Optical probing of the mechanical impulse response of a transducer

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The mechanical impulse response of a piezoelectric transducer has been plotted by using an optical interferometric heterodyne probe. The sensitivity of this Mach–Zehnder type probe is better than 10^{-4} Å/$\sqrt{\text{Hz}}$. Transient displacements of a few angstroms have been detected in a single sweep with a 20-MHz bandwidth.

The regular development of acoustic waves in such different fields as signal processing, nondestructive testing, and medical imaging derives from the properties of these waves to propagate at a low velocity (10^3 to 10^4 m/s) and to penetrate into optically opaque media. Furthermore, they are easily generated by a transducer made of a piezoelectric plate provided with two electrodes. The characteristics of the acoustic wave train transmitted are dependent upon parameters linked to the nature, shape, and dimensions of the piezoelectric material and of the electrodes, and also to its matching to the signal generator and its backing. Thus, it is necessary to verify the acoustic field (homogeneity, shape) and, for some applications (medical imaging, nondestructive testing), the transient transducer response. For bulk waves, these spatial and temporal measurements can be carried out in water with a small piezoelectric probe[1] or by reflection on a ball target.[2]

Optical methods are more interesting because they do not require any mechanical contact and they allow local and absolute measurements of acoustic displacement. The techniques are based on different principles: acousto-optic interaction in a transparent propagation medium,[3] deflection of a laser beam by the ripple of a surface (method suitable for Rayleigh waves[4]), and optical interferometry. In the last technique, the normal surface displacement is deduced from the path-length variation of a laser beam reflected by the surface. Stabilized Michelson interferometers[5] and heterodyne methods,[6,7] less sensitive to thermal and mechanical optical path-length fluctuations, are used. With the adjunction of a coherent electronic detection to the heterodyne probe, a sensitivity of 2×10^{-3} Å has been achieved in harmonic regime with the use of a narrow bandwidth (0.3 Hz) lock-in amplifier.[8]

The plotting of the mechanical impulse response of a transducer requires a broadband detection (5–50 MHz) for restituting the transients, which increases the noise level. Measuring a displacement amplitude of a few angstroms in a 50-MHz bandwidth with a signal to noise ratio of 20 dB requires a sensitivity of 10^{-4} Å/$\sqrt{\text{Hz}}$. A few experiments on this subject have been reported: they use a stabilized Michelson displacement interferometer[9–12] or a Fabry–Perot velocity interferometer.[13]

The object of this letter is to show that the compact optical heterodyne probe of the Mach–Zehnder type that we have recently built[14] is quite suitable for sensing the mechanical impulse response of a piezoelectric transducer.

The optical part of the compact heterodyne interferometer is shown in Fig. 1. The horizontally polarized input laser beam (frequency f_L, wavelength λ_L) is half-power splitted by the cube beamsplitter (BS). The reference beam R is directed through a Dove prism into the photodiode. The probe beam is upshifted by f_B (70 MHz) in a collinear input-output Bragg cell and reflected by the vibrating surface. This beam (S), vertically polarized after passing through the quarter wavelength plate, is reflected at a right angle by the polarizing beamsplitter (PBS) along the direction of the reference beam R. The polarizer, oriented at $\pi/4$ with respect to the polarizations of R and S, allows the two beams, respectively at frequencies f_L and f_L+f_B, to be mixed on the photodetector. The photocurrent at frequency f_B is phase modulated by the vibration of the object surface (frequency f_A, amplitude d). The spectrum of this current contains components at frequencies $f_B \pm Nf_A$ having for relative amplitudes the Bessel functions $J_N(4\pi d/\lambda_L)$. For $d < 100$ Å only the components at f_B and $f_B \pm f_A$ are significant. The ratio $r = J_0/J_1$ between the carrier level $J_0(4\pi d/\lambda_L) \simeq 1$ and the side component level $J_1(4\pi d/\lambda_L) \simeq 2\pi d/\lambda_L$ gives the amplitude d of the vibration. For the He-Ne laser ($\lambda_L = 6328$ Å)

$$d \simeq \frac{1000}{r}\ \text{Å}. \tag{1}$$

This structure, compared to previous devices,[7,8] presents advantages: the time for beam alignment does not exceed a few minutes, the optical unit can operate in a vertical or horizontal position, and the stability is improved by more than one order of magnitude[14] because of the shortening of the optical paths and the rigidity of the small support. Figure 2 shows a typical result obtained when a mechanical coherent vibration at 160 kHz of amplitude 3×10^{-4} Å is observed in a

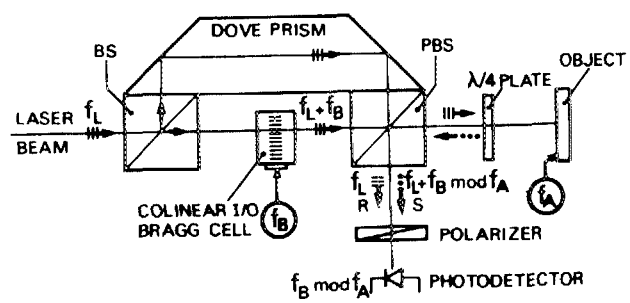

FIG. 1. Optical structure of the compact heterodyne interferometer.

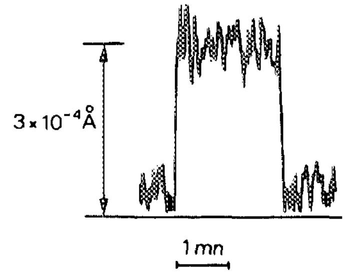

FIG. 2. Recording of the output signal detected with a 1-Hz bandwidth for a periodic vibration of amplitudes 3×10^{-4} Å.

selected narrow bandwidth $B = 1$ Hz by a lock-in amplifier. The sensitivity better than 10^{-4} Å, reaches the theoretical shot–noise limit[7]

$$\delta_{\min} = \frac{\lambda_L}{\pi}\left(\frac{eB}{I_0}\right)^{1/2}, \qquad (2)$$

where I_0 is the dc photodiode current intensity and e the electron charge. For an optical power on the photodiode of 1 mW ($I_0 = 0.3$ mA) and $B = 1$ Hz, Eq. (2) gives a detection limit of 0.5×10^{-4} Å.

For sensing the impulse response of a transducer, the photocurrent must be processed with large bandwidth electronics. The detection diagram is shown in Fig. 3. The signal from the photodiode ($f_B, f_B \pm f_A$) is split into two parts. The first one is simply amplified, the second one goes through a low pass filter (66.5 MHz) which eliminates the spectral components of frequencies f_B and $f_B + f_A$. The mixing of the two signals gives the vibration (amplitude and phase) of the object.

Figure 4 shows the result of an experiment performed with a Panametric transducer of frequency bandwidth 15 MHz (diameter 5 mm). An electric pulse of 60 V having a duration of 30 ns was applied to the transducer. The only preparation of the transducer consisted in a slight polishing of the transmitting surface, i.e., of the front matching layer. The peak of this mechanical impulse response corresponds to a displacement of 8.5 Å. The vertical scale was calibrated with a steady harmonic displacement according to Eq. (1). The shot noise limits the minimum detectable displacement to 0.5 Å. This figure could be divided by two with a better reflecting sample.

This transducer appears to be strongly acoustically damped. However, another experiment performed with a longer feeding cable (125 cm instead of 16 cm for the first

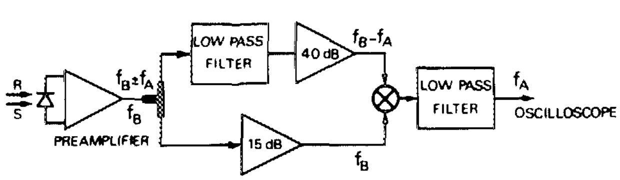

FIG. 3. Electronic detection diagram. The bandwidth of the output filter here is 20 MHz.

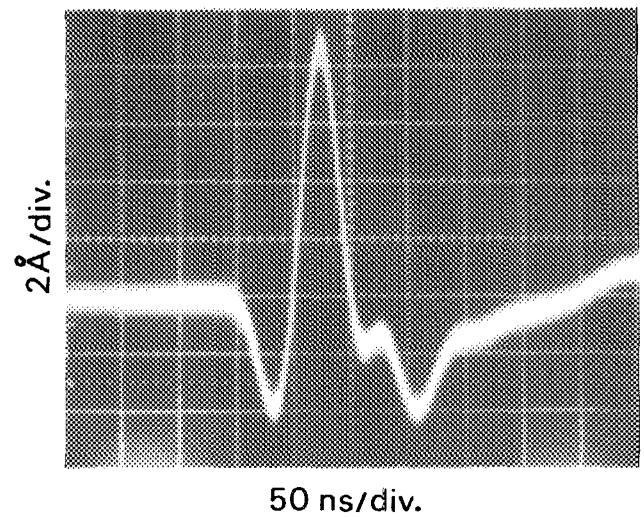

FIG. 4. Mechanical impulse response of a standard piezoelectric transducer.

experiment) shows supplementary oscillations (Fig. 5). These oscillations indicate that the electrical impedance of the transducer is not perfectly matched to that (50 Ω) of the generator.

This experiment demonstrates that the mechanical impulse response of a transducer can be optically sensed in real time. The signal to noise ratio allows the detection in a single sweep of displacements down to 0.5 Å with a transient time of 20 ns. The sensitivity can be improved by averaging several recordings. Shorter pulses could be plotted by enlarging the detection bandwidth up to the Bragg cell frequency f_B (here 70 MHz). This optical probe is suitable for measuring the mechanical displacement of transient Rayleigh waves or bulk waves produced by laser pulses.

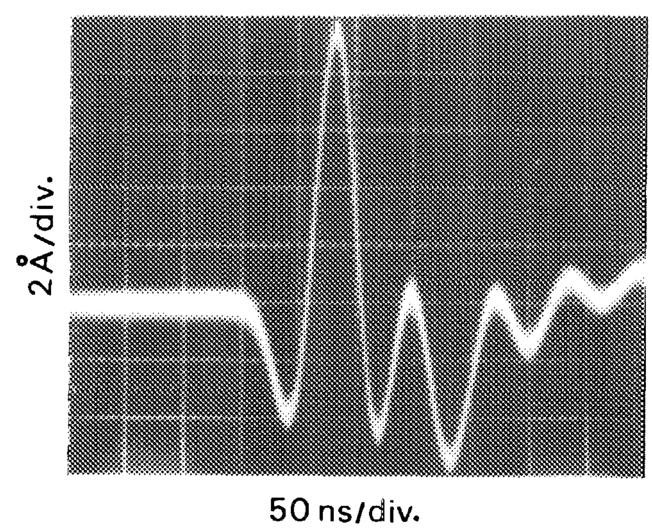

FIG. 5. Mechanical impulse response of the same transducer fed with a longer cable (125 cm instead of 16 cm for Fig. 4).

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[1]W. Dürr, D. A. Sinclair, and E. A. Ash, *Proceedings of the 1980 Ultrasonics Symposium* (IEEE, New York, 1980), p. 594.
[2]E. P. Papadakis, *Proceedings of the 1977 Ultrasonics Symposium* (IEEE, New York, 1977), p. 104.
[3]R. Torguet, C. Carles, J. M. Rouvaen, E. Bridoux, and M. Moriamez, J. Appl. Phys. **45**, 1574 (1974).
[4]R. Adler, A. Korpel, and P. Desmares, IEEE Trans. Son. Ultrason **SU-15**, 157 (1968).
[5]S. Sizgoric and A. A. Gundjian, Proc. IEEE **57**, 1313 (1969).
[6]G. A. Massey, NASA Rep. under NASA CR-985 (1967).
[7]R. L. Whitman and A. Korpel, Appl. Opt. **8**, 1567 (1969).
[8]R. M. De la Rue, R. F. Humphryes, I. M. Mason, and E. A. Ash, Proc. IEE **119**, 117 (1972).
[9]M. Kroll and B. B. Djordjevic, *Proceedings of the 1982 Ultrasonic Symposium* (IEEE, New York, 1982), p. 864.
[10]L. E. Drain, J. H. Speake, and B. C. Moss, 1st European Congress on Optics Applied to Metrology, Proc. SPIE **136**, 52 (1977).
[11]P. Cielo, F. Nadeau, and M. Lamontagne, Ultrasonics 55 (1985).
[12]D. A. Hutchins and F. Nadeau, *Proceedings of the 1983 Ultrasonics Symposium* (IEEE, New York, 1983), p. 1175.
[13]J. P. Monchalin, Appl. Phys. Lett. **47**, 14 (1985).
[14]D. Royer, E. Dieulesaint, and Y. Martin, *Proceedings of the 1985 Ultrasonic Symposium* (IEEE, New York, 1985), p. 432.