PRELIMINARY ANALYSIS OF SOUND FIELD CONVERGED BY CONVEX ACOUSTIC LENS FOR INSTALLING IN SMALL AUV'S BOW

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Abstract: *AUVs haves been developed to conduct underwater surveys in unexplored areas such as those around marine volcanoes and in frozen seas that are dangerous and difficult to investigate with manned submersibles. Many AUVs are comparatively small, with various mounted measuring devices; thus, their power supply and mounting space are limited. Under such circumstances, an acoustic lens mounted on the bow of the AUV, was proposed for use as an underwater imaging sonar for obstacle avoidance. Recently, this acoustic lens system has attracted renewed attention due to its fast frame rate, compact size, and low power consumption by utilizing its own refraction effect.*

In this study, we investigated the aberration and converged sound field of a convex acoustic lens for installation in an AUV bow. It was assumed that the lens consisted of solid shell and inner liquid. Aberration was analyzed by the ray tracing method, and converged sound field was computed by the finite difference time domain method. In order to minimize the aberration and maximize the focused sound pressure, material combinations and shell shapes were investigated for optimal lens design. The preliminary analysis results showed that an effective convergence performance was obtained by a shell combining a spherical outer surface and aspherical inner surfaces, and with a material combination of syntactic foam and silicone oil or syntactic foam and fluorinert.

Keywords: *AUV, Underwater imaging sonar, Acoustic lens*

1. INTRODUCTION

AUVs have been developed to conduct underwater surveys in unexplored areas, such as those around marine volcanoes and in frozen seas that are dangerous and difficult to investigate with manned submersibles. Several studies have been conducted using AUV's underwater imaging sonar acoustic lens for obstacle avoidance. Tsukioka et al. produced a spherical lens for AUV mounting and succeeded in actually obtaining images in water [1].

As the acoustic lens has refractive properties, the underwater sonar system using acoustic lens does not need large-scale array and a dedicated signal processing device for beam foaming. Thus, the acoustic lens is useful for real-time processing, miniaturization, and power saving. Recently, it has attracted renewed attention as a method for realizing underwater imaging sonar.

In this study, we investigated the aberration of a designed underwater acoustic lens using the ray tracing method. The lens was assumed to be mounted on the bow of an AUV and its converged sound field was calculated by the finite difference time domain method (FDTD method).

2. INVESTIGATION OF LENS ABERRATION

2.1. Lens shape

It was assumed that the acoustic lens in this study would be used in an AUV underwater imaging sonar system for obstacle avoidance. It was also assumed that the acoustic lens would be mounted on the bow of the AUV, as the bow receives the most water resistance, and it is desirable that its effect be as small as possible. In this study, the surface facing the water is a convex shape (sphere).

In a previous study of spherical lenses, Takano analyzed the converged sound field of a shell-shaped diffusing spherical lens composed of two layers of different mediums by simulation and experiment in a tank [2]. Figure 1 shows a schematic view of a three-layer spherical lens mounted on an AUV bow. Each lens surface is defined S_1, S_2, S_3 and S_4 and each layer's thickness is defined as T_1, T_2 and T_3. This lens is arranged on the shell in a medium that has a sound speed higher than water; internal liquid has a sound speed slower than water. The design of the lens structure sought to eliminate sound waves from the lens edges, which causes spherical aberration.

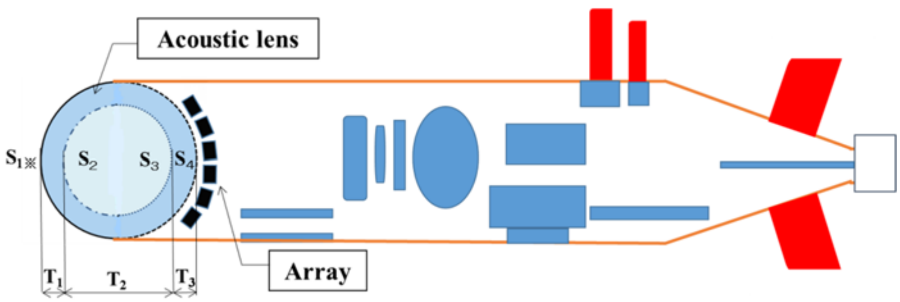


Fig. 1 Schematic view of definition of lens surface and thickness mounting on AUV bow (S_1 becomes the AUV bow; thus, it is a fixed spherical surface).*

2.2. Lens optimization

It is property of spherical lenses that spherical aberration always occurs when sound waves are normally incident to the lens surface. When sound waves are obliquely incident to the lens surface, coma aberration occurs. Both cause blurring of the obtained image. In order to correct these aberrations, ray tracing was performed for lenses of various shapes, and aberrations were investigated. The lens shape was then optimized, and the aberrations minimized. Table 1 shows the constants of the lens medium used. Where c is the sound speed, ρ is the density, Z is the acoustic impedance, γ_2 is the attenuation constant, and n is the refractive index.

Table 1: Constants of lens medium.

Medium	c (m/s)	ρ (kg/m^3)	Z (MP$_a$・s/m^2)	γ_2 (dB/λ)	n
Water	1500	1000	1.500	0.0	1.00
Syntactic foam	2206	700	1.544	0.1	0.68
Silicone oil	990	972	0.962	0.0	1.52
Silicone rubber (RTV-11)	1050	1180	1.239	0.3	1.43
Fluorinert (FC-72)	512	1680	0.860	Unknown (0.0)	2.93

Figure 2 shows the ray tracing results for each lens at incidence angles of 0 and 10 degrees. Lens1 was designed by Takano. As it is composed of spherical surfaces, spherical aberration occurs, and it is evident that the acoustic ray is not converged on the focal point in Fig. 2(a).

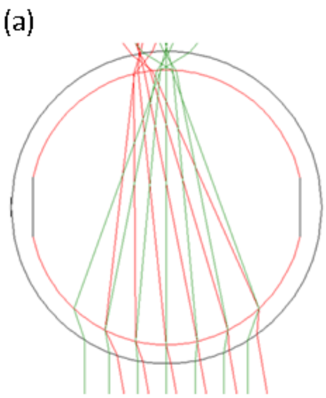
In Lens2, an acoustic impedance matching layer of λ/4 was inserted between the outer shell and inner medium, and the thickness of the outer shell was reduced to decrease transmission loss. As a result, this lens demonstrates improved acoustic converging performance. However, like Lens1, Lens2 is composed of spherical surfaces. Thus, spherical aberration is not corrected. The focal point is formed further away from the lens than that of Lens1 in Fig. 2(b).

Lens3 is composed of S_1 as the spherical surface, and the surfaces S_2-S_4 as the following aspheric surfaces were used to correct the aberration in Fig. 2(c).

$$z = \frac{rx^2}{1+\sqrt{1-(K+1)r^2x^2}} + A \cdot x^4 + B \cdot x^6 + C \cdot x^8 + \mathrm{D} \cdot x^{10} + E \cdot x^{12}$$
$$+\mathrm{F} \cdot x^{14} + G \cdot x^{16} + H \cdot x^{18}$$

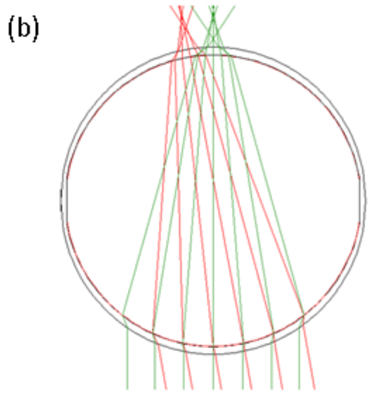
where r is the vertex curvature of the surface (mm^{-1}), and K is the Korenich coefficient. Optimization to minimize aberrations was performed by varying r, K, and A-H in the above equation, and thickness T_1, T_2 and T_3, and aspheric surfaces were obtained.

Lens4 was made by removing the S_3 and S_4, and changing the inner medium to Fluorinert, and the aberrations were also corrected, as shown in Fig. 2(d). This lens had the smallest aberrations at the focal point.



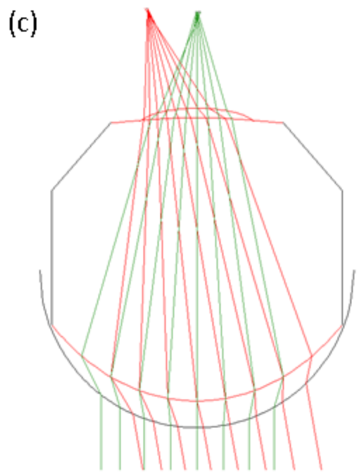
<table><tr><td>Surface</td><td colspan="2">S1</td><td colspan="2">S2</td><td colspan="2">S3</td><td colspan="2">S4</td></tr><tr><td>Radius (m)</td><td colspan="2">0.2</td><td colspan="2">0.176</td><td colspan="2">-0.176</td><td colspan="2">-0.2</td></tr><tr><td>Thickness(m)</td><td></td><td colspan="2">0.024</td><td colspan="2">0.352</td><td colspan="2">0.024</td><td></td></tr><tr><td>Material</td><td>W</td><td colspan="2">SF</td><td colspan="2">SO</td><td colspan="2">SF</td><td>W</td></tr></table>

W: Water, SF: Syntactic foam, SO: Silicone oil



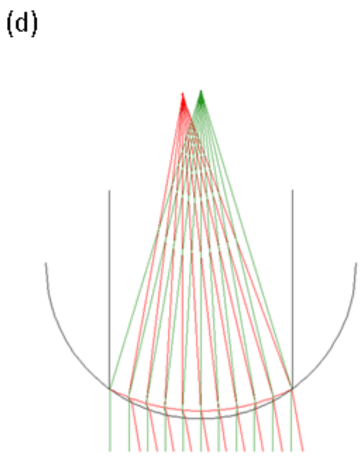
<table><tr><td>Surface</td><td colspan="2">S1</td><td colspan="2">S2</td><td colspan="2">S3</td><td colspan="2">S4</td></tr><tr><td>Radius (m)</td><td colspan="2">0.2</td><td colspan="2">0.195</td><td colspan="2">-0.195</td><td colspan="2">-0.2</td></tr><tr><td>Thickness(m)</td><td></td><td colspan="2">0.01</td><td colspan="2">0.39※</td><td colspan="2">0.01</td><td></td></tr><tr><td>Material</td><td>W</td><td colspan="2">SF</td><td colspan="2">SO</td><td colspan="2">SF</td><td>W</td></tr></table>

W: Water, SF: Syntactic foam, SO: Silicone oil
※value of including 1/4 layer(0.00053m).
Material of 1/4 layer is silicone rubber "RTV-11".



<table><tr><td>Surface</td><td colspan="2">S1</td><td colspan="2">S2</td><td colspan="2">S3</td><td colspan="2">S4</td></tr><tr><td>Radius (m)</td><td colspan="2">0.2</td><td colspan="2">0.206</td><td colspan="2">-0.567</td><td colspan="2">-0.2</td></tr><tr><td>Thickness(m)</td><td></td><td colspan="2">0.034</td><td colspan="2">0.36</td><td colspan="2">0.012</td><td></td></tr><tr><td>Material</td><td>W</td><td colspan="2">SF</td><td colspan="2">SO</td><td colspan="2">SF</td><td>W</td></tr><tr><td>Korenich coefficient</td><td colspan="2">0</td><td colspan="2">-0.38</td><td colspan="2">-85.36</td><td colspan="2">9.41</td></tr></table>

W: Water, SF: Syntactic foam, SO: Silicone oil



<table><tr><td>Surface</td><td colspan="2">S1</td><td colspan="2">S2</td></tr><tr><td>Radius (m)</td><td colspan="2">0.2</td><td colspan="2">0.260</td></tr><tr><td>Thickness (m)</td><td></td><td colspan="2">0.01</td><td>∞</td></tr><tr><td>Material</td><td>W</td><td colspan="2">SF</td><td>FL</td></tr><tr><td>Korenich coefficient</td><td colspan="2">0</td><td colspan="2">-0.54</td></tr></table>

W: Water, SF: Syntactic foam, FL: Fluorinert

Fig. 2 Ray tracing results for (a) Lens1, (b) Lens2, (c) Lens3, and (d) Lens4 at incidence angles of 0 and 10 degrees.

3. ANALYSIS OF CONVERGED SOUND FIELD BY FDTD METHOD

3.1. Setting of FDTD method

Simulations using the FDTD method were performed on the lenses described above, and the converged sound field was analyzed. The analytical domain was two-dimensional on the x-z plane, and a line sound source was arranged at a position 0.01 m from S_1. A burst wave of 500 kHz was radiated from the line sound source, and a plane wave goes forward to the lens. For analysis areas other than the lens and sound source, it was filled with water. The edge of the analysis domain was set so that the reflected wave did not interfere with the sound waves propagating through the lens using the absorption layer and the first order Mur's boundary condition.

3.2. Results of analysis

Figure 3 shows the sound pressure distributions of (a) Lens1, (b) Lens2, (c) Lens3 and (d) Lens4 at normal incidence, respectively. In Fig. 3(b), the focal point of Lens2 is formed more rearward than that of Lens1. Figure 3(c) shows that the focal point of Lens3 was formed more rearward than that of Lens2. In the beam patterns shown in Fig. 4(a), Lens3 has the smallest side lobes compared to other lenses, although the maximum sound pressure at the focal point is lower than that of Lens2. Therefore, the correction of the aberrations contributes to the reduction of the side lobe. Figure 4(b) shows the on-axis characteristics. Lens4 has the largest maximum sound pressure at the focal point. Also as with the sound pressure distribution, the focal point of Lens3 is more rearward than the other lenses.

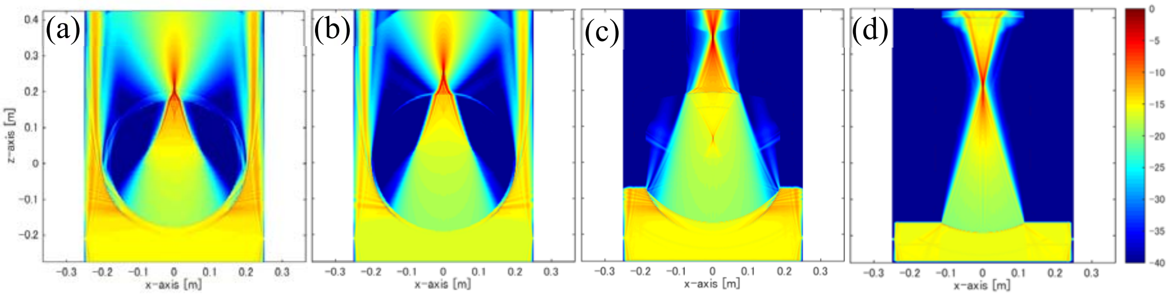


Fig. 3 Sound pressure distribution of each lens at the normal incidence (a)Lens1, (b)Lens2,(c)Lens3, and (d)Lens4.

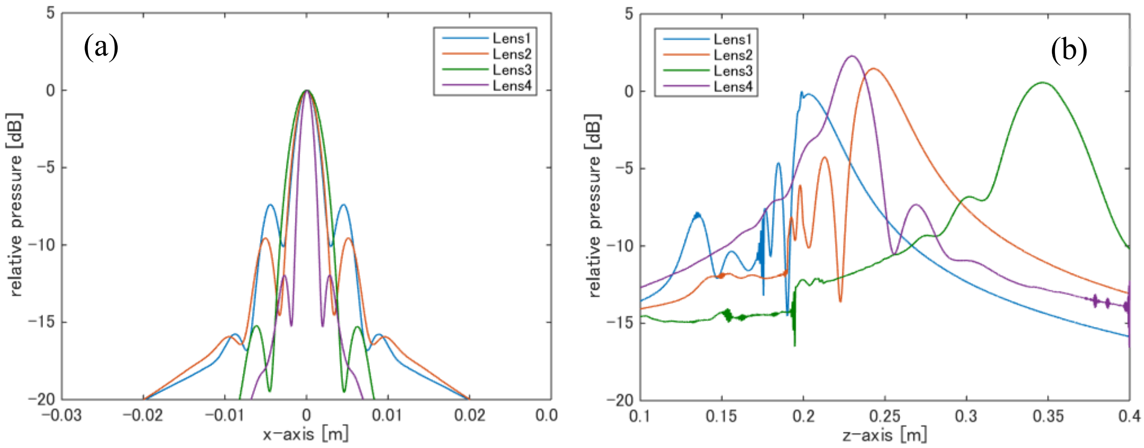


Fig. 4 (a) Simulation results for beam patterns on the horizontal plane at the focal point (normalized by the each peak), and (b) simulation results for on-axis characteristics of the lens (normalized by the maximum sound pressure at the focal point of Lens1).

4. CONCLUTIONS

Compared to the outer-shell diffusion-type spherical lens designed by Takano, it was possible to improve the maximum sound pressure of the focal point by inserting the acoustic impedance matching layer and by thinning the outer shell. By correcting the aberration using an aspherical surface and optimizing the lens, it was possible to suppress side lobes in the beam pattern. The focal points of Lens2, Lens3 and Lens4 were more rearward than that of Lens1.

In a future research, we plan first to attempt to improve sound pressure at the focal point. In the lens of the outer-shell diffusing type lenses, as sound waves are diffused outside the lens, it is impossible to converge all the sound rays of the entire aperture of the lens, resulting in a decrease in focused sound pressure. Like Lens1 and Lens2, Lens3 had a spherical surface S_1, and used a material with high sound speed for the outer-shell. Therefore, the area of the sound rays path through the lens aperture was narrowed to suppress spherical aberration, and thickness was also increased, so that the maximum sound pressure was lower than that of Lens2. In addition, Lens4 did not use the entire aperture. In the near future, we will try to improve the maximum focused sound pressure by determining the ideal material for the lens, and so on.

In addition, in future work we will attempt to secure the angle of view at oblique incidence of sound waves. In both Lens1 and Lens2, the spherical lens was independent of the incident angle of sound waves, the focus sound pressure was the same at all incident angles, and a wide angle of view could be ensured. However, as Lens3 and Lens4 used the aspheric surfaces, they depended on the angle of incidence of sound waves, and the angle of view was narrowed to about 10 degrees. We will also study the design of lenses with a large angle of view.

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