RELATION BETWEEN APERTURE DIAMETER AND INCIDENT ANGLE
OF UNDERWATER ACOUSTIC LENS

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ABSTRACT
A real-time underwater acoustic imaging system is required to check the safety during underwater construction or to survey after underwater construction at port facilities, seawall and so on. Authors have been working on the acoustic lens analysis, lens material examination, lens design and measurement its acoustic fields. It is well known that the aperture diameter and incident angle limitation are very important factors to design a good underwater acoustic lens. An acrylic lenses were fabricated and measured its focused acoustic characteristics to obtain the relation between the aperture diameter and the incident angle.

INTRODUCTION
In port and harbour area, underwater imagines system is required to maintain the safety of port for 24 hours a day. Some types of previous work have been succeeded like DIDSON [1], but authors need a different type 3D acoustic imaging sonar system because we have to do location survey in murky water. Our previous works in ECUA 2006 [2] reported about a refraction index of material and focal characteristics of spherical lens calculated by PE (parabolic equation) method. An acoustic lens system with multi-lens designed by OpTaliX (Optical lens designed software based on geometric ray path) [3] was also reported. The measured acoustic fields behind its lens system almost matched with both calculation results by both OpTaliX and PE [4]. This showed that the OpTaliX had a possibility to design a multi acoustic lens system [5] in water. An acoustic beam width, however, was wider than expected optical beam width. In this paper, a wide view single lens was designed and researched about its acoustic characteristics.

WIDE VIEW SINGLE LENS
A wide view single lens that allowed geometric un-sharpness is less or equal 0.55 mm in diameter was designed when an entire visual angle was up to 8.0 degrees. The lens material is acrylic resin and refraction index is 0.532 at a temperature of 18.0 deg. [6]. The effective and real diameter of lens was 150 mm and 156 mm, respectively. If an entire visual angle is up to 8.0 (image diameter 21.6 mm equivalents), geometric un-sharpness is less or equal 0.55 mm (Fig.1). In this figure, red curve shows the designed lens. The red, green, blue, pink and light blue straight lines show geometric ray path at incident angle of 0.0, 2.0, 3.0 and 4.0, respectively. In this figure, diameter of curve surface in focal plane is 21.6 mm. The first and second surface of lens is given by the next equation, respectively.

\[ Z_{d1}(Y) = \frac{Y^2/(-364.6)}{1 + \sqrt{1 - (1 + (-16.0))Y^2/(-364.6)^2}} + (-2.052 \times 10^{-8}) \]

\[ Z_{d2}(Y) = \frac{Y^2/84.92}{1 + \sqrt{1 - (1 + (-0.1030))Y^2/(84.92)^2}} + (1.927 \times 10^{-8})Y^4 \]
The acoustic fields behind the designed lens were calculated by PE method (Fig.2) to investigate whether or not to match ray path results and PE calculation results. Figure2 (a)-(c) shows the calculation results at incident angle 0.0, 2.0 and 4.0 deg. respectively. It is clearly shown that the focal point gradually shifted to upper position with an increase of incident angle. The maximum focal points coordinate in each Fig.2 (a)-(c) shifted plus vertical and minus horizontal axis direction with an increase of incident angle. The focal point in the figure also agreed with ray path results. In other words, the ray diagram of the acoustic lens design corresponds to PE method results at all incident angles up to 4.0 deg.

A manufactured Lens designed by OpTaliX was made from acrylic resin and is shown in Picture 1. The left photo shows the first surface S1 and right photo shows the second surface S2 mentioned above.

Figure 1. Geometry of wide view single lens.
Red curve: lens
Straight line is incident angle deg: red=0.0, green=1.0, blue= 2.0, pink=3.0, light blue=4.0.

Figure2. Calculated results using PE method. From top to bottom, incident angle is changed as follows
(a) 0.0 deg. (b) 2.0 deg. (c) 4.0 deg.
**Measured acoustic field behind lens**

Acoustic fields behind the designed lens were measured in water tank (Fig.3). A 1 MHz burst sound pulse with 10 cycles was projected, passed thorough the acoustic lens, and received by a hydrophone. The hydrophone mounted on tri-axial precise moving apparatus measured the acoustic fields in each XY, XZ and YZ plane.

The source was fixed at a coordinate origin, the lens centre was adjusted to X=Z=0.0 and Y=0.15 m. The acoustic fields were measured at a source angle 0.0, 4.0 and 8.0 deg. respectively. The 8.0 deg. is just for comparison of other one, in this case. Note that the source tilt angle was substituted for the lens rotation by a rotating shaft system.

Some results at XY plane were shown in Fig.4. Fig4-(a) shows the result of normal incident. Almost of all sound go through the lens centre, it means no refraction. Fig4-(b) is in case of incident angle 0.4 deg. This figure shows that the sound almost propagated along the Y-direction but tiled a little upward. In the case of incident angle of 0.8 deg is shown in Fig4-(c). The sound tilted much more than in case of 0.4 deg.

![Figure 3. Aspheric lens measurement system](image-url)
CONCLUSIONS

Authors reported about an acoustic lens design for 3D acoustic imaging sonar system in port and harbour area. In this paper, a margin of acoustic beam width was investigated to introduce an acoustic lens design method using OpTaliX. A wide view single lens that allowed geometric un-sharpness is less or equal 0.55 mm was designed when an entire visual angle was up to 8.0 deg. The acoustic fields behind the lens were calculated by PE method. The designed lens was made from an acrylic resin. Acoustic fields behind it were measured in water tank.

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