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Optimal Design of an Annular 1-3 Piezocomposite High Intensity Focused Ultrasound (HIFU) Transducer of a Concave Geometry for Medical Treatment

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1. Introduction

A HIFU transducer composed of several phased array elements has an advantage of dynamic focusing. However, the phased array is likely to produce a grating lobe or a considerably large sidelobe, which can deteriorate the performance of the transducer. Thus, the research to suppress the grating lobe is necessary for accurate operation of the array transducer [1]. Various works have been carried out to address this issue. One of the representative works is to space the elements of the array at a distance of a half-wavelength [2].

In this study, after deriving an equation to describe the sound field of a concave annular high intensity focused ultrasound (CA-HIFU) array transducer, we designed the structure of the transducer to achieve dynamic focusing at desired points along the normal axis of the transducer while maintaining the level of the grating lobe within a certain limit. In the process, we analyzed the relation between the grating lobe and the number of channels. Based on the relation, kerf widths of the CA-HIFU transducer were optimized using the OptQuest-Nonlinear Programming algorithm to minimize the level of the sidelobe including the grating lobe while focusing the ultrasound beam at a desired point.

2. Theoretical Acoustic Field Analysis

Fig. 1(a) illustrates the schematic structure of the CA-HIFU array transducer considered in this study comprising several concentric annuli. In order to facilitate the sound field analysis, the concentric annuli were replaced with multiple piston sources distributed on the hemisphere as shown in **Fig. 1(b)**. The overall concave annular transducer has an inner diameter of 15 mm and an outer diameter of 30 mm.

An analytical equation was derived to express the eventual sound pressure field radiated by the CA-HIFU transducer as Eq. (1), where $H_a(\theta, \varphi)$ is a directional factor of the array transducer composed of point sources in Eq. (2) [3]. $p_p(r, \theta, \varphi, t)$ in Eq. (3) is the sound pressure of a piston source, and $B_{nm}(h)$ in Eq. (4) is a unit step function expressing the baffled effect of the hemisphere. ρ_0 denotes density; c, speed of sound; U_0, particle velocity; a_p, radius of the piston source; J_1, 1^{st} order Bessel function in the equations.

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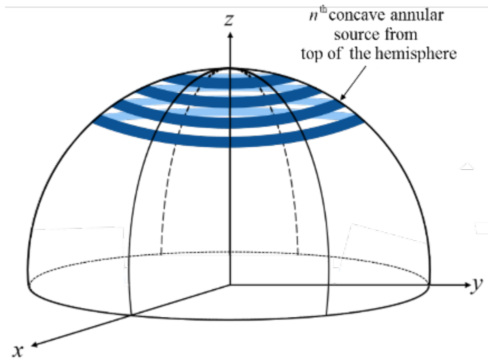
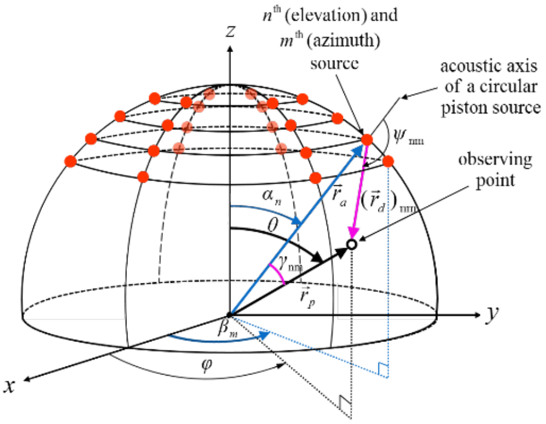


(a) array of concave annular sources



(b) array of circular piston sources on a hemisphere

Fig. 1 Configuration of the CA-HIFU transducer.

$$p(r,\theta,\phi,t) = H_a(\theta,\phi) \times p_p(r,\theta,\phi,t) \times B_{nm}(h) \qquad (1)$$

$$H_a(\theta,\phi) = \frac{H_1(\theta,\phi)}{\max(H_1(\theta,\phi))}$$

$$\text{, where } H_1(\theta,\phi) = \left| \sum_{m=1}^{M}\sum_{n=1}^{N} \frac{|(\vec{r}_d)_{nm}|_{\theta=0}|}{|(\vec{r}_d)_{nm}|} e^{-i\vec{k}((\vec{r}_d)_{nm} - (\vec{r}_d)_{nm}|_{\theta=0})} \right| \qquad (2)$$

$$p_p(r,\theta,\phi,t) = \sum_{m=1}^{M}\sum_{n=1}^{N} \frac{i}{2}\rho_0 c U_0 \frac{k a_p^2}{|(\vec{r}_d)_{nm}|}\left[\frac{2J_1(k a_p \sin\psi_{nm})}{k a_p \sin\psi_{nm}}\right] e^{i(\omega t - \vec{k}\bullet(\vec{r}_d)_{nm})} \qquad (3)$$

$$B_{nm}(h) = 1 \text{ if } h > 0 \text{ or } 0 \text{ if } h \le 0 \text{, where } h = -\frac{|\cos\psi_{nm}|}{\cos\psi_{nm}} \qquad (4)$$

The sound pressure distribution calculated with the equation was compared with that from the finite element analysis of the same transducer, which confirmed the validity of the equation.

3. Sound Field Analysis of the CA-HIFU Array Transducer

The CA-HIFU array transducer in this work has a geometric focal point at 40 mm from the zenith of the hemisphere. We want to move the focal point dynamically to the distance as close as 30 mm from the zenith by applying proper phase difference to the concentric annular channels. During the process, the level of sidelobes or the grating lobe should not go over a certain limit.

It is well known that the generation of grating lobes can be suppressed if the interval between the channels in an ultrasound array is shorter than a wavelength. Based on this idea, the sound pressure from the transducer was calculated with Eq. (1) in relation to the number of channels. **Fig. 2** shows that the grating lobe exists only when the number of channels is less than sixteen and the level of the grating lobe decreases as the number of channels increases. It means that we can suppress the grating lobe by increasing the number of channels.

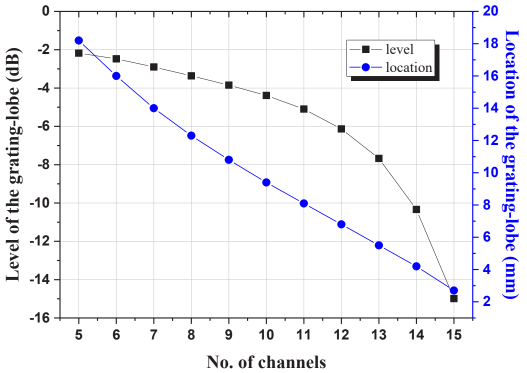


Fig. 2 Variation of the level and location of the grating lobe in relation to the No. of channels.

4. Structural Optimization of the Transducer

Based on the results in Fig. 2, we optimized the kerf widths of the transducer to meet the following requirements when focusing at 40 mm.

Objective function: Minimize the sidelobe level
Constraints:
1. 0.95M ≤ Location of the mainlobe ≤ 1.05M
, where M is the desired dynamic focal point
2. Max. sidelobe level ≤ -12.0 dB

The optimization was carried out for two design cases: (1) the equal area structure by setting the area of all the channels identical and (2) the equal angle structure by setting the width of all the channels identical.

As a result of the optimization, the smallest number of channels that satisfied all the constraints turned out to be twelve for the equal area structure and eleven for the equal angle structure. The transducers having the structure optimized for focusing at 40 mm were tried to focus the ultrasound beam at 30 mm as well. The maximum sidelobe levels when focusing at 40 mm and 30 mm were -13.3 dB and -14.1 dB for the equal area structure while -12.3 dB and -13.2 dB for the equal angle structure, respectively, as shown in **Fig. 3**.

Of the two structures, the equal angle structure is concluded to be the better model of the CA-HIFU transducer because its smaller number of channels can provide higher ease in real fabrication of the transducer. **Table I** shows detailed kerf widths for the equal angle structure of the transducer.

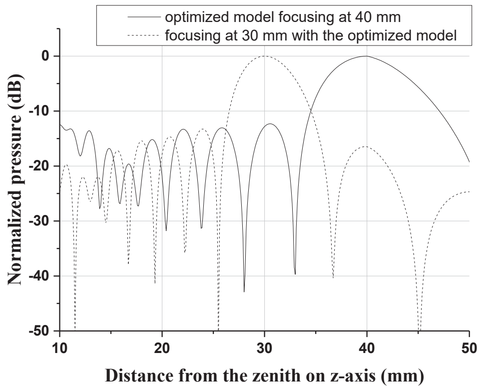


Fig. 3 Normalized sound pressure distribution of the optimized model when focusing at 40 and 30 mm.

Table I The optimized dimension of kerf widths.

Kerf No.	Kerf width (μm)	Kerf No.	Kerf width (μm)
1st	46	6th	65
2nd	186	7th	59
3rd	144	8th	41
4th	106	9th	200
5th	80	10th	71

5. Conclusion

The structure of the CA-HIFU array transducer was optimized to enable geometric and dynamic focusing while satisfying the sidelobe level constraints.

Acknowledgment

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