by a source having a uniform velocity distribution $v_0(t)$ on its surface S (piston model), the velocity potential is given by

$$\phi(\mathbf{r},t)=\int_S\frac{v_0(t-R/c)}{2\pi R}dS, \quad (7)$$

where R is the distance between the observation point and the source point. This potential can be expressed as the convolution of the piston velocity waveform $v_0(t)$ and a function $h(\mathbf{r},t)$ defined as the diffraction impulse response of the transducer

$$\phi(\mathbf{r},t)=v_0(t)*h(\mathbf{r},t). \quad (8)$$

Analytic solutions for this function, which represent the velocity potential resulting from an impulse velocity excitation of the source

$$h(\mathbf{r},t)=\int_S\frac{\delta(t-R/c)}{2\pi R}dS \quad (9)$$

have been derived for a plane circular piston[11] and for a spherical shell.[12] The geometry of the concave (focused) transducer is defined by its radius of curvature F (focal length) and by the radius a of its circular boundary. The

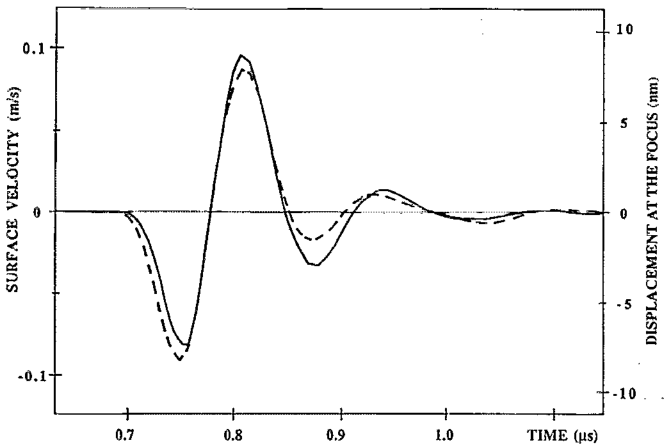

FIG. 3. Comparison between the particle velocity at the vicinity of the transducer (continuous line) and the particle displacement at the focus (dashed line).

impulse diffraction response $h(r,z,t)$ is a function of the abscissa z on the axis of symmetry and of the distance r to this axis. As the field point approaches to the focus ($r=0$, $z\cong F$), the impulse response tends to a Dirac function[13]

$$h(z,0,t)=e\delta(t-z/c) \tag{10}$$

of amplitude

$$e=F-\sqrt{F^2-a^2} \tag{11}$$

equal to the thickness of the transducer. Then, near the focus, the velocity potential is a replica of the normal surface velocity $v_0(t)$ so that

$$\phi(z,0,t)=ev_0(t-z/c) \tag{12}$$

and the z component of the particle velocity $v_Z=-\partial\phi/\partial z$ is the time derivative of $v_0(t)$ delayed by z/c. By time integration, a similar relation can be found between the mechanical displacement at the focus and the particle velocity at the surface of the transducer so that

$$u_z(z,0,t)=\frac{e}{c}v_0(t-z/c). \tag{13}$$

Figure 3 shows the particle velocity at the surface of the transducer obtained by differentiation of the signal in Fig. 2(a) (continuous line) and the mechanical displacement at the focus (dashed line). The two signals are very close to each other as predicted by the impulse diffraction theory. In order to compare the magnitudes, scales used in this graph are absolute and take into account the factor e/c in Eq. (13) that is found to be 9.2×10^{-8} s for the tested transducer ($F=23$ mm, $a=2.5$ mm which imply $e=0.136$ mm) and in water ($c=1480$ m/s). This result is a direct verification of the delta-like shape and of the amplitude e of the diffraction impulse response at the focus, as given by Eq. (10).

The ultrasonic field pattern was also measured in the focal plane of the transducer. The variations along two orthogonal directions of the energy of the acoustic pulse are plotted in Fig. 4. The spatial sampling increments were 0.1 mm ($\cong\lambda/2$ at 7 MHz) and the spatial resolution was

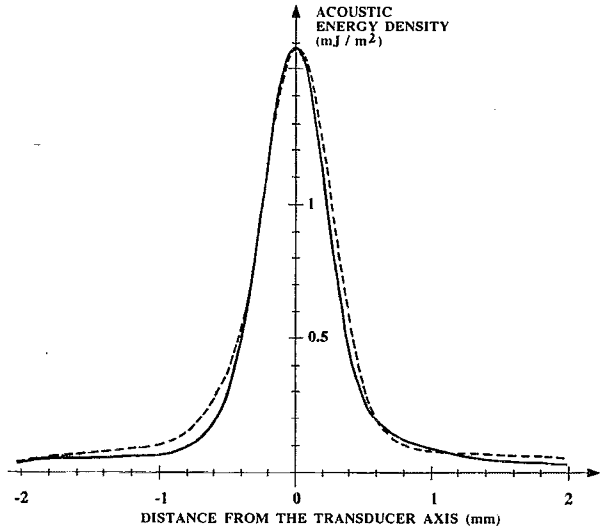

FIG. 4. Variation of the acoustic energy in the focal plane of the transducer in two perpendicular directions.

approximately 50 μm. The experimental half-peak energy width of the focal spot was found to be 0.6 mm and the sensitivity of the optical detection is sufficient to prove the absence of sidelobes as expected in the transient regime.

The optical interferometric technique reported in this letter provides a versatile tool for probing pulsed acoustic fields and for the calibration of ultrasonic transducers used in non-destructive testing and medical diagnosis. The wide bandwidth (20 MHz) of the optical detection system permits absolute measurements of the diffraction impulse response. Other advantages of this method are that accurate measurements of mechanical displacements as small as 1 Å can be performed in water at frequencies up to 20 MHz with a spatial resolution of 50 μm so that the acoustic energy of the pulse can be determined.

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[1] W. Dürr, D. A. Sinclair, and E. A. Ash, *Proceedings of the 1980 IEEE Ultrasonics Symposium* (IEEE, New York, 1980), p. 584.
[2] E. P. Papadakis, *Proceedings of the 1977 IEEE Ultrasonics Symposium* (IEEE, New York, 1977), p. 104.
[3] B. D. Cook and J. C. Berlinghieri, J. Acoust. Soc. Am. **61**, 1477 (1977).
[4] S. Nagai, Ultrasonics, 77 (March 1985).
[5] F. P. Higgins, S. J. Norton and M. Linzer, J. Acoust. Soc. Am. **68**, 1169 (1980).
[6] D. R. Bacon, IEEE Trans. Ultrason. **35**, 152 (1988).
[7] D. Royer and E. Dieulesaint, Appl. Phys. Lett. **49**, 1056 (1986).
[8] D. Royer and E. Dieulesaint, *Proceedings of the 1986 IEEE Ultrasonics Symposium* (IEEE, New York, 1986), p. 527.
[9] H. S. Yadav, D. S. Murty, S. N. Verma, K. H. C. Sinha, B. M. Gupta, and D. Chand, J. Appl. Phys. **44**, 2197 (1973).
[10] L. E. Kinsler and A. R. Frey, *Fundamentals of Acoustics* (Wiley, New York, 1962), p. 138.
[11] P. R. Stephanishen, J. Acoust. Soc. Am. **49**, 1629 (1970).
[12] A. Penttinen and M. Luukkala, J. Phys. D **9**, 1547 (1976).
[13] M. A. Fink and J. F. Cardoso, IEEE Trans. Sonics Ultrason. **31**, 313 (1984).