

Frequency Characteristic of Transmission Efficiency Depended on Matching Condition of Transducer in Ultrasonic Wireless Power Transmission System

Kazuhiro Fujimori^{#1}, Shota Tominaga^{#2}, Koichiro Tanda[#],
Kenji Tsuruta[#], Shigeji Nogi[#]

[#]The Graduate School of Natural Science and Technology, Okayama University
3-1-1 Tsushima-naka, Okayama-shi, Kita-ku, Okayama, 700-8530, Japan

¹fujimori@okayama-u.ac.jp

²en19442@s.okayama-u.ac.jp

Abstract— The ultrasonic wireless power transmission technology is researching as the one option of wireless power transmission technologies, because the loss of the electromagnetic wave becomes larger around a human body area or under juicy environments. For highly efficient power transmission, it is necessary to investigate the transducer as the transmitter and the receiver.

In this paper, the frequency characteristic of transmission efficiency depended on matching condition of developed transducer is investigated. As results, the transmission efficiency is made wideband to select optimal matching condition at each frequency. Especially, maximum transmission efficiency is 75.1% at designed frequency 1.20MHz.

I. INTRODUCTION

From a past, a healthcare is important issue for human life, and many medical devices have been developed. Especially, in recent years, the developments of the in-vivo devices are remarkable and various researches are reported^{[1]-[3]}. Generally, the in-vivo devices need an internal battery. To replace the battery, the surgical operation is demanded to the patient. It takes risks and the physical burden of the patient. For overcoming of these problems, the wireless power transmission (WPT) technology has been studied^{[4]-[5]}. In the WPT technology, systems using electromagnetic wave are mainly researching now. However, there are some reports which the electromagnetic wave influences harmfully to a human body^[6]. On the other hand, the loss of electromagnetic wave becomes larger under juicy environments, and it is difficult to apply wireless power transmission technologies using electromagnetic wave.

Then, the WPT technology using ultrasonic is investigated^{[7]-[9]}. The ultrasonic is used for the sonography of a baby in a womb, because there is no report of exerting influence on human bodies, medical equipment and ecosystem by ultrasonic up to now. In the most simplified ultrasonic WPT system, a pair of transducers that mutually convert electrical energy and vibrational energy is used, and the electric power is transmitted between these transducers as the vibration.

In previous our reports, we designed the transducer which is suitable for the ultrasonic WPT system in water based on design theory derived by the Mason's equivalent circuit^{[10]-[14]}. For deciding and tuning structural parameters and materials of the transducer, we used ANSYS well-known as the multi-physics simulator. It was confirmed that the designed transducer is electrically matched to 50Ω and acoustically matched to the acoustic impedance of water in our simulations. In results of experiments by using manufactured transducers, the transmission efficiency of ultrasonic WPT system in water was improved to about 60% while it when the commercial transducer is used was about 1%. At these examinations, the electrical matching is done to connect with the inductor for cancelling the parasitic capacitance of the piezoelectric element. However, the transducer's impedance does not match at other frequencies because the imaginary part is only canceled at the designed frequency. As a result, the bandwidth is narrowed.

In this paper, we investigate frequency characteristic of transmission efficiency depended on matching condition of transducer. Consequently, we demonstrate that the transmission efficiency and its bandwidth improve drastically to select the matching inductor and the load resistance to cancel imaginary part at each frequency.

II. THE DESIGN THEORY OF TRANSDUCER

For the realization of the ultrasonic WPT system, a transducer suitable for electric power transmission is necessary. Main factors of the transducer's loss are the conversion loss caused by physical properties of materials, the electrical mismatch between the input source and the transducer, and the acoustical mismatch between the transducer and propagation medium. To select the low loss material, the conversion loss is able to reduce. The design approach that considers these points is shown as follows.

A. Matching condition of transducer

Fig. 1 shows the physical structure of the transducer including the input source and the matching inductor for cancelling the imaginary part of the transducer's impedance.

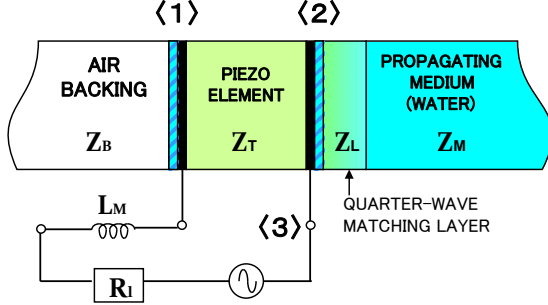


Figure. 1 Physical arrangement of a piezoelectric transducer

In Fig. 1, <1>, <2> and <3> are the air backing side, $\lambda/4$ layer side and the electrical terminal, respectively. The transducer is assumed a disc-shape, and its piezoelectric element resonates in the thickness direction at a half wavelength. The high-polymer material as the matching layer to the propagation medium is bonded in one respect of the piezoelectric element. This layer has the acoustical impedance Z_L and the thickness $\lambda/4$. Fig. 2 shows the equivalent circuit of Fig. 1 based on the Mason's model about the longitudinal effect of transducer.

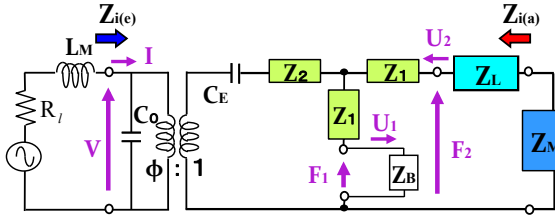


Figure. 2 Equivalent circuit representation of transducer

F_1 and F_2 mean forces at the acoustic face <1> and <2>, respectively. U_1 and U_2 mean particle velocities at the acoustic face <1> and <2>, respectively. V_3 and I_3 is the voltage and the current at the electrical terminal, respectively. The simultaneous equations about these parameters are expressed as follows;

$$\begin{pmatrix} F_1 \\ F_2 \\ V_3 \end{pmatrix} = \begin{pmatrix} a_1 & a_2 & a_3 \\ a_2 & a_1 & a_3 \\ a_3 & a_3 & a_4 \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ I_3 \end{pmatrix} \quad (1)$$

B. Electrical and Acoustic matching

At acoustic face <1> and <2>, termination conditions are become

$$F_1 = -S_T Z_B U_1 \quad (2)$$

$$F_2 = -Z_{L/M} U_2 \quad (3)$$

$$V_3 = -Z_{el} I_3 \quad (4)$$

Calculating the equation (1) by using the equation (2), (3) the input impedance $Z_{i(e)}$ become as follow:

$$Z_{i(e)} = \text{Re}\{Z_m\} + \text{Im}\{Z_m\} + \frac{1}{j\omega C_0} \quad (5)$$

Here, Z_m so-called "motional impedance" components of the electric terminal. The necessary condition it supplies available power or to take it out is when the imaginary part of the equation (5) is canceled and the real part is equal to external resistance. And it becomes the maximum power supply condition. This is concluded the following;

$$\text{Re}\{Z_m\} = R_l \quad (6)$$

$$\text{Im}\{Z_m\} = 0 \quad (7)$$

$$\omega L_0 C_0 = 1 \quad (8)$$

The eq. (8) implies when I match L_0 in ω_0 (in fact $L_0 = 1/\omega_0^2 C_0$), eqs. (5) and (6) are simplified like the following equation:

$$\text{Re}\{Z_m\}_{\omega=\omega_0} = \left(\frac{2h_{33}}{\omega_0}\right)^2 \frac{1}{S_T Z_B + Z_{L/M}} = R_l \quad (9)$$

C. The design formula of transducer

Here, we assume backing an air backing, if it can regard as $Z_B/Z_M \ll 1$, it can keep transmission loss of available energy low. And, it gives a configuration methodology that suitable for a transducer aimed at the energy transmission. So, it is shown the following from the equation (7) and (9),

$$R_l \cong \frac{4}{\pi^3} \left(\frac{h_{33}}{r_T}\right)^2 \left(\frac{l_T}{v_t^D}\right)^2 \frac{Z_M}{Z_L^2} \quad (10)$$

D. The design of transducer

Here, we show the calculation example of the design about transducer. We choose the anti-resonance frequency 1.2MHz as single driving frequency. Tab. 1 shows material constant using the transducer's design and the designed value of transducer.

TABLE 1 CIRCUIT PARAMETER AND DESIGNED VALUE OF TRANSDUCER

Parameters	Value
h_{33}	3.0×10^9 [V/m]
Z_T	31.9×10^6 [kg/m ² s]
Z_L	3.5×10^6 [kg/m ² s]
Z_M	1.5×10^6 [kg/m ² s]
Z_B^D	408 [kg/m ² s]
v_t^D	4528 [m/s]
v_L	2500 [m/s]
f_0	1.2 [MHz]
r_T	22 [mm]
l_T	1.88 [mm]
l_L	0.52 [mm]

III. EXPERIMENTS BY USING DEVELOPED TRANSDUCERS

Fig. 3 shows the measured frequency characteristic of transducer's input impedance connected with a matching inductor L_0 . At this time, the transducer will be matched only at the design frequency.

In Fig. 3, the real part of transducer's input impedance is about 50Ω and imaginary part of it is 0Ω at 1.25MHz . It is confirmed that this transducer's impedance is matched to the signal generator or the receiver.

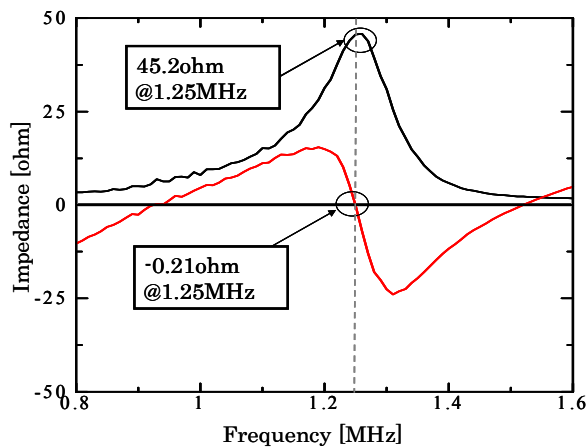


Figure. 3 Frequency characteristic of input impedance

Fig. 4 shows the experiment system for obtaining the transmission efficiency of the ultrasonic WPT.

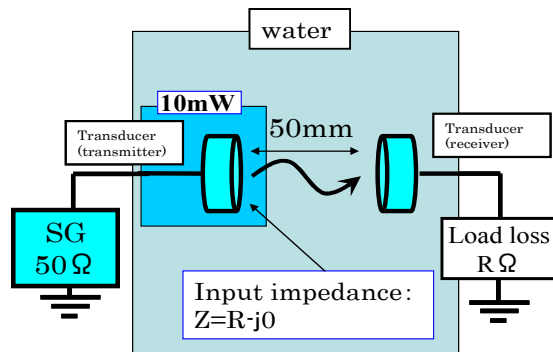


Figure. 4 The experiment system to measure transmission efficiency

In experiments, the signal generator as the power source outputs 10mW . This electrical power is converted to the acoustic power by the transducer, then, it is transmitted in water. The acoustic wave is received at another transducer and converted again to the electrical power. This electrical power is consumed at the load. Fig. 5 shows the frequency characteristic of transmission efficiency when the matching inductor and the load resistance are fixed to optimum at 1.25MHz . The transmission Efficiency $\eta\%$ about

transmitting and receiving system is calculated as follow:

$$\eta = \frac{P_R}{P_{source,max}} \times 100 \quad (11)$$

$$P_R = \frac{V_{rms}^2}{R} \quad (12)$$

- P_R : AC power consumed at load resistance [W]
 $P_{source,max}$: Input power to the transducer [W]
 V_{rms} : Effective voltage at the load resistance [V]
 R : The load resistance [Ω]

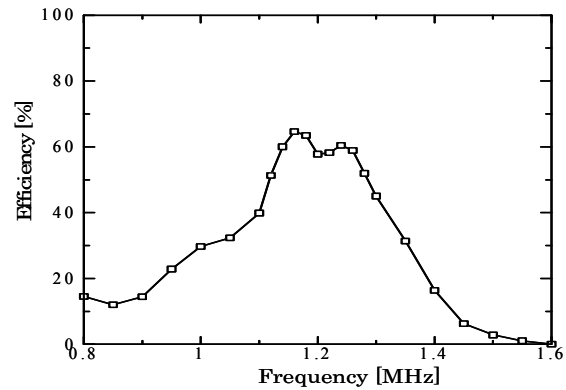


Figure. 5 Transmission Efficiency about transmitting and receiving system

In Fig. 5, the maximum transmission efficiency is about 60% at designed frequency. It is also confirmed that the transmission efficiency decreases rapidly as the frequency is parted from the design frequency.

IV. FREQUENCY CHARACTERISTIC OF EFFICIENCY BY SUITABLE MATCHING CONDITION AT EACH FREQUENCY

It is understood that the factor of narrow-band characteristic of efficiency is caused by the electrical matching in Figs. 4 and 5. Therefore, we investigate the frequency characteristic of transmission efficiency when the transducer's impedance is matched to the transmitter and the receiver at each frequency, because the conversion ability of piezoelectric element is clarified. Fig. 6 shows the measured frequency characteristic of transducer's input impedance without a matching inductor L_0 .

In this figure, the imaginary part of input impedance does almost the same change as Fig. 3, and it indicates almost 0Ω at 1.2MHz . Moreover, it is confirmed that there is no change in the real part of input impedance and only the imaginary part is changed with the matching inductor. Then, in experiments, optimal matching inductor at each frequency is connected to cancel the imaginary part by the reference to measurement results of input impedance. The optimal resistance is also connected to the transmitting transducer for matching to the signal generator and same resistance is connected to the receiving

transducer as the load resistance. The identical experiment system is used shown in Fig. 4. At this time, the input power to the transmitting transducer decreases because the resistance is connected to the transducer. Then, the output power is calibrated so that the input power to the transmitting transducer is 10mW.

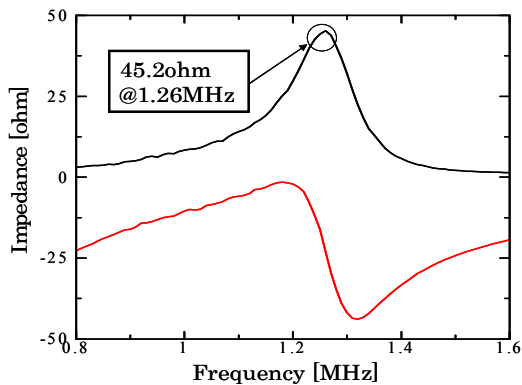


Figure. 6 Frequency characteristic of input impedance

Fig. 7 shows the measured frequency characteristic of the transmission efficiency comparing with one shown in Fig. 5. Red square points indicate measured efficiencies when the appropriate matching condition is selected at each frequency, and the black line is shown in Fig. 5.

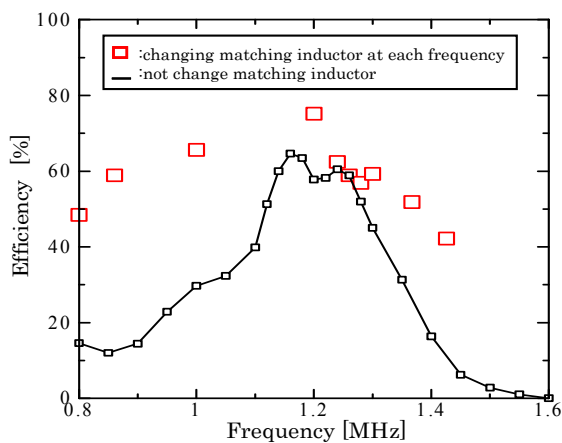


Figure. 7 Transmission Efficiency about transmitting and receiving system

In Fig. 7, it is more efficient to choose the appropriate value at each frequency, and the maximum efficiency is 75.1% at 1.20MHz. This is because the thickness of acoustic matching layer and the piezoelectric material are designed at 1.2MHz shown in Tab. 1. Moreover, the bandwidth where the transmission efficiency becomes 50% or more has expanded to three times.

V. CONCLUSION

In this paper, we investigated the frequency characteristic of transmission efficiency depended on matching condition of transducer. As results, we

demonstrate that the transmission efficiency becomes higher and its frequency characteristic is expanded by connecting with the appropriate resistance and matching inductor for cancelling the imaginary part of transducer at each frequency. The maximum transmission efficiency is 75.1% at 1.20MHz. This frequency means the designed frequency of acoustic characteristics. Furthermore, it is also indicated that the bandwidth where the transmission efficiency becomes 50% or more has expanded to three times.

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