TRANSIENT ACOUSTIC FIELD IMAGING USING THE MIXING OF ULTRASONIC WAVES

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Abstract

We describe a method, which uses a high frequency ultrasonic beam to probe surface motions of a solid immersed in a liquid. The analysis shows that two physical phenomena are involved in the measurement: on one hand the Doppler effect, and on the other hand the nonlinear interaction between the reflected probe wave and the low frequency acoustic wave transmitted into the liquid by the moving surface. We study the relative importance of these effects in various experimental configurations. A comparison between the results of experiments carried out with a 30-MHz ultrasonic probe and with an optical heterodyne interferometer demonstrates the interest of our active ultrasonic probe to investigate acoustic fields.

Introduction

Ultrasounds are usually generated by piezoelectric transducers. Their conception evolves to optimize their performances for particular applications. So, acoustic fields launched by transducers have to be characterized. For example, it is useful to test the zone irradiated by an ultrasonic non-destructive test, to calibrate a transducer or to validate a propagation model. For these applications, the laser beam of an optical interferometer is an ideal probe, providing an absolute measurement of the normal displacement of the vibrating surface without any mechanical contact, in a large bandwidth. However, the implementation of an optical method is sometimes difficult.

We have conceived an active ultrasonic probe, which operates in water, on the same principle that an heterodyne optical interferometer [1]. Since acoustic wavelengths are greater than optical ones, this ultrasonic probe is easier to implement on diffusive surfaces immersed in water.

In this paper, after presenting the principle of the active ultrasonic probe, we discuss the relative parts of the two effects involved in the measurement: the Doppler effect and the bulk nonlinear interaction. The characteristics of the acoustic probe are determined. A particular attention is given to the lateral resolution and its relation with the use of a focused probe beam. Measurements obtained in various configurations are compared with those given by an optical interferometer, considered as the reference instrument.

Principle

The movement of a vibrating surface modifies the phase of a reflected beam. Optical probes designed to measure subnanometric displacements operate on this principle, parented to the Doppler effect [2]. This method is transposable to an ultrasonic probe beam in a fluid, if the frequency f_{HF} of the probing wave is much higher than the one f_{LF} of the vibrating surface. The HF and LF shortenings indicates that the two waves have a high frequency ratio (typically $f_{HF}/f_{LF} > 10$), whatever their frequency range. Assuming that the speed of sound c_0 is much higher than the particle velocity induced by ultrasounds, a quasi-static approach can be used [3]. Then the variations of the acoustical path, induced by the normal displacement u_S of the surface, modulate the phase of the probe beam:

$$\Phi_D(z,t) = 2k_{HF}\ u_S(t - z/c_0)\ . \qquad (1)$$

k_{HF} denotes the wave vector of the probe beam and z is the distance between the vibrating surface and the probing transducer. However, the role of the fluid medium in between the vibrating surface and the probing transducer has to be taken into account. Indeed, due to the fluid nonlinearity, the probe beam interacts with the wave generated by the vibrating surface in the surrounding fluid.

To describe this nonlinear interaction (also called parametric interaction), a simple approach consists in considering the interaction of two plane waves. A plane acoustic wave emitted by a vibrating surface in a fluid modifies the propagation of other acoustic waves, by changing the speed of sound c_0. Two effects are involved. First, the medium displacement induced by the propagation (or convection) is considered by adding the particle velocity to the speed of sound. Secondly, the nonlinear response of the medium to a mechanical oscillation (described by the equation of state) has also to be taken into account. With these hydrodynamic and thermodynamic effects, the celerity variation Δc_+ induced by the acoustic wave propagation can be written as:

$$\Delta c_+(z,t) = b\ v_{LF}(z,t)\,, \qquad (2)$$

where $v_{LF} = \partial u_{LF}/\partial t$ denotes the particle velocity of the acoustic wave radiated by the surface and b is the nonlinearity parameter of the medium, including both the convection effect and the intrinsic nonlinearity. In a liquid, b is defined by:

$$b = \tfrac{B}{2A} + 1\,, \qquad (3)$$

where A and B are the coefficients of the linear and quadratic terms in the Taylor series expansion of the isentropic equation of state [4]. In water, the quadratic nonlinearity is sufficient to describe this nonlinear phenomenon, even for high amplitude waves.

A higher frequency wave propagating in the same direction that the wave emitted by the vibrating surface will be phase-modulated by the sound speed variations. Since the two waves propagate together in the same direction with approximately the same speed, the nonlinear effect is cumulative and the phase modulation Φ_P^+ is proportional to the interaction distance z and to the wave speed variation Δc_+:

$$\Phi_P^+(z,t) = \frac{2p\ f_{HF}}{c_0^2}\, b\ z\, v_{LF}(z,t)\ . \qquad (4)$$

When the probe beam and the wave generated by the vibrating surface propagate in an opposite direction, the celerity variation Δc_- can be written:

$$\Delta c_-(z,t) = \left(\frac{B}{2A} - 1\right) v_{LF}(z,t)\,. \qquad (5)$$

There is no cumulative interaction. If the LF wave is harmonic, the HF probe beam crosses a succession of positive and negative LF acoustic pressure zones, whose mean effect is almost null in terms of phase modulation. If the distance z is a multiple of the LF wavelength, this interaction has no effect. Otherwise, the interaction is only constructive on a distance smaller than the LF wavelength. For a transient motion of the surface, the nonlinear interaction occurs only during a short distance corresponding to the duration Θ of the transmitted pulse. In the two cases, the nonlinear interaction results in an edge effect and the phase modulation is proportional to the surface displacement [5].

For a plane wave, $v_{LF} = -c_0\, \partial u_{LF} / \partial z$ and the phase modulation is:

$$\Phi_P^-(z,t) = \frac{2p\ f_{HF}}{c_0}\left(\frac{B}{2A} - 1\right)\left[u_{LF}(t,0) - u_{LF}(t,z)\right].\ (6)$$

with $u_{LF}(t,0) = u_S(t)$ and $u_{LF}(t,z) = 0$ if $\Theta << z / c_0$.

Finally, the three effects (the Doppler effect and the nonlinear interactions in opposite directions) modify at the same time z/c_0 (travel time between the moving surface and the HF transducer) the phase of the probe beam. The total phase modulation is:

$$\Phi(z,t) = \frac{2p\ f_{HF}}{c_0}\, b\left[u_S(t - z/c_0) + \frac{z}{c_0} v_S(t - z/c_0)\right].\ (7)$$

In a previous paper [6], we analyzed the nonlinear interaction of two acoustic waves in a more detailed manner. The interaction of two primary waves generates secondary waves at sum and difference frequencies ($f_\pm = f_{HF} \pm f_{LF}$). A diffraction model, based on the Fourier formalism, has been applied to weak nonlinear interactions of two acoustic waves propagating in an absorbing medium. With respect to diffraction effects, we have shown that in the Fresnel zone of directive transducers, the parametric interaction of two waves with a high frequency ratio can be written as a phase modulation Φ_P^+ of the HF velocity potential. The index of modulation is again given by equation (4). Thus, the probe beam can be considered as a carrier, whose phase is modulated by the bulk nonlinear interaction, even if the primary waves are not plane but launched by directive transducers. This approach generalizes the plane wave model developed above.

Experimental Setup

A block diagram of the experimental setup is shown in fig. 1. A HF concave piezoelectric transducer (diameter D = 6 mm, focal length L = 18 mm in water) is focused on a vibrating surface, immersed in a water tank. This probe is working in an emission-reception mode and generates a 30 MHz-frequency continuous wave. The HF wave is reflected by the moving surface and its phase is modulated both by the Doppler effect and the parametric interaction during its return path. The HF modulated signal is then extracted by a 180°-hybrid junction and amplified, before being demodulated with a broadband detection, whose principle is described elsewhere [1]. The output signal is proportional to the LF particle velocity v_{LF}, if $\Phi(t) << 1$ radian. The vibrating surface can be moved in two perpendicular directions to obtain 2-D images.

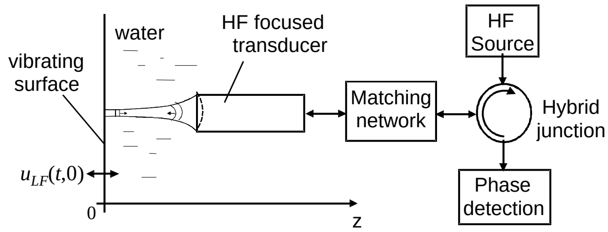

Figure 1: Experimental setup.

Doppler effect versus parametric interaction

The relative importance of the bulk nonlinear interaction and the Doppler effects is fundamental to analyze the probe working. This problem has lead to a controversy between Piquette and Censor in the middle eighties [7] [8]. Here, the question is to know the measured physical quantity: do we measure a displacement, a particle velocity or a mix of these quantities?

From equation 7 and for a LF harmonic motion generated by a planar transducer, the amplitude ratio $R = \Phi_P^+ / \left(\Phi_D + \Phi_P^-\right)$ of the phase modulation coming from the volume and surface effects is easy to estimate:

$$R = 2p\ z / l_{LF}\ . \qquad (8)$$

The gain of the parametric interaction versus the Doppler effect is then directly related to the number of wavelength l_{LF} included in the interaction distance z.

Fig. 2 shows the phase modulation detected with the ultrasonic probe, when the LF motion is a pulse generated by a 2.5-MHz frequency planar transducer (25.7-mm diameter). In such a configuration, the parametric interaction is efficient along the total path L between the LF transducer and the probe. The ratio R is equal to 190 and the bulk nonlinear interaction dominates the measurement. The detected signal is compared with the derivative of the surface displacement measured with the optical interferometer. The two waveforms are very close and they are very different from the mechanical displacement. Thus the ultrasonic probe measures a particle velocity, when the parametric interaction is efficient all along the distance L between the vibrating surface and the ultrasonic probe.

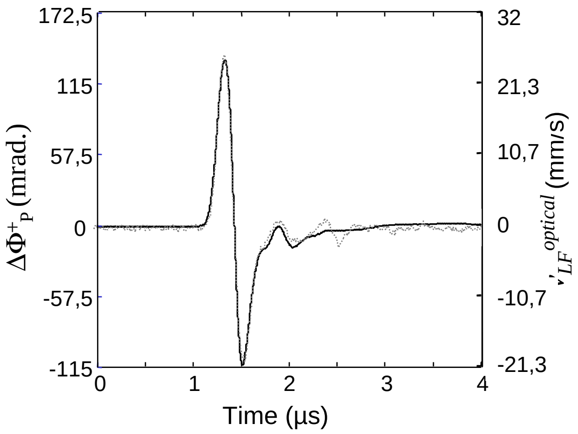

Figure 2: Phase modulation $\Delta\Phi_P^+$ detected with the ultrasonic probe (thick line), when the LF motion is generated by a 2.5-MHz planar transducer (diameter: 25.4 mm). This result is compared with the particle velocity $v_{LF}^{optical}$ (dashed line) derived from the optical measurement of the displacement. The acoustic measurement has been shifted by a quantity equal to the travel time L/c_0 between the vibrating surface and the probe transducer.

We consider now a LF spherical wave generated by a pinpoint transducer. The nonlinear interaction, which increases linearly with the propagation distance z, is then limited by the LF amplitude decreasing approximately as $1/z$. So, does the parametric interaction still dominate the measurement? An experiment has been performed with a small quartz crystal having a 0.4-mm square section and emitting a 455-kHz continuous wave. In water, the wavelength $l_{LF} = 3.3$ mm is larger than the side of the crystal, leading to a poor directivity. Since the Fresnel distance a^2/λ_{LF} is about 50 µm, the crystal can be considered as a pinpoint source. The resulting phase modulation f_P^+ is then calculated on the axis of the probe beam by integrating the LF particle velocity. At a 18-mm distance from the pinpoint source, the ratio R is 0.19 and the Doppler effect *a priori* predominates. The amplitude displacement of the crystal surface was measured with the optical interferometer: $u_{LF}^{optical} \approx 3.2 \pm 0.2$ nm. With a harmonic LF wave, the waveforms of the displacement and the velocity can not be distinguished. However, the phase modulation measured with the active ultrasonic probe gives the same amplitude displacement $u_{LF}^{acoustic} \approx 3.2 \pm 0.4$ nm, if we neglect the nonlinear terms in equation (7). In this case, the acoustic measurement is based on the Doppler effect.

Between these two extreme cases, the surface and volume effects are both involved in the measurement with the ultrasonic probe. The relative influence of these two effects is closely related to the directivity of the LF wave radiated in water. However, when acoustic fields generated by focused transducers emitting in the MHz range (like transducers used for non-destructive testing or medical applications) are imaged, the bulk nonlinear interaction is efficient along the depth of field, which usually contains several LF wavelengths. Thus, the operation of the active ultrasonic probe is the more often based on this nonlinear interaction.

Focused probe and lateral resolution

Firstly, the use of a focused probe, less sensitive to a possible tilt of the vibrating surface, allows a quick setting. Secondly, on the measurement of a LF wave generated by a planar transducer, the focusing of the probe beam does not change the signal recorded after the phase demodulation. An experimental proof is given by the measurement made on the LF planar transducer (fig. 2): the velocity amplitudes found with the acoustic and optical probes are very close.

Moreover, a focused transducer provides a good lateral resolution, when the LF acoustic field is also focused. Indeed, the focalization of the probe beam limits spatially the region of the nonlinear interaction, especially if the amplitude maximum of the LF field is near the probe focus.

In the experimental setup used to measure acoustic fields in water with the nonlinear ultrasonic probe, the probe beam is focused on a 10-µm thick metallic membrane. It acts as a mechanical filter, reflecting at least 50% of the HF wave without filtering the frequency content of the LF wave. The transmitted LF wave and the reflected HF beam interact along the path included between the membrane and the probe surface. Fig. 3 presents the two amplitude profiles measured in the focal plane of a 2.25-MHz frequency transducer focused on the other side of the metallic membrane (f-number $\approx$ 1), with the ultrasonic and optical probes. Since the spatial resolution of the optical interferometer is about 50 µm, this comparison allows a determination of the lateral resolution r of the acoustic probe: $r \approx 0.25$ mm. r is approximately equal to the 3-dB width of the HF probe beam (0.17 mm) and is comparable to the lateral resolution of a PVDF-membrane hydrophone.

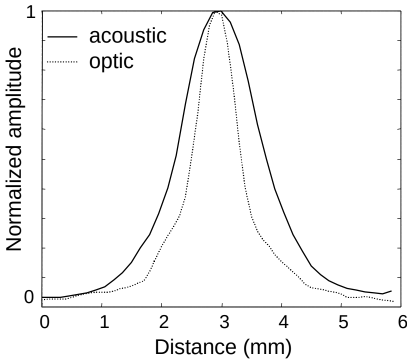

Figure 3: Amplitude profiles measured in the focal plane of a 2.25-MHz frequency transducer (f-number ≈ 1) with the ultrasonic and optical probes.

Bandwidth and dynamical range

The probe transducer and the analog filtering impose the frequency bandwidth of the ultrasonic probe. We have determined it experimentally by emitting tone-bursts. The 3-dB bandwidth of the probe is 4.5 MHz.

At the output of the phase detection, the noise amplitude is about 0.2 mrad. It corresponds to a 0.04-mm/s velocity amplitude, if the nonlinear interaction is efficient all along the L distance. The sensitivity is ten times better than the one provided by an optical interferometer [2]. A saturation of the phase detection occurs, when the amplitude of the phase modulation reaches $\pi/4$ that corresponds to a 0.15-m/s velocity, with L = 18 mm. In this case, the dynamical range of the nonlinear ultrasonic probe is equal to 70 dB.

Acoustic fields radiated by an industrial sample

We applied the ultrasonic probe for measuring the acoustic field emitted by an industrial sample. The result obtained in this complex configuration is again compared with the one given by the optical interferometer. Fig. 4 shows the experimental configuration. A metallic cylinder, partially cut out, is tested by ultrasounds with a dual transducer working in an emission-reception mode. The emitter E has a rectangular aperture (9×2.5 mm^2). It generates a 5-MHz frequency shear wave, under a 45° angle of incidence in the cylinder. After reflection on the curved surface of the cylinder, the acoustic beam is focused towards the P plane, where some cracks can be located. A crack diffracts a wave, which can be detected with the receiving transducer R. The cylinder has been cut off along the P plane, to examine with our probes the region irradiated by the emitter E.

Fig. 5 shows the C-scan images of the velocity measured on the P plane with the acoustic and optical probes. The two images are very close: the detected field has a pear shape due to the cylindrical focusing. On the acoustic scan, a spot can be observed upper the "pear". The analysis of a B-scan representation shows that this spot comes from a beam, which directly encounters the P plane without being reflected by the cylinder. The wave converted in the fluid, approximately plane, is better detected by the parametric interaction than the focused part of the field, which cylindrically diverges. Finally, thanks to its sensitivity and its low sensibility to diffusion, the ultrasonic probe provides a good quality image, compared with the optical scan.

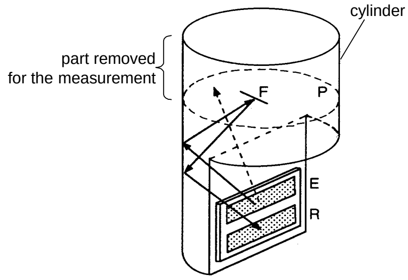

Figure 4: Industrial part tested by a dual transducer. The region highlighted for the non-destructive test is determined by probing the surface denoted P. Dashed arrow shows the direct acoustic path from the emitter E to the P plane.

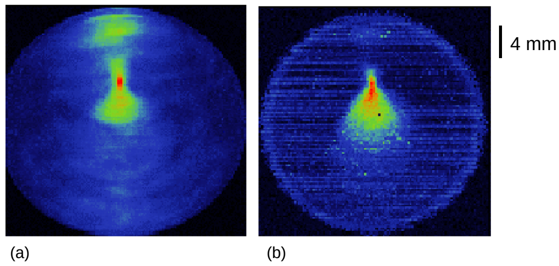

Figure 5: C-scan images of the velocity measured on the P plane, with the ultrasonic (a) and optical (b) probes.

Conclusion

An active ultrasonic probe based on a nonlinear effect has been compared with optical interferometry. We demonstrated the ability of this probe to measure acoustic fields on industrial surfaces. Its implementation is easy on rough surfaces immersed in water, with the same experimental setup than for a standard nondestructive test.

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