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Measurement of Pressure Distribution on Focusing Source Using a Small Reflector

小反射体を用いた集束音源の音圧分布の測定

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1. Introduction

The pressure distribution on a focusing source is significant for predicting its field[1]. Even a needle type hydrophone cannot be used for the distribution measurement for a high frequency sound source because of the large size. In this study, the measurement of the pressure distribution only with a small reflector is presented using the concept of time reversal and transducer reciprocity.

2. Theory

2.1 Time reversal

Since the wave equation in lossless liquid contains only a second-order time-derivative operator, the identical equation holds for a negative time.

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} = \nabla^2 p - \frac{1}{c^2}\frac{\partial^2 p}{\partial(-t)^2} = 0\,. \qquad (1)$$

In **Fig. 1**, when a pressure is known on surface S_0, the pressure on surface S can be obtained using the Green's function of the wave equation in a free field. By the principle of time reversal, the pressure distribution on surface S_0 is derived from the pressure on surface S by using a complex conjugate of the same Green's function[2].

$$P_0(\boldsymbol{r}_0) = -\frac{1}{4\pi}\iint_{S} P_S(\boldsymbol{r})\frac{\partial G^*}{\partial z}dS$$

$$\approx j\frac{k}{2\pi}\iint_{S} P_S(\boldsymbol{r})\frac{\exp(jk|\boldsymbol{r}-\boldsymbol{r}_0|)}{|\boldsymbol{r}-\boldsymbol{r}_0|}dS\,. \qquad (2)$$

2.2 Transducer reciprocity

The vibrational velocity of the transmitting transducer is proportional to the electric driving current I. Therefore,

$$P_S(\boldsymbol{r}) \propto I\iint_{S_0}\frac{A(\boldsymbol{r}_0)}{|\boldsymbol{r}-\boldsymbol{r}_0|}\exp(-jk|\boldsymbol{r}-\boldsymbol{r}_0|)dS\,, \qquad (3)$$

where $A(\boldsymbol{r}_0)$ is the coefficient to define the sensitivity distribution on the transducer. When the reflection of this pressure from a small reflector is received with the same transducer, the receiving voltage $E(\boldsymbol{r})$ is expressed by

$$E(\boldsymbol{r}) \propto P_S(\boldsymbol{r})\iint_{S_0}\frac{A(\boldsymbol{r}_0)}{|\boldsymbol{r}-\boldsymbol{r}_0|}\exp(-jk|\boldsymbol{r}-\boldsymbol{r}_0|)dS\,. \qquad (4)$$

Equations (3) and (4) lead to

$$P_S(\boldsymbol{r}) \propto \sqrt{E(\boldsymbol{r})I}\,. \qquad (5)$$

Hence $P_S(\boldsymbol{r})$ in eq. (2) can be replaced by $\sqrt{E(\boldsymbol{r})}$.

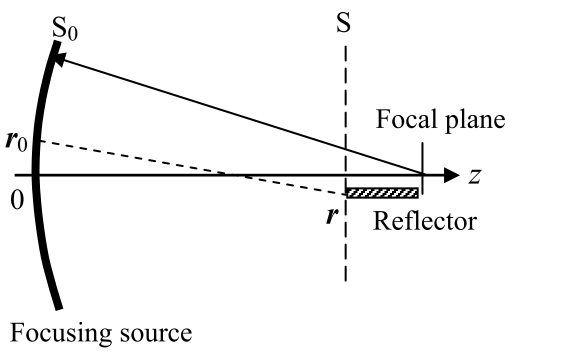

Fig.1 Arrangement of reflector in focused field.

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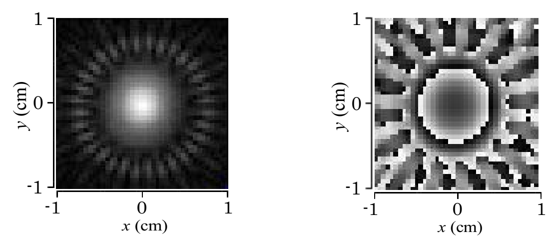
3. Experiment

3.1 1.9-MHz focusing source

The measurement of the on-source pressure is examined for a 40-mm radius focusing transducer of 1.9 MHz, whose focal length is 85 mm. The electrode of this transducer is apodized in a 16 point star-shape for realizing a Gaussian beam[3,4]. A 20 cycle burst wave is detected with a needle type hydrophone of 1 mm diameter located on the plane of z=66 mm. The hydrophone is two dimensionally scanned with an interval of 0.5 mm in a square of 20×20 mm^2. The output voltage E of the transducer detecting the reflected sound from the hydrophone is also measured. The amplitude and phase are obtained through an FFT of the received waveform.

The two-dimensional mapping result for the pressure on the hydrophone placed at z=66 mm is shown in **Fig. 2** in gray scale. Small side lobes of 32 pieces are found in amplitude. In the same area,



(a) amplitude (b) phase

Fig. 2 Distribution of $P_S(\boldsymbol{r})$ of 1.9-MHz focusing source detected with needle type hydrophone.

the phase alternately changes by π rad in the circumferential direction. The pressure on the source calculated with eq. (2), shown in **Fig. 3**, has the same profile as the 16 point star-shape electrode.

On the other hand, $E(\boldsymbol{r})$ is obtained as shown in **Fig. 4**. **Figure 5(a)** shows the pressure amplitude distribution calculated with $\sqrt{E(r)}$ derived from these data. Since the reflected sound is insensitive to π rad phase difference, π rad is alternately added to the phase derived from Fig. 4(b) at the side robe positions. The electrode pattern is not clear in Fig. 5(a). When Fig. 2(b) is employed as the phase of $\sqrt{E(\boldsymbol{r})}$, the star shape is clearer as shown in **Fig. 5(b)**. Thus the precision of phase of $\sqrt{E(\boldsymbol{r})}$ is significant for obtaining $P_0(\boldsymbol{r}_0)$.

3.2 18.6-MHz focusing source

The present method is also examined for the high frequency focusing source of 18.6 MHz, which consists of a $LiNbO_3$ plate and synthetic silica lens[5]. The curvature radius of the lens is 8 mm and the focal length in water is 10.65 mm. A 32 point twisted star-shape electrode is employed for realizing a Gaussian beam. A thin steel rod of 0.1 mm diameter located on the plane of z=8.65 mm is used for the reflector. The rod moves two dimensionally with an interval of 0.05 mm in a square of 2×2 mm^2. **Figure 6** shows the amplitude and phase of $\sqrt{E}$. No side lobe is found, but the phase reveals a complicated distribution in the small amplitude region. When a theoretical phase value in a spherical wave is employed in this small signal region, the on-source pressure distribution is obtained as shown in **Fig. 7**. The calculated pressure of the dotted curve in Fig. 7(b) is approximated by a Gaussian distribution as intended by apodizing the electrode.

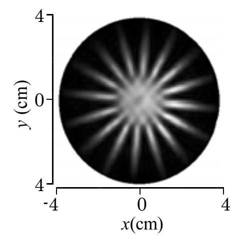
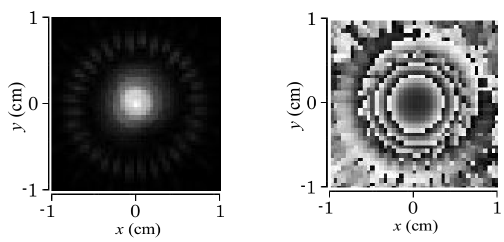
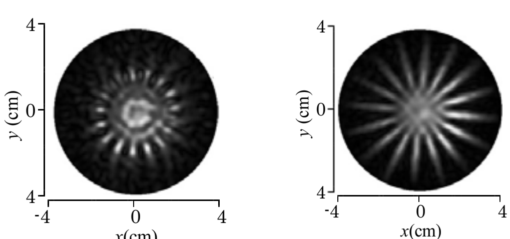


Fig. 3 Estimated $|P_0(\boldsymbol{r}_0)|$ from data of Fig. 2.



(a) amplitude (b) phase

Fig. 4 $E(\boldsymbol{r})$ obtained for 1.9-MHz focusing source.



(a) result using phase in Fig. 4(b)
(b) result using phase on Fig. 2(b)

Fig. 5 Estimated $|P_0(\boldsymbol{r}_0)|$ from amplitude data in Fig. 4 together with different phase data.

4. Conclusion

A convenient method for estimating the pressure distribution on the transducer by obtaining the time reversal of the square root of the output voltage from a transducer which merely receives the reflected wave from a small reflector was presented. This method is weak to fields containing π rad phase jumps. A high sensitivity of the transducer is necessary for the precise estimation.

References

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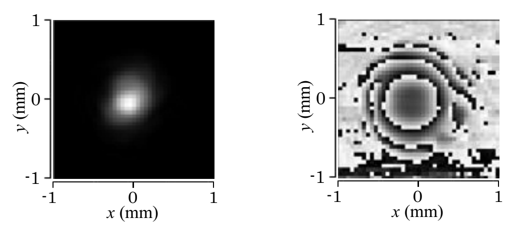
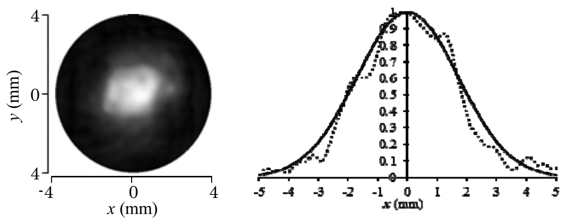


(a) amplitude (b) phase

Fig. 6 $E(\boldsymbol{r})$ obtained for 18.6-MHz focusing source.



(a) amplitude
(b) comparison with Gaussian on x-axis

Fig. 7 Estimated $|P_0(\boldsymbol{r}_0)|$ for 18.6-MHz source.