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Design and Focusing Characteristic of Wide-angle and Thin Acoustic lens

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1. Introduction

Recently, the cooperative use of multiple underwater vehicles has attracted attention for more efficient ocean exploration [1]. Underwater acoustic (UWA) communication is one of the techniques to establish an underwater mobile network. However, the establishment of an UWA network is still challenging, since the collision of packets on a shared single channel can result in performance degradation. Thus, multiple access techniques (*e.g.*, time-, frequency-, code- or space-division multiplexing) or packet scheduling algorithms have been considered.

As an alternative, we have proposed a space-division multiplexing UWA communication system using acoustic lenses and mirrors. The use of lenses has the potential to realize a simple UWA network because it can transmit and receive multiple beams simultaneously without the need for complicated circuits.

When sound waves enter a boundary surface beyond the critical angle, total reflection occurs, limiting the angle of view. To solve this problem, a wide-angle lens with a hemispherical incident surface has been designed [2]. In this report, we attempted to design a thin wide-angle lens. When total reflection occurs, an evanescent field is generated, which decreases exponentially in the direction perpendicular to the boundary surface. When lenses are used for the UWA communication, the evanescent field extends because the lower frequency band is used. When the evanescent field reaches the radiation surface of the lens, it repropagates as ordinary sound waves [3]. A thin lens with an angle of view beyond the critical angle can be designed by utilizing this repropagation. In addition, we will attempt to vary the focusing characteristics by using different media on each side of the lens.

In this report, we formulate the direction of repropagation when the sound wave is incident beyond the critical angle, and design the lens based on this formulation. The focusing characteristics of the designed lens are obtained by simulations. We compare two conditions: (a) Water – Water condition, *i. e.*, the medium around the lens is water, and, (b) Water – Fluorinert condition, *i. e.*, the media around the lens are water and Fluorinert.

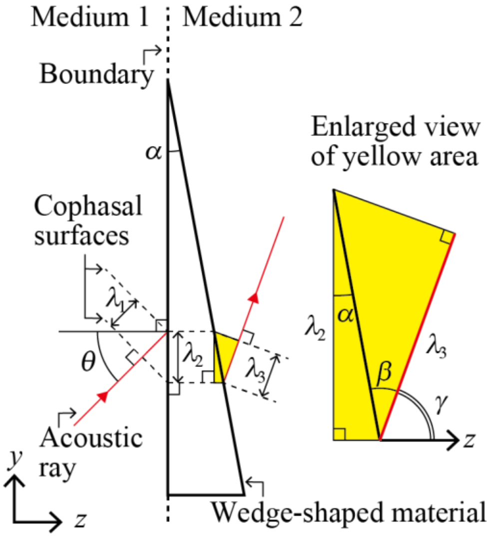

Fig. 1 Schematic view of sound waves incident on a wedge-shaped material.

2. Design

A schematic view of sound waves incident on a wedge-shaped material is shown in **Fig. 1**. The red lines indicate acoustic rays and the dotted lines indicate cophasal surfaces. When the angle of incidence θ exceeds the critical angle, the cophasal surfaces are formed perpendicular to the incidence plane of the wedge-shaped material. The cophasal surfaces are continuous at the incident and radiation planes, and the spacing between them corresponds to the wavelengths in each medium. In this case, the following geometrical relationship holds for the incident plane.

$$\lambda_2 \sin\theta = \lambda_1. \qquad (1)$$

When we define the angles α, β, and γ, as shown in the yellow area in Fig. 1, the following relationship holds for the radiation plane.

$$\lambda_3 \cos\alpha = \lambda_2 \cos\beta. \qquad (2)$$

Eliminating λ_2 from Eqs. (1) and (2), we obtain the following equation.

$$\lambda_1 \cos\beta = \lambda_3 \sin\theta \cos\alpha. \qquad (3)$$

The angle of the radiated ray with respect to the z-axis, γ is,

$$\gamma = 90^{\circ} + \alpha - \beta. \qquad (4)$$

Next, we describe how to design a lens using the above equations. A schematic view of the lens design is shown in **Fig. 2**. In this report, the incident

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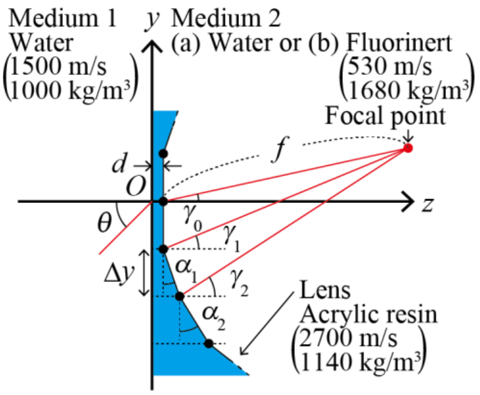

Fig. 2 Schmatic view of the lens design.

plane is flat and corresponds to the y-axis. The radiation surface is discretized in the Δy interval. First, the angle of incidence θ is determined. Lenses are usually designed with $\theta = 0$. However, we design the lens with θ = 45°, which exceeds the critical angle 33.75°. Next, we find the acoustic ray passing through the thinnest part of the lens, *i.e.*, the point where the incident and radiation surfaces are parallel. Substituting $\alpha = 0°$ for Eqs. (3) and (4), to obtain the angle γ_0. For the lens to be z-axis symmetric around the thinnest point, the focal point must be on this acoustic ray. Therefore, the position of the focal point is determined by the distance from the center of the radiation surface as the focal length f. Next, the angle γ_1 is determined with the coordinates of the adjacent discrete point and the focal point. the corresponding α_1 can be calculated with Eqs. (3) and (4). The coordinate of the next discrete point is determined from α_1 and Δy. This procedure is repeated sequentially until the target aperture is reached.

The parameters used in the design are shown in Fig. 2 and the designed lenses are shown in **Fig. 3**. The aperture is 400 mm, the focal length f is 800 mm. Comparing shapes, the lens designed with (b) Water - Fluorinert condition is slightly thicker.

3. Simulation

The sound pressure fields are calculated using the 2-dimensional finite difference time domain method with Yee's algorithm. The caluculated area is 1200 mm × 1600 mm, the discretization length is 1 mm, the total calculation time is 5 ms, and the sampling freqency is 8 MHz. The center of the incidence surface is used as the origin, and a line source is placed at z = -300 mm. A chirp signal (center frequency: 37.5 kHz and bandwidth: 5 kHz) is emitted from the line source. The angle of incidence θ is varied from 0° to 45° at the intervals of 5° by rotating the lens. The sound velocity and the density of each medium are the same as in Fig. 2. Acrylic resin is given attenuation rate 1.36 Np/m.

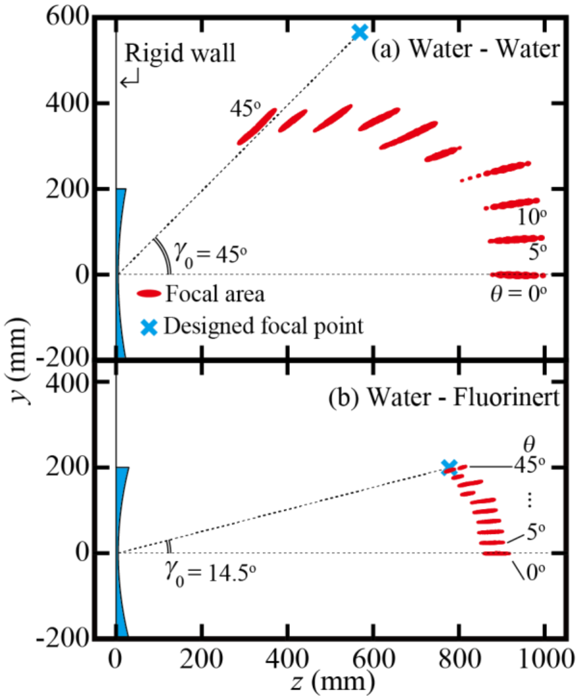

Fig. 3 Lens shapes and focal areas.

The calculated focal areas are shown in Fig. 3. Here, the focal area was defined as the area that shows more than 99% of the maximum value for each lens at each angle of incidence. Since the focal areas are formed even when the angle of incidence θ exceeds the critical angle in both conditions, the wide-angle design is successful. The lens designed with the Water - Water condition shows that the places of the designed focal point and the simulated focal area are not agreed as shown in Fig. 3(a). A strong field curvature is observed. On the other hand, the lens designed with the Water - Fluorinert condition shows that the place of the designed focal point and the simulated focal area are agreed as shown in Fig. 3(b). The field curvature aberration is relatively slight.

4. Conclusion

We designed two lenses using the evanescent field and repropagation. The focusing characteristics of the designed lenses were obtained by simulation. When the medium on the radiation side of the lens was Florinert, the location of the simulated focal area and the designed focal point coincided.

Acknowledgment
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References

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