CO-KR-3**Shape optimization of acoustic lens beamformers***

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Abstract

Shape optimization of an acoustic lens system is presented by using the hybrid approach that employs geometric acoustics as well as wave acoustics. Geometric acoustics is used to obtain the rays of acoustic wave from the wave source to the exit plane that is placed right after the final lens. Snell's law is used to calculate paths of rays and transmitted pressures through lenses are calculated by multiplying the incident wave with transmission coefficients. Diffraction of the wave is not considered in the geometric acoustics. Two methods are used to obtain the acoustic pressure distribution at the pressure field. The first and second method uses the Kirchhoff integral theorem and the Boundary Element Method (BEM) to calculate the acoustic pressure distribution from the exit plane to the image plane, respectively; the pressure magnitude at the focal point as well as those at side lobes can be calculated. A lens design problem is formulated as the optimization problem that maximizes the pressure magnitude at the focal point. The effectiveness of the proposed approach is verified by showing a design example for a spherical lens system.

Key words: Acoustics lens system; Shape optimization; Geometric acoustics; Wave acoustics; Kirchhoff integral theorem; BEM

1. Introduction

Due to the very limited range of visibility in underwater environment, the use of an optical camera system is not available to obtain underwater images even if artificial light is supplied. An acoustic camera, a high resolution ultrasound imaging device [1], is used as an alternative to produce underwater image sequences. It can be mounted on an autonomous underwater vehicle or carried by a diver to observe potentially harmful objects.

Two types of acoustic cameras are widely used: an acoustic camera array and an acoustic lens camera. The acoustic camera array creates an image by using a set of phased microphones. The signals from an array of microphones are phase-synchronized and summed to form a single signal from the entire array. An image of the intensity of the sound source distribution throughout a field of view of the camera is mapped out [2]. This camera can be used to create an ultrasonic image with a sound source in the far-field. However, the main disadvantage of using an acoustic camera array is that data from multiple microphones must be collected, increasing the complexity of the electronics and it is limited in a frequency range [3]. The acoustic lens cameras have the advantage of using no power for beamforming and ease to transmit and receive from the same beam [4].

In this investigation, an acoustic lens camera system is optimized to obtain acoustic pressure with higher intensity on

the focal region of the camera. To this end, the acoustic pressure field is calculated by using the hybrid analysis approach by K. Fink [5, 6] among other existing analysis method [7, 8, 9 and 10]. Initial designs of acoustic lens can be obtained based on the geometrical acoustics (or the ray theory). However, it is difficult to evaluate the convergence gain of the focused beam in the lens using the ray theory. While the wave theory is more accurate in pressure field calculation than the ray theory, very complicated calculation is required to deal with transmission of waves through different mediums. To deal with this, the hybrid method in [5, 6] is used in this study where the geometrical acoustics is applied from the source to the exit plane of the lenses and the wave acoustics is used from the exit plane to the image plane.

The geometries of spherical lenses for thick and dual-thin-lens systems are optimized to show the effectiveness of the proposed approach.

2. Hybrid analysis approach

A hybrid method is combined the geometrical acoustics with the wave acoustics. Geometrical acoustics is applied from a source to the interface of the lens, and wave acoustics is applied in the image space. Geometrical acoustics, realized by ray-tracing, calculate the complex pressures on the final lens interface. Wave acoustics uses those pressures as boundary values in order to solve the Kirchhoff integral, which gives the pressure at points in the focal region.

Geometrical acoustics or ray acoustics is the equivalent principle of geometrical optics applied in acoustics. Geometrical acoustics describes sound propagation in terms of rays. So that, the laws governing sound's behavior can be described geometrically using ray theory.

In this paper, the Snell's law is used to describe the relationship between the angles of incidence and refraction, when referring to waves passing through a boundary between two different medium.

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{c_1}{c_2} \quad (1)$$

with each θ as the angle measured from the normal, c as the velocity of acoustic ray in the respective medium (SI units are meters per second, or m/s) and ρ as the density of the respective medium.

And the transmission coefficient from one medium to the other medium as [11]:

$$T = \frac{2\rho_2 c_2 \cos \theta_1}{\rho_2 c_2 \cos \theta_1 + \rho_1 c_1 \cos \theta_2} \quad (2)$$

Acoustic waves are longitudinal waves that exhibit phenomena like diffraction, reflection and interference. Acoustic waves travel with the speed of sound which depends on the medium they are passing through.

2.1 Using the Kirchhoff integration method:

The acoustics waves are applied to calculate the pressure at a point in the pressure field by using Kirchhoff integration method. Figure 1 shows that, at focal region the complex pressure was calculated by using Kirchhoff integral at points in the pressure field.

$$P(x, y) = -\frac{ik_x}{2\pi} \iint P(s) \frac{e^{ikR(s, x, y)}}{R^2(s, x, y)} s ds d\phi \quad (3)$$

where $P(x, y)$, $P(s)$, k , R and e^{ikR}/R^2 refer to the complex pressure at point P_2 in image space, the complex pressure at point P_1 on the exit plane, the wave number, the distance between the point P_1 on the exit plane and the point P_2 in image space and the point-source Green's function, respectively.

Fig. 1 – Configuration for the Kirchhoff integral theorem

We can approximate the integral equation above as

$$P(x, y) = -\frac{ik_i x}{2\pi} \iint P(s) \frac{e^{ik_i R(s, x, y)}}{R^2(s, x, y)} s ds d\phi \quad (4)$$

In this paper, we use Romberg Integration Method to numerically evaluate this integral.

2.2 Using the Boundary Element Method:

Fig. 2 – Configuration for the Boundary Element Method

The complex pressure was calculated by using BEM at an arbitrary point inside the image space as follows:

$$p_i = \sum_{j=1}^N \int_{S_j} p \frac{\partial g}{\partial \hat{n}} dS - \sum_{j=1}^N \int_{S_j} g \frac{\partial p}{\partial \hat{n}} dS \quad (5)$$

where p_i , p , g and S_j refer to the complex pressure p at an arbitrary point inside the image space, the complex pressure on all boundary elements, the Green's function and the surface of element j on the boundary, respectively.

3. Optimization formulation

In this paper, we propose an optimal design method for the shapes of the acoustic lens that leads to a prescribed pressure distribution in the fluid, and especially a pressure concentration at the desired focus point.

The optimization problem is formulated as:

Maximize Pressure at focal point

Subjected to $R_L \leq R \leq R_U$

$t_L \leq t \leq t_U$

where R , t refer to the radius, thickness of the lens, respectively. The flow chart of the optimization procedure is shown in Fig.

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Fig. 3 - Flow chart of the optimization procedure

4. Design example

Thick lens is designed for sonar device operating at 100 kHz. The shell of the lens was made of ABS and the sound speed of the shell is 2040 m/s [11]. The fluid mix is used in the thick lens is 71% FS5, 29% FC72, it has sound speed and density refer to 778.79 m/s and 1870 kg/m³, respectively.

Fig. 4 - The thick lens system

The optimized values for design variables are listed in Table 1.

Table 1 – Design variables before and after optimization

Design value	Initial [mm]	Optimized [mm]
R_{out}	132.5	113.5
R_{in}	107.5	100.15

Fig. 5 - Focal depth

Figure 5 shows that the pressure distribution along the center line of the acoustic field (star line: initial pressure distribution, solid line: optimized pressure distribution). As was intended by the use of the objective, the pressure at the focal point is increased. Nonetheless, the pressure distribution shows fluctuating behavior, which should be resolved in a future research. Figure 6 shows the acoustics pressure field near the focal point.

Fig. 6 - The acoustics pressure field

5. Conclusions

Design optimization of an acoustic lens camera was presented based on the hybrid analysis method that uses both geometrical acoustics and wave acoustics. The geometries and aperture sizes were used as design variables to have maximized pressure intensity at focal points with frequency sound waves in 100 kHz and 1 MHz. The benefits of the use of the acoustic lens system are simple structure, low cost, and simple electronics for data acquisition and processing. Future works in this area involve investigations on optimization formulations to consider more acoustic responses for clearer underwater images and more general parameterization of lens geometry.

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