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Application of optical interferometry in focused acoustic field measurement

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ABSTRACT

Optical interferometry has been successfully applied in measuring acoustic pressures in plane-wave fields and spherical-wave fields. In this paper, the "effective" refractive index for focused acoustic fields was developed, through numerical simulation and experiments, the feasibility of the optical method in measuring acoustic fields of focused transducers was proved. Compared with the results from a membrane hydrophone, it was concluded that the optical method has good spatial resolution and is suitable for detecting focused fields with fluctuant distributions. The influences of a few factors (the generated lamb wave, laser beam directivity, etc.) were analyzed, and corresponding suggestions were proposed for effective application of this technology.

1. Introduction

Focused transducers have been widely used as ultrasound devices for medical applications, and their parameters are mostly detected by hydrophones. However, the presence of hydrophones will limit the spatial resolution and cause disturbances of the acoustic field such as reflection or standing wave artefacts [1,2]. To obtain high-resolution images of focused transducers, novel methods should be developed and validated. As a noninvasive method, optical interferometry has been widely used for micro-vibration measurement in both laboratorial and industrial areas [3,4]. By means of a thin membrane (pellicle), the optical interferometer is able to detect particle velocities in plane-wave fields and spherical-wave fields, and acoustic pressures can be acquired accurately through the particle velocities [5,6].

In a pellicle-based interferometry system, laser beam from a vibrometer is projected onto a pellicle which is fixed in the acoustic field, and the particle velocity on the pellicle will be detected through the reflected laser signal. Since the laser beam interacts with acoustic waves that pass through the pellicle, piezo-optic effect of the water medium should be taken into account when the measured particle velocity is being converted to acoustic pressure. "Effective" refractive index has been introduced to make corrections for the piezo-optic effect of both plane waves and spherical waves [7,8]. For applications of optical interferometry in focused field measurement, the related piezo-optic effect should be examined.

In this paper, focused acoustic fields and the corresponding piezo-optic effect were studied theoretically. The acoustic field of a typical focused transducer was measured using an optical interferometer and a membrane hydrophone, and results from the two methods were compared inside the focal region and in the Fresnel zone. To explain the deviation from the two methods outside the focal region, spatial averaging effect of the membrane hydrophone was discussed. Other influences from the "effective" refractive index, for example, the generated lamb wave in the pellicle, the directivity of the interferometer, and the

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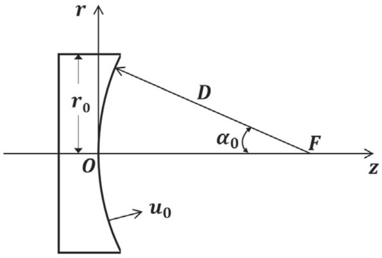

Fig. 1. Geometry of a focusing radiator.

acoustic attenuation of the pellicle were also analyzed. Finally, some suggestions were proposed for focused field measurement using optical interferometry.

2. Methodology

2.1. Acoustic field of focused transducer

For a spherically curved source with radius r_0, curvature radius D and half aperture angle α_0, as shown in Fig. 1, under the condition that its radius r_0 is large relative to the acoustic wavelength and to the depth of the concave surface, and the active surface radiates with a uniform velocity u_0, the velocity potential for the concave source can be written as:

$$\phi = \frac{u_0}{2\pi} \iint_S \frac{e^{ikr}}{r} dS, \tag{1}$$

where k is wavenumber. In Eq. (1), the time dependence $e^{-i\omega t}$ is omitted for convenience.

The solution to Eq. (1) requires a double numerical integration, for axisymmetry sources, their velocity potential can be decomposed as [9]:

$$\phi(r,z) = e^{ikz} Q(r,z), \tag{2}$$

where $Q(r,z)$ is a quantity related to the velocity potential.

For $r > r_0$, the velocity potential $\phi(r, 0)$ is zero. When the half aperture angle α_0 is fairly small and the aperture size is large in comparison to acoustic wavelength (i.e. $\sin\alpha_0 \ll 1$ and $kr_0 \gg 1$), $Q(r,z)$ could be expressed as [9]:

$$Q(r,z) = \frac{-u_0}{z} e^{[ik(\frac{r^2}{2z})]} \int_0^{r_0} e^{[\frac{ikx^2}{2}(\frac{1}{z}-\frac{1}{D})]} \cdot J_0(\frac{krx}{z}) x dx. \tag{3}$$

In Eq. (3), x is a point on the r axis coordinate system. The acoustic pressure p and particle velocity u_0 can be derived from ϕ: $p = ik\rho c\phi$ and $u_0 = \nabla\phi$ (ρ is the mass density and c is the sound-speed of the medium), respectively. From Eq. (2) and Eq. (3), the acoustic pressure and the axial particle velocity can be written as follows:

$$p(r,z) = -\frac{ik\rho c u_0}{z} e^{[ik(\frac{r^2+2z^2}{2z})]} \int_0^{r_0} e^{[\frac{ikx^2}{2}(\frac{1}{z}-\frac{1}{D})]} \cdot J_0(\frac{krx}{z}) x dx, \tag{4}$$

$$u_z(r,z) = -\frac{\partial}{\partial z}\{\frac{u_0}{z} e^{[ik(\frac{r^2+2z^2}{2z})]} \int_0^{r_0} e^{[\frac{ikx^2}{2}(\frac{1}{z}-\frac{1}{D})]} \cdot J_0(\frac{krx}{z}) x dx\}. \tag{5}$$

2.2. Piezo-optic effect in pellicle-based interferometry

In a pellicle-based interferometry, the laser beam will be perturbed by the acoustic waves propagating through the pellicle. The interferometer could interpret these perturbations as velocity. To identify the vibration of the pellicle, the piezo-optic effect of the water medium must be taken into account.

For a pellicle-based interferometry system depicted in Fig. 2, both acoustic waves and the laser beam propagate along the same axis (z axis). An optically reflective pellicle is placed in the plane $z = 0$ and moves a small distance $a(t)$ in response to the acoustic wave at time t. When the wavefront propagates to the plane $z = l$, the difference in optical path length, $q(t)$, caused by the presence of the acoustic wave is [10]:

$$q(t) = -2n_0 a(t) + \frac{2n_1}{\rho c^2} \int_{a(t)}^{l} p(z,t) dz, \tag{6}$$

where n_0 is the refractive index of water, n_1 is the piezo-optic coefficient and $p(z, t)$ is the acoustic pressure along z axis at time t.