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Articles

Development of a Divided Transducer Type Ultrasound Source System for Hydrophone Calibration

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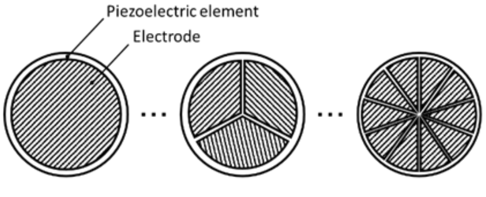
I. Introduction

In recent years, the use of high intensity ultrasound has increased in medical fields. High intensity focused ultrasound (HIFU), apparatus for sonoporation etc. are examples. Therefore, it is necessary to develop a tough hydrophone capable of measuring a high intensity ultrasonic acoustic field 1) and a high intensity ultrasound source to calibrate the tough hydrophone considering the nonlinear acoustic characteristics. In the process of calibrating the tough hydrophone, the membrane type hydrophone used as the primary standard hydrophone should be absolutely calibrated using high intensity plane wave. However, it is difficult to achieve both high intensity and plane wave simultaneously. Therefore, much lower intensity ultrasound than that in therapeutic application is used for actual calibration. In the previous study, our laboratory succeeded in improving the transmission sensitivity by placing a cylindrical acoustic waveguide at the focal position of a spherical transducer with large aperture size. However, the ultrasound intensity was not sufficient.2, 3)

We thought this was due to decrease in input impedance caused by increase in the area of the piezoelectric transducer. However, we could not determine whether to prioritize the maximum input power or the maximum applied voltage. In this study, we propose a divided transducer type ultrasound source with the transducer divided as shown in ***Figure 1*** and report the results of computer simulation based on Mason's equivalent circuit and the F-parameter matrix.



(a) One division (b) Three divisions (c) Ten divisions

Fig.1 Examples of dividing a PZT transducers

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II. Experimental Methods

2-1. System of divided transducer type ultrasound source

Figure 2 shows that the block diagram of divided transducer type ultrasound source system proposed in our study. In this system, a large-area piezoelectric transducer is divided into equal parts, and the output acoustic wave from the each transducer pieces is converged by an acoustic lens and input into a cylindrical acoustic waveguide to form a high intensity plane wave ultrasound field.

The transmission circuit of this system was developed by Associate Professor Shigeru Igarashi in the Polytechnic University. [2, 3]

2-2. Mason's equivalent circuit

Mason's equivalent circuit is one of the equivalent circuit representations to make it easier to understand the vibration phenomenon of piezoelectric transducers, their characteristics, and design. [4]

In this study, we considered the equivalent circuit of a piezoelectric transducers with thickness longitudinal vibration, assuming that the transducer is used for a divided transducer type ultrasound source system.

Equations (1) show the piezoelectric equations.

$$\left.\begin{aligned} T_3 &= c_{33}{}^{E} S_3 - e_{33} E_3 \\ D_3 &= e_{33} S_3 + \varepsilon_{33}{}^{S} E_3 \end{aligned}\right\} \qquad (1)$$

In these equations, T_3 shows stress in the thickness direction, S_3 shows strain in the thickness direction, E_3 shows electric field between electrodes, D_3 shows electric flux density, c_{33}^{E} shows elastic stiffness at constant electric field, c_{33}^{S} shows dielectric constant at constant strain, ε_{33}^{S} shows piezoelectric stress constant.

Mason's equivalent circuit derived from Equations (1) is shown in ***Figure 3***. [4, 5]

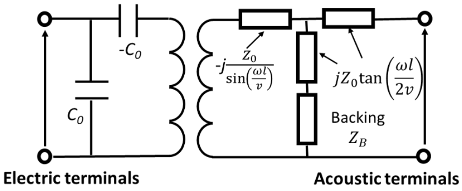


Fig.3 Mason's equivalent circuit for piezoelectric transducer

2-3. F-parameter matrix

The equation and equivalent circuit of the F-parameter matrix based on Mason's equivalent circuit derived in the previous section are shown in Equation (2) and ***Figure 4***.

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \frac{1}{\phi Q}\begin{bmatrix} 1 & j\frac{\phi^2}{\omega C_0} \\ j\omega C_0 & 0 \end{bmatrix} \begin{bmatrix} cos\left(\frac{\omega l}{v}\right) + jz_b\, sin\left(\frac{\omega l}{v}\right) & Z_0\left\{z_b cos\left(\frac{\omega l}{v}\right) + jsin\left(\frac{\omega l}{v}\right)\right\} \\ \frac{j\, sin\left(\frac{\omega l}{v}\right)}{Z_0} & 2\left\{cos\left(\frac{\omega l}{v}\right) - 1\right\} + jz_b\, sin\left(\frac{\omega l}{v}\right) \end{bmatrix} \qquad (2)$$

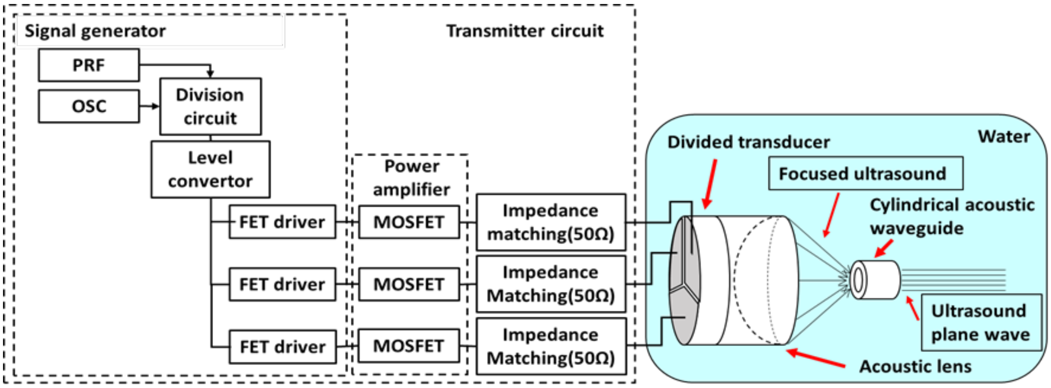


Fig.2 Block diagram of divided transducer type ultrasound source system

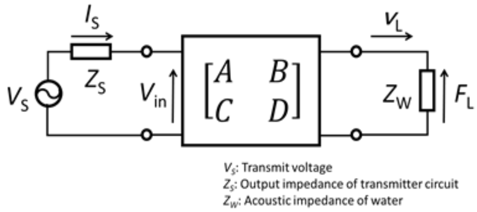


Fig.4 Equivalent circuit of an ultrasound source system using F-parameter matrix.

In this study, Equation (3) for the input impedance and Equation (4) for the stress (pressure) for computer simulation were derived from the equivalent circuits in ***Figures 3 and 4***.

$$Z_{in} = \frac{AZ_W+B}{CZ_W+D} \tag{3}$$

$$F_L = \frac{V_S Z_W}{Z_S(CZ_W+D)+AZ_W+B} \tag{4}$$

III. Results and discussions

Computer simulations on a divided transducer type ultrasound source system were performed using MATLAB (MathWorks).

Figures 5 and 6 show the frequency characteristics of the input resistance (real pat of impedance) and input reactance (imaginary part of impedance) of the divided transducer. ***Figure 7*** shows the relationship between the number of parts of the divided transducer and the input resistance (reactance is nearly equal with 0 Ω) at the anti-resonance frequency (1.1 MHz). As results, the input resistance of the ultrasound source system increased as it was divided into smaller pieces. Input resistance (reactance is nearly equal with 0 Ω) of transducer was similar with the output impedance (resistance) of the transmitter circuit (50 Ω) when it was divided into three parts. ***Figure 8*** shows that the irradiated acoustic pressure by one transducer piece was the highest when the transducer was divided into three pieces. However, ***Figure 9*** shows the total acoustic pressure of all the divided transducer pieces increased as the

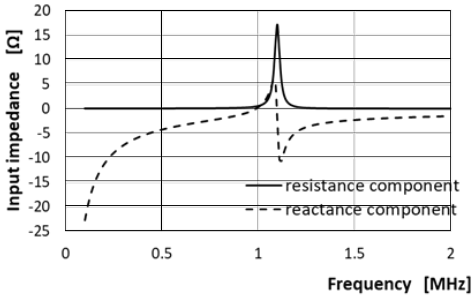
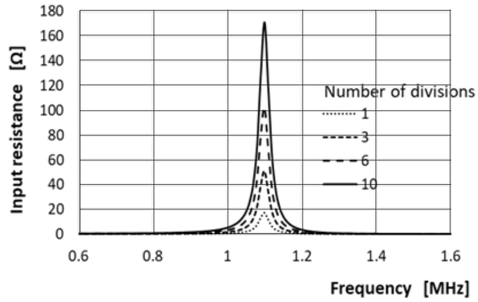
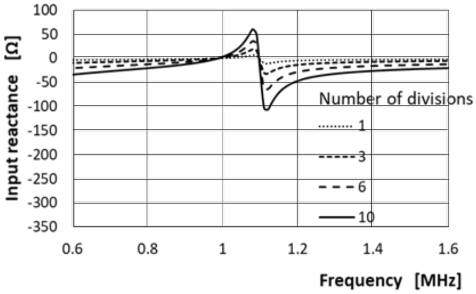


Fig.5 Frequency characteristics of the input impedance (resistance and reactance) of non-divided transducer.



(a) Resistance component of divided transducer



(b) Reactance component of divided transducer

Fig.6 Frequency characteristics of the input resistance and input reactance of each divided transducer

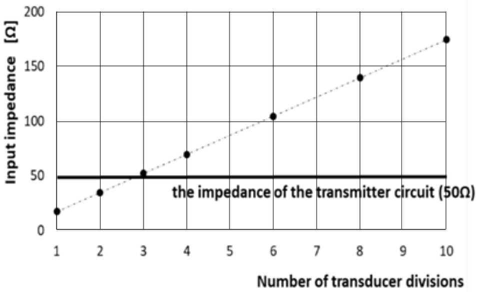


Fig.7 Relationship between the number of parts of the divided transducer and the input impedance (equal with input resistance) at the anti-resonance frequency (1.1 MHz).

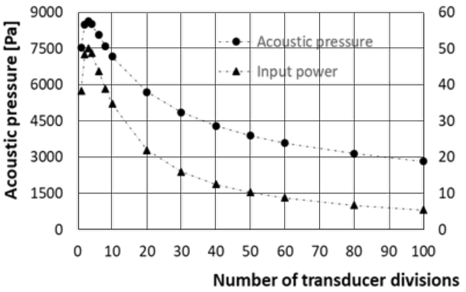


Fig.8 Relationships between the number of pieces of the divided piezoelectric transducer and acoustic pressure by one piezoelectric transducer piece, input power

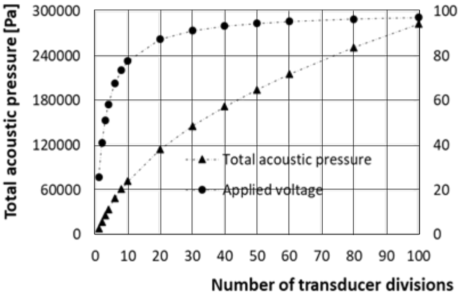


Fig.9 Relationships between the number of pieces of the divided piezoelectric transducer and the total acoustic pressure of all divided piezoelectric transducer pieces, applied voltage

number of transducer division was increased. The results suggested that increasing the applied voltage, rather than the input power, would result in higher intensity of ultrasound radiation.

IV. Conclusions and future works

Computer simulations based on the equivalent circuit were carried out using MATLAB for the divided transducer type ultrasound source system proposed in this study. The results suggested that increasing the applied voltage, rather than the power input, would result in higher intensity ultrasound radiation. At the present, we are preparing to simulate a three-dimensional acoustic field formed by our proposed high power ultrasound source system using the finite element method (ANSYS). Moreover, we will measure the input impedance and the irradiated acoustic pressure of the actual trial fabricated divided transducer type ultrasound source system as our future works.

[Notes]

1) F. Kaise *et al*., Journal of the journal of the acoustical society of Japan, vol.75, Nov., 2020

2) S. Igarashi *et al*., Spring Meeting of Acoustic Society of Japan, 1002, Mar., 2018

3) S. Igarashi *et al*., Japanese Journal of Applied Physics. 56, 07JF19, 2017

4) Don A. Berlinccourt, Daniel R. Curran and Hans Jaffe; “PHYSICAL ACOUSTICS Principles and Methods Edited by Warren P. Mason, Volume I — Part A, Section 3, Piezoelectric and Piezomagnetic Materials and Their Function in Transducers”, pp.233–256, ACADEMIC PRESS (New York, San Francisco, London), 1964

5) Shinichi Takeuchi; “Tutorial on the underwater or medical ultrasound transducer”, The Journal of the Acoustical Society of Japan, Vol.72, No.5, pp.264–272, 2016