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Development of Intensity Microphone for Airborne Ultrasound Using Optical Fiber

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1. Introduction

Acoustic intensity is a vector quantity representing the acoustic energy passing through a unit area in a unit time, which can be practically used for measuring acoustic power and identifying the positions of sound sources. Intensity microphones for audible sounds have been sold up to now [1]. As the use of high-intensity ultrasonic waves in the air progresses, it is expected that intensity microphones for ultrasonics will be demanded.

The P-P type, which places two pressure microphones in close proximity, is common for intensity microphones [1]. Using the fact that the time derivative of particle velocity is proportional to the spatial derivative of sound pressure, the particle velocity is approximately obtained by the spatial difference of sound pressure. By multiplying the obtained particle velocity by the sound pressure and taking the time average, the acoustic intensity can be calculated. To conduct this measurement correctly, it is required to minimize the spacing between the microphones and ensure that the microphones themselves do not disturb the sound field. Particularly in the ultrasonic band, a probe sufficiently thin compared to the wavelength is necessary to meet these requirements.

We propose an intensity microphone for ultrasonic waves using optical fibers as probes. A microphone using a 0.9 mm diameter optical fiber as a probe is almost omnidirectional for ultrasonic waves of 40 kHz (wavelength 8.5 mm) [2]. Therefore, it can be expected that arranging two of these will hardly disturb the sound field.

In this paper, we explain the principle of the proposed optical fiber P-P intensity microphone and confirm its validity by experiments. This paper is based on the proceeding of Japanese-domestic meeting [3].

2. P-P intensity microphone

2.1 Principle [1]

The r-direction component of the acoustic intensity I_r [W/m^2] is represented as the time average of the product of the sound pressure p [Pa] and the r-direction component of the particle velocity u_r [m/s] in the following equation.

$$I_r = \overline{p(t)\, u_r(t)} \tag{1}$$

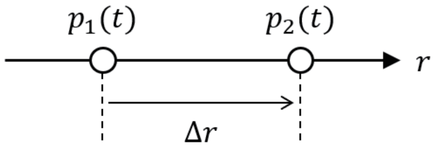

Fig. 1 Arrangement of two microphones

Here, t [s] represents time.

If we denote the sound pressure measured by two microphones arranged at an interval Δr [m] in the r direction (**Fig. 1**) as p_1 and p_2, then I_r can be approximately calculated by the following equation.

$$I_r \approx \frac{1}{2T\rho\Delta r}\int_0^T \left\{[p_1(t)+p_2(t)]\int_0^t [p_1(\tau)-p_2(\tau)]\mathrm{d}\tau\right\}\mathrm{d}t \tag{2}$$

Here, T [s] and τ [s] represent time, and ρ [kg/m^3] denotes the density of the air.

2.2 Pure tone

When using high-intensity ultrasonic waves, a specific frequency (for example, 40 kHz) often dominates. Assuming a signal with a single frequency ω [rad/s], the sound pressure measured by the two microphones, denoted as amplitude A [Pa] and phase difference φ [rad], is represented as follows.

$$\begin{cases} p_1(t) = A\cos(\omega t) \\ p_2(t) = A\cos(\omega t - \varphi) \end{cases} \tag{3}$$

By substituting equation (3) into equation (2) and calculating, we obtain the following equation.

$$I_r \approx \frac{A^2 \sin\varphi}{2\omega\rho\Delta r} \tag{4}$$

In equation (2), it is necessary to perform time integration and time averaging, but in equation (4), the acoustic intensity can be obtained by Fourier transforming the signal measured by each microphone and acquiring the amplitude and phase of the target frequency. It can also be expected that the latter method is less susceptible to noise.

3. Experiments

3.1 Setup

The experimental setup constructed inside an

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anechoic chamber is shown in **Fig. 2**. We formed the target ultrasonic focus (frequency 40 kHz, focal distance 200 mm, output setting 0.1) using a phased array ultrasonic transducer 4). We used a single-mode fiber with a diameter of 0.9 mm, including the coating, and exposed about 1 cm of the core wire with a diameter of 0.125 mm at the tip. To prevent the optical fibers from bending, we reinforced them with 0.9 mm diameter metal wires and held them in place with an XYZ stage. We placed the tips of the two optical fibers at the position of the ultrasonic focal point. By moving the tip of the optical fiber close to the phased array with the XYZ stage, we changed the microphone interval Δr.

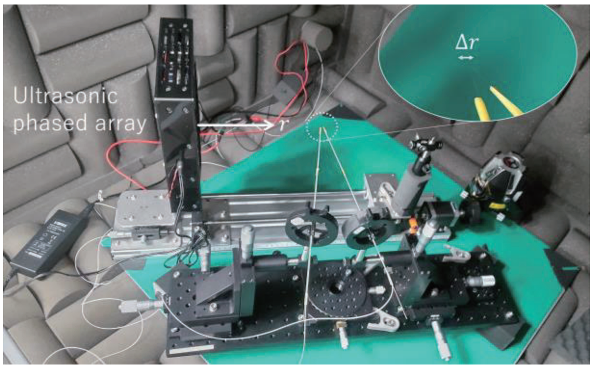

Fig. 2 Experimental setup

3.2 Optical fiber P-P intensity microphone

The equipment configuration of the prototype is shown in **Fig. 3**. Light emitted from an ASE (Amplified Spontaneous Emission) light source (40 mW, 1528-1563 nm) was incident on two optical fibers through a beam splitter. At the tips of the optical fibers, the reflectance coefficients change due to changes in air density associated with sound waves 2). The reflected light at these points were guided to a photodiode via a circulator, and the detected results were output as voltage.

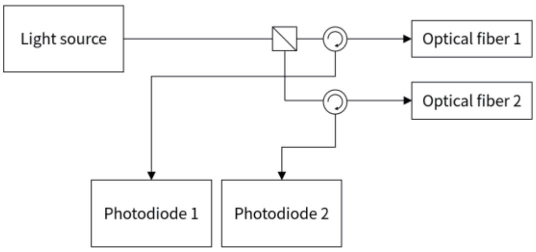

Fig. 3 Equipment configuration of intensity mic.

The voltage output V [V] from the photodiode was recorded with an oscilloscope. The obtained data were subjected to FFT (Fast Fourier Transform), and the DC components V_1^{DC} and V_2^{DC}, the AC components (in this case, 40 kHz) V_1^{AC} and V_2^{AC}, and the phases of the AC components φ_1^{AC} and φ_2^{AC} were acquired. At this time, A and φ to be substituted into equation (4) are given as the average of the amplitude of the measurements by the two microphones and the difference of the phases, respectively, by the following equations. Here, α [Pa] is a coefficient used for calculating the sound pressure in the optical fiber microphone 2) (in air, $\alpha = 1.02 \times 10^8$ Pa).

$$A = \alpha \times \frac{1}{2}\left(\frac{V_1^{\mathrm{AC}}}{V_1^{\mathrm{DC}}} + \frac{V_2^{\mathrm{AC}}}{V_2^{\mathrm{DC}}}\right) \tag{5}$$

$$\varphi = \varphi_1^{\mathrm{AC}} - \varphi_2^{\mathrm{AC}} \tag{6}$$

3.3 Results

The results of changing the microphone interval Δr from a minimum of 0.2 mm to 10.2 mm in increments of 0.5 mm, measuring each condition once, are shown in **Fig. 4**.

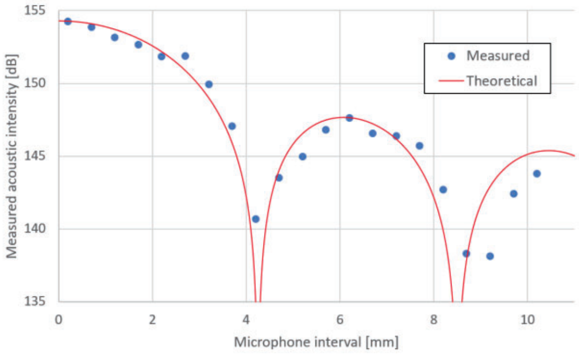

Fig. 4 Experimental results on mic. interval

The measurement values of the acoustic intensity are theoretically derived to follow the sinc function of Δr 1), and the microphone interval where the effect is within 1 dB is calculated to be less than 1.6 mm for 40 kHz. The theoretical curve that matches the measurement values at $\Delta r = 0.2$ mm is displayed in Fig. 4.

4. Conclusion

In this paper, we proposed a P-P intensity microphone targeting ultrasonic waves and conducted experiments with a prototype. Although some deviations were observed, the measurement values generally showed the same trend as the theoretical values, confirming the validity of the proposed method. Going forward, we plan to consider probe structures suitable for practical use and structures that can measure acoustic intensities in multiple directions.

References

1) S. Gade, B&K Tech. Review, (3), 3-29 (1982).
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