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Experimental Verification of Nonlinear Attenuation of Airborne Ultrasound
空中超音波の非線形減衰の実験的検証

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1. Introduction

Social implementation of parametric speakers [1] and ultrasonic phased arrays [2] has been attempted, and high-intensity ultrasonic waves are becoming familiar to us in our daily lives. Most of these devices radiate 40-kHz ultrasonic waves at around or over 140 dB SPL. This SPL is so high that nonlinear effects are evoked in air, such as self-demodulation that used for parametric speakers and acoustic radiation pressure that used for noncontact interaction.

Nonlinear absorption also occurs in the propagation process. Based on the theory, it is predicted that saturation occurs as the result of nonlinear absorption and the upper bound of the saturated amplitude is determined only by the distance from the sound source no matter how high the SPL is radiated from the sound source [3][4]. Here we call this process "nonlinear attenuation." This is an important effect when we discuss the efficiency and the safety of the high-intensity ultrasonic devices.

In this paper, first, we introduce the theory of nonlinear attenuation of plane and spherical waves. Next, we measure the ultrasound radiated from an ultrasonic device in beam and focus modes.

2. Theory

A high-intensity ultrasonic wave decreases its amplitude and is eventually saturated. This process is shown in **Fig. 1**. First, the waveform is distorted because the instantaneous sound speed changes according to the sound pressure. That is, higher sound pressure comes earlier, and lower sound pressure comes later. Next, the waveform becomes a shock wave after distortion, whose rise of sound pressure is steep. Then, nonlinear absorption starts after shock wave formation. The excess acoustic energy due to continued waveform distortion is dissipated. Finally, the waveform is saturated as a sawtooth wave. The distance from the ultrasonic device where this sawtooth wave is formed and its sound pressure depend on the initial sound pressure at the sound source, and the upper bound of the sound pressure is obtained by increasing the initial sound pressure to infinity.

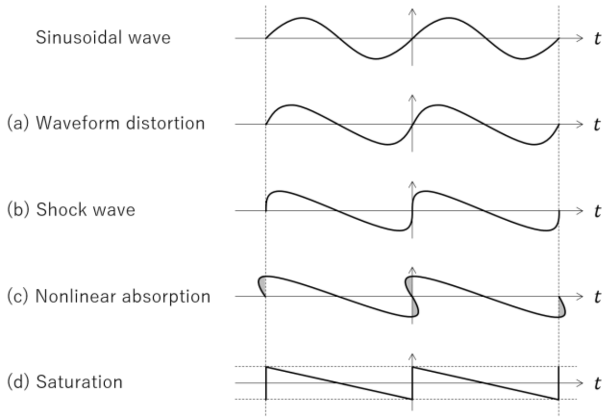

Fig. 1 Nonlinear propagation process.

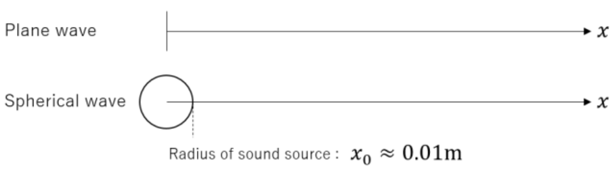

Fig. 2 Coordinate system for formulation.

The upper bound of the saturated sound pressure has been mathematically discussed [3][4]. Here, we consider plane and spherical waves as shown in **Fig. 2**.

The saturated sound pressure $p_1(\infty)$ [Pa] of the fundamental frequency component of a plane wave is given by the following equation,

$$p_1(\infty) = \frac{2\rho_0 {c_0}^3}{\beta\omega x}$$

where ρ_0 [kg/m^3] is the density of air, c_0 [m/s] is the speed of sound in air, $\beta = 1.2$ is the nonlinear coefficient of air, and ω [rad/s] is the angular frequency of ultrasound.

The saturated sound pressure $p_1(\infty)$ [Pa] of the fundamental frequency component of a spherical wave is given by the following equation,

$$p_1(\infty) = \frac{2\rho_0 {c_0}^3}{\beta\omega x}\frac{1}{\ln\frac{x}{x_0}}$$

where x_0 [m] is the radius of the spherical sound source, and this time we assume 10 mm as a typical value representing the size of a focal point of ultrasonic waves.

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3. Experimental Setup

To confirm the nonlinear attenuation occurs as predicted by the theory, we conducted a measurement experiment in an anechoic chamber of $5 \times 5 \times 5\ \mathrm{m}^3$, using an ultrasonic phased array and an optical microphone. The origin point of measurement was set at the center of the phased array and at 200 mm from its surface (**Fig. 3**).

3.1 Phased Array

We used a phased array which has 271 ultrasonic transducers (Nippon Ceramic Co., Ltd., T4010B4, 10-mm diameter) in a hexagonal arrangement. It can be operated in beam and focus modes. All the transducers are driven by the same signal in the beam mode, and the transducers are driven so that a single focal point is generated at 200 mm in the focus mode.

3.2 Optical Microphone

We used an optical microphone (XARION Laser Acoustics GmbH, Eta100 Ultra, Freq. 10 Hz to 1 GHz, 80 to 180 dB SPL) to measure high-intensity ultrasound directly. It was calibrated by another calibrated microphone (ACO Co., Ltd., TYPE4158N, 1/4 inch) without protection gird.

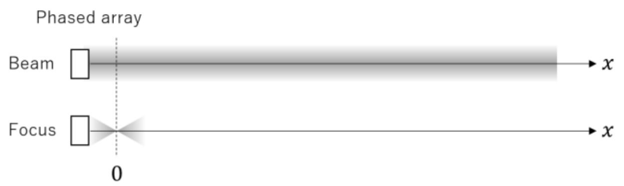

Fig. 3 Beam and focus modes of the phased array.

4. Experimental Results

4.1 Fluctuation of Measurement

We preliminarily checked the fluctuation of measurement. In the focus mode with the maximum output, at $x = 2$ m, when measured 10 times, the maximum value was 117.46 dB SPL, and the minimum value was 111.48 dB SPL. So, the fluctuation was determined as ± 3 dB. In the following results, we just plot the average value of 10 measurements for each point.

4.2 Distribution on Acoustic Axis

We measured the sound pressure distribution every 50 mm in the beam mode (**Fig. 4**) and the focus mode (**Fig. 5**) at the output setting values 1.0 and 0.1 of the maximum output.

4.3 Angle dependence

We measured the sound pressure distribution every 5 deg from the front (0 deg) to the side (90 deg) in the focus mode with the maximum output (**Fig. 6**) to check there were no exceptions.

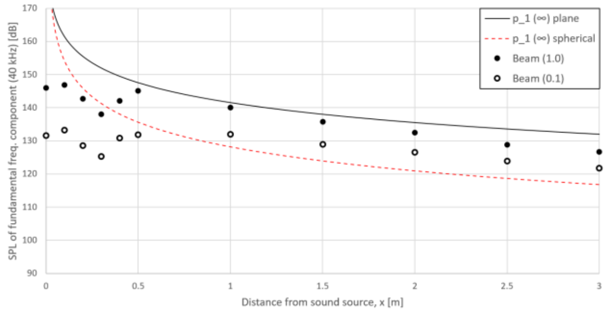

Fig. 4 Sound pressure distribution (beam mode).

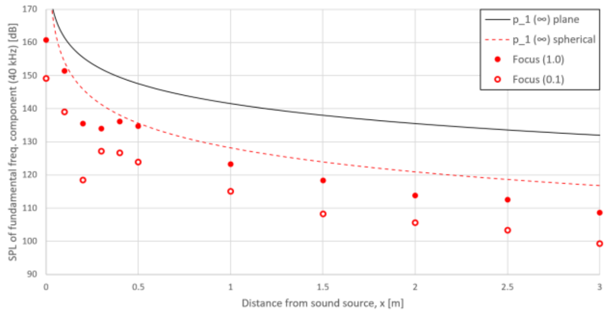

Fig. 5 Sound pressure distribution (focus mode).

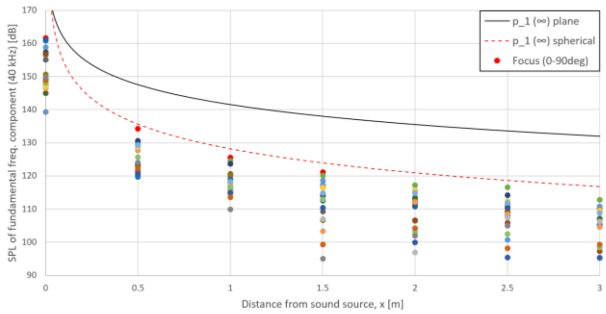

Fig. 6 Angle dependence (focus mode, maximum).

5. Conclusion

We conducted a measurement experiment to verify the theoretically predicted upper bound of the high-intensity ultrasound. It was observed that the sound pressure in the beam mode did not exceed the upper bound of the plane wave, and the sound pressure in the focus mode did not exceed the upper bound of the spherical wave. We confirmed that the nonlinear attenuation surely occurs in air, and the theory gives us a quantitatively reliable prediction as far as this experimental observation.

References

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