Reconstruction of Vibrating Surface of Ultrasonic Transducer Using O-CT and Acoustical Holography

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1. Introduction

For the measurement of phase objects such as distribution of sound pressure or temperature, acoustical non-contact probes are widely used\(^1\)\(^-\)\(^3\). The performance of the acoustic probe affects the accuracy of measurement, so it is important that the vibrating surface of the ultrasonic transducer, constituting the acoustic probe, is measured. The conventional method for measuring sound fields is combined use of the hydrophone and the mechanical scanning. The method, however, has problems that the hydrophone influences the sound fields or is damaged because of touching the transducer. On the other hand, the method using the optical probe can measure noncontact and does not influence the sound fields\(^4\).

In this paper, the vibrating surface of the ultrasonic transducer is reconstructed from using the acoustic holography method\(^5\). It is based on the data those are the two-dimensional complex sound fields reconstructed using Optical- Computerized Tomography (O-CT) method. In the following section, the measurement principle, experimental method, and visualization results are described.

2. Principles of Measurement

2.1 Measurement of the radiated sound fields

Michelson interferometer is used as optical probes to measure the sound fields. The test light \(i_{\text{test}}\) that passes through the water, in which ultrasonics are radiated, interfere with the reference light \(i_{\text{ref}}\). The optical intensity \(I_{\text{out}}\) of the interference light given by

\[
I_{\text{out}} = I_{\text{test}} + I_{\text{ref}} + 2\sqrt{I_{\text{test}}I_{\text{ref}}} \cos(\phi_x + \phi_y),
\]

where the optical intensity of the test light, reference light, initial phase, and phase-change by the ultrasonics are \(I_{\text{test}}, I_{\text{ref}}, \phi_x,\) and \(\phi_y\). In this paper, the test light and reference light are constant intensity, so the optical intensity varies by the phase-change as shown in the following expression.

\[
\phi_j(x, y, z, t) = \frac{4\pi\delta_j}{\lambda} \int p_0(x, y, z) \exp\left[j(\omega t - \phi_j(x, y, z))\right] dy,
\]

where \(\delta_j, \lambda, p_0, \omega,\) and \(\phi\) are the proportionality factor pertaining to the sound pressure and refractive index\(^6\), wavelength of the light, amplitude of the ultrasonic, drive frequency of the ultrasonic transducer, and phase of the ultrasonic.

The intensity of the interference light is detected by the avalanche photodiode (APD), and the real part and imaginary part of sound fields \((I_{\text{re}}, I_{\text{im}})\) is electrically obtained by the quadrature detector. \(I_{\text{re}}\) and \(I_{\text{im}}\) are given by

\[
I_{\text{re}} \propto \int p_0(x, y, z) \sin(\phi(x, y, z)) dy,
\]

\[
I_{\text{im}} \propto \int p_0(x, y, z) \cos(\phi(x, y, z)) dy.
\]

Here, \(I_{\text{re}}\) and \(I_{\text{im}}\) are the projection data of sound fields. The radiated Sound Fields is reconstructed from the projection data using CT method\(^4\).

2.2 Reconstruction of the Vibrating Surface

The complex pressure of the sound fields given by the above section at the plain of \(z=z\) is expressed as \(p(x, y, z)\). The complex pressure at the vibrating surface of the ultrasonic transducer is reconstructed from the experimental data at the plain of \(z=z\). Here, we consider the coordinate system as shown in Fig.1. The vibrating surface is in parallel with the measurement plane, and the ultrasonic transducer
only vibrates along the $z$-axis. The relationship between the complex sound pressure at the vibrating surface and at the measurement plane is given by

$$ p(x, y, z) = p(x, y, 0) * h(x, y, z), \quad (5) $$

where * and $h$ denote convolution integral and the propagation function. Fourier transform of the complex pressure of the sound fields and the propagation function are $P(u, v, z)$ and $H(u, v, z)$. Eq.(5) is transformed to

$$ P(u, v, 0) = \frac{P(u, v, z)}{H(u, v, z)}. \quad (6) $$

Then, the complex sound pressure at the vibrating surface is reconstructed by computing the inverse Fourier transform of $P(u, v, 0)$ obtained by Eq.(6).

Here, the Fourier transform of the propagation function is given by

$$ H(u, v, z) = \exp\left[2\pi i z \sqrt{(f/c)^2 - (u^2 + v^2)}\right], \quad (7) $$

where acoustic velocity and frequency of the ultrasonic are $c_s$ and $f^3$.

3. Experimental Results

The diameter of the transducer radiating the ultrasonic beam, that is the object for visualization, is 8.0 mm, and frequency of the signal applied to the transducer is 1.43 MHz. The sound fields at 10.0 mm form the vibrating surface are measured by optical probe that is a He-Ne laser with a light wavelength of 632.8 nm. The transducer is set to the mechanical $x - \theta$ stages and is scanned relative to the light beam. The linear scanning region in $x$ direction is $-32 \leq x \leq 32$ (mm) with 1.0 mm steps, and the range of rotation is $0 \leq \theta < \pi$ (rad) with $\pi / 32$ rad rotation step angles; 36 projection data are acquired.

**Fig.2** shows the central parts of the reconstructed images, which denote the complex pressures at the vibrating surface and the measurement plane. The measurement results of the sound fields at 10.0 mm form the vibrating surface are shown in Fig.2(a) and (b), and the reconstructed images at the vibrating surface are shown in Fig.2(c) ~ (f). Fig.2(a) ~ (d) show the experimental results, and Fig.2(e) and (f) show the numerical results. The reconstructed images at the vibrating surface were in fair agreement with the numerical results. The amplitude located directly below the ultrasonic transducer in Fig.2(c) shows up the striped pattern as well as the numerical result in Fig.2(e), and the phase in Fig.2(d) is almost constant below the transducer. In contrast, the noisy part in Fig.2(b) and (d) is due to the very low signal.

4. Conclusions

The two-dimensional visualization of sound fields realized using the Michelson interferometer and O-CT. Sound fields radiated from a circular transducer with a diameter of 8.0 mm and driven at a frequency of 1.43 MHz were measured. The reconstructed images at the measurement plane were in fair agreement with the numerical results.

In addition, the complex pressure at the vibrating surface is reconstructed using acoustical holography from the data acquired at the plane 10.0 mm from the transducer. The reconstructed images at the vibrating surface were also in fair agreement with the numerical results. The accuracy will improve by measuring at nearer plane from the vibrating surface.

References