Quantitative measurements of ultrasonic shock waves using a standard optical interferometer

Christophe Barrière, Gabriel Montaldo, Xavier Jacob, Daniel Royer and Mathias Fink.
Laboratoire Ondes et Acoustique, Paris, France, Email: christophe.barriere@espci.fr.

Abstract

We measure high intensity ultrasonic displacements and shock waves in water, using the phase modulation of an optical beam reflected from a thin immersed membrane materialising moving particles. This sensitive optical method provides absolute measurements up to 20-MPa acoustic pressures, with a 50-µm lateral resolution, in a large bandwidth (50 MHz).

Introduction

Measuring shock waves is a complex problem of acoustical instrumentation: the probes have to provide absolute measurements of high acoustic pressures, with a large bandwidth in order to capture the fast rising front of the shock. The most popular sensor is the PVDF-membrane hydrophone, which is built by pasting metallic electrodes on a thin (~ 10-µm thick) PVDF membrane [1]. However, the sensitive parts of the hydrophone are gradually damaged by the acoustic cavitation induced by the high power shocks. The usual PVDF hydrophone bandwidth goes from 0.5 to 20 MHz. These hydrophones are usually calibrated using moderate power waves of a few MPa, extrapolating the results to high power waves of several tens MPa. As nonlinear effects can be expected, the calibration factor can be overvalued by the extrapolation. 70-MPa ultrasonic pressures have been measured in water with PVDF hydrophone [2]. Fiber-optic interferometers are also used to sense acoustic shock waves. Typically, a glass optical fiber, which reflects at its end the light of a laser source, is placed in the intense acoustic field [3]. The reflected light depends on the refractive index of the surrounding fluid, which changes synchronously with the acoustic pressure. The pressure is deduced from the time dependence of the reflected light. This small flexible sensor provides shock wave measurements (up to 80-MPa) with a very good lateral resolution. Nevertheless, the acoustic cavitation gradually damages the fiber extremity, so that it changes the calibration factor of the instrument. The sensitivity of the fiber-optic interferometer is low due to the small changes in the refractive index, even for relatively high acoustic pressures (the refractive index of water changes of 1.35×10^{-3}, under a 10-MPa acoustic pressure). This sensor seems to be inappropriate for characterizing ultrasonic pressures lower than 0.1 MPa in water and especially to detect the small amplitudes of the higher harmonics.

In this paper we use a commercially available optical interferometer to measure ultrasonic shock waves. This interferometer was modified to measure acoustic pressures up to 20 MPa in water.

Measurement principle

Figure 1 shows the experimental setup. The high-pressure acoustic wave is launched in a water tank by a focused transducer able to provide a pulse with a 40-MPa peak pressure, at a central frequency $f = 1$ MHz [4]. A thin (5-µm thick) optically reflective membrane of mylar is immersed in water at the focus of the ultrasonic transducer, for materializing the water particle displacements induced by the wave propagation [5]. This membrane does not filter ultrasonic waves below 50 MHz.

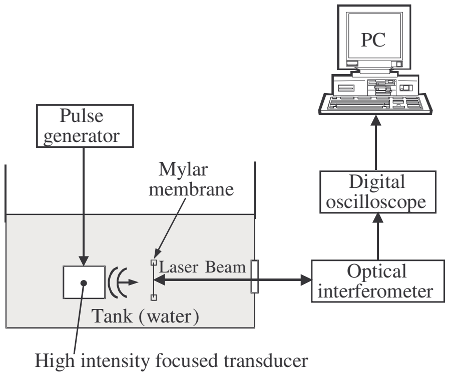

Fig. 1: Experimental setup.

For the measurement, we used the compact heterodyne probe of the Mach-Zehnder type described elsewhere [6]. The laser beam (wave number $K = 2\pi/\Lambda$, with $\Lambda = 633$ nm for a He-Ne laser) of the interferometer is split into two parts: the reference and probe beams. This latter is up-shifted by $f_B = 70$ MHz in a Bragg cell and then reflected by the mylar membrane. The mechanical displacement $u(t)$ of the membrane, induced by the acoustic wave, changes the optical path, resulting in a phase modulation $\phi(t)$ of the probe beam (Doppler effect):

$$\phi(t) = 2K\, n_0\, u(t), \qquad (1)$$

where n_0 is the refractive index of the medium. On the photodiode, the beating of the reference and probe beams generates a phase modulated photocurrent $i(t)$ at a 70-MHz frequency:

$$i(t) = I \sin\left[\omega_B t + \phi(t)\right]. \qquad (2)$$

The mechanical displacement is then usually restored with an analog demodulation circuit. In a previous paper [7], this circuit has been modified to measure large transient mechanical displacements, by using a quadrature phase demodulation. In order to increase the maximum detectable pressure and the robustness of the technique, we propose to extract digitally the phase modulation from the carrier.

Digital demodulation

To extract the phase modulation $\phi(t)$, we search for the zeros of the photocurrent $i(t)$ shown in figure 2-a.

These zeros occurs at times t_n defined by: $\omega_B t_n + \phi(t_n) = n\pi$, where n is an integer. In figure 2-b, the values founded for $n\pi$ are plotted versus their times of occurrence t_n. As the delay of the carrier $\omega_B t_n$ is much larger than $\phi(t_n)$, $n\pi$ increases quasi-linearly with t_n, while the phase modulation $\phi(t_n)$ produces only small superposed oscillations. The phase modulation is then simply obtained by subtracting the straight line $\omega_B t_n$ to $n\pi$ (figure 2-c). Since this demodulation technique is based on the detection of the zero-crossings of the carrier, it works even if the photocurrent is amplitude modulated due to the limited photodiode bandwidth B (figure 2-a).

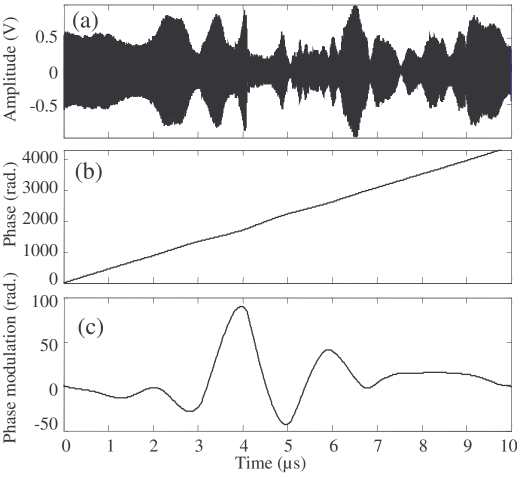

Fig. 2: Principle of the demodulation. (a) Photocurrent *i*(*t*). (b) Phase of *i*(*t*). (c) Phase modulation $\phi(t)$.

Experiments

Experiments were conducted with a 1-MHz central frequency transducer, having a 15-cm focal length and a 5-cm diameter. The displacement measured with the interferometer in water is time-derivated to obtain the particle velocity, which is a more usual physical quantity in underwater ultrasonic. Figure 3 shows the displacement and the particle velocity detected at the focus of the transducer for three different excitation levels.

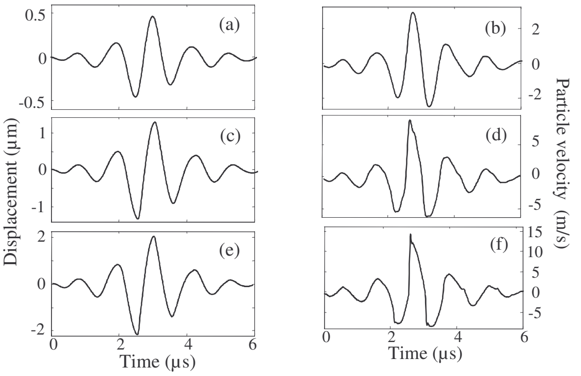

Fig. 3: Displacement and particle velocity detected with the interferometer at the focus of a 1-MHz frequency high power transducer, for three different excitation levels.

For a relatively low excitation level generating a 4.6-MPa peak ultrasonic pressure in water (figures 3-a and 3-b), the propagation is weakly nonlinear. In figures 3-e and 3-f, a 21.8-MPa acoustic pressure (or 13-m/s particle velocity, corresponding to a Mach number M = 0.01) is measured. Because of strong nonlinear effects, an angular point appears in the displacement waveform: it corresponds to a discontinuity, typical of a shock wave, in the waveform of the particle velocity.

Limitations of the method

When the phase modulation increases, the photocurrent frequency content spreads in the bandwidth *B*. Thus the amplitude of the displacement, which can be detected, depends on the bandwidth *B* of the photodiode, on the Bragg cell frequency f_B and on the central frequency f_0 of the displacement spectrum. In our configuration, we have shown that the maximum acoustic pressure detectable in water is around 20 MPa [7].

Conclusion

We have described an optical method to measure high power ultrasonic pulses or shock waves. Our interferometer provides absolute measurements of large transient mechanical displacements with a 50-µm lateral resolution, in a 50-MHz bandwidth. If the low cost membrane used in the experimental setup is damaged by the acoustic cavitation, it can be replaced very easily, without changing the calibration factor of the interferometer. With a digital demodulation, a 21.5-MPa pressure has been measured in water. The particle velocity is deduced from a time derivative of the displacement. This is a weak point of the method, because derivative algorithms are unstable, especially around an angular point, which gives a discontinuity in the velocity. The maximum measurable displacement can be improved by increasing the Bragg cell frequency, to obtain a wider bandwidth. For example, a 37-MPa pressure could be measured by using a 125-MHz Bragg cell. This absolute detection method could be used to calibrate hydrophones designed for high intensity ultrasonic field measurements.

References

[1] R. Preston, D. Bacon, A. Livett and K. Rajendran, *J. Phys. E. Sci. Instrum.*, vol. 16, p. 786-796, 1983.

[2] D. Cathignol, *Proc. of the 1990 IEEE Ultrasonics Symposium*, pp. 341-344, 1990.

[3] J. Staudenraus and W. Eisenmenger, *Ultrasonics*, vol. 31, 4, pp. 267-273, 1993.

[4] G. Montaldo, P. Roux, A. Derode, C. Negreira and M. Fink, *J. Acoust. Soc. Am.*, vol. 110, 6, pp. 2849-2857, 2001.

[5] D. Royer and E. Dieulesaint, *Appl. Phys. Lett.*, vol. 49, 17, pp. 1056-1058, 1986.

[6] D. Royer and O. Casula, *Proc. of the 1994 IEEE Ultrasonics Symposium*, pp. 1153-1162, 1994.

[7] C. Barrière and D. Royer, *Appl. Phys. Lett.*, vol. 79, 6, pp. 878-880, 2001.