24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

MATCHING LAYER DESIGN OF AN ULTRASONIC TRANSDUCER FOR WIRELESS POWER TRANSFER SYSTEM

Gunn Hwang

Electronics and Telecommunications Research Institute, Multidisciplinary Sensor Research Group, Daejeon, South Korea
email: hwangun@etri.re.kr

WooSub Youm and Sung Q Lee

Electronics and Telecommunications Research Institute, Multidisciplinary Sensor Research Group, Daejeon, South Korea

The wireless power transfer technology with ultrasound has been introduced and several study results have been reported as an alternative wireless power transfer technology. The ultrasonic wireless power transfer system has mainly two components, the transmitter which converts electrical energy to ultrasonic energy and the receiver which changes the ultrasonic energy to the electrical energy again. It is very important for the ultrasonic transducer and receiver to have the high energy transfer efficiency as a transducer or a sensor. The transducer with high energy transformation efficiency would be able to get a high sensitivity as a sensor, or to transmit high wireless energy transferring capacity as a wireless power transducer. The matching layer design is one of the most important factors to get a high energy transfer efficiency of the ultrasonic transducer. This document describes the development of the mathematical model, and the experimental study of the matching layer for an ultrasonic transducer in a wireless power transfer system considering the volume fraction of the piezo ceramic, PMN-30PT and impedance of materials.
Keywords: ultrasonic transducers, matching layer design

1. Introduction

It is very important for the ultrasonic transducer to have the high energy transfer efficiency especially for wireless ultrasonic power transmission technology. One of the important part of ultrasonic transducer design is to optimise the impedance of the matching layer that is located between piezo ceramic and acoustic medium such as air or water. Because there is a large mismatch between the piezo ceramic and medium, the acoustic energy loss is occurred for acoustic reflection. To make an optimal design of the matching layer, the transducer can have better efficiency to transmit or receive the acoustic power. A 1-3 piezocomposite transducer can be made to have variable impedance to control the fraction ratio between the piezo ceramic and epoxy. The various materials as matching layer can be matched with the 1-3 piezocomposite transducer with this characteristic. This paper is focused on the development of the mathematical model and the experimental study of the optimum matching layer of ultrasonic transmitter for wireless power transmission considering the volume fraction of the piezo ceramic, PMN-30PT and impedance of materials.

2. Theory

The efficiency of an ultrasonic transducer is defined as a ratio of the acoustic output power to the input electric power. The acoustic output power is obtained by the integration of acoustic intensity at the total radiated area of the ultrasonic acoustic power. The input electric power can be calculated based on input voltage and current. However, to get the acoustic output power is not easy because it is time consuming process to get the integration of acoustic intensity to the total radiated area. Instead of the acoustic intensity integration, this paper estimates the efficiency of an ultrasonic transducer with a relative simple method using a mathematical model of the ultrasonic transducer and an impedance analysis method[1].

2.1 Governing Equation theory

It is shown for the mathematical model of an ultrasonic transducer that changes electric energy into acoustic energy as shown in Fig. 1. The electrical impedance is Z_{EB} when the displacement of the transducer is supposed to zero and a capacitance of the piezoelectric transducer. The mechanical impedance is Z_{ms} when the signal input terminal is shorted. The radiation impedance is Z_r, and transformation factor ø. The electrical impedance and the mechanical impedance changed to an electrical impedance with a transformation factor, ø, is described as a parallel structured mathematical model as shown in Fig. 1[1, 2].

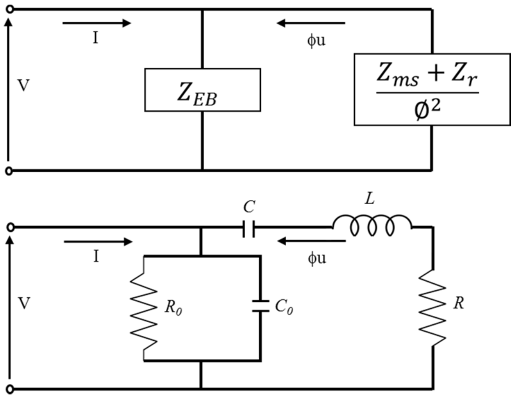

Figure 1: Mathematical model of the ultrasonic transducer [2].

When an ultrasonic transducer is under resonant state, the efficiency of the transducer, η, is calculated as following:

$$\eta = \eta_{EM} \cdot \eta_{MA} = \frac{R_0}{(R_0 + R)} \cdot \frac{R_r / \phi^2}{R} \tag{1}$$

where an electrical-to-mechanical energy conversion efficiency is η_{EM}, a mechanical-to-acoustical energy conversion efficiency η_{MA}, mechanical resistance R_m, radiation resistance R_r, and $R = \frac{R_m+R_r}{\phi^2}$.

The conductance, G_E, is defined as:

$$\mathrm{G_E} = \frac{1}{\mathrm{R_0}} + \frac{1}{\mathrm{R}} \tag{2}$$

when the ultrasonic transducer is at resonant condition, $\omega = \omega_0$ in Fig. 2.

In Fig. 2, the conductance, $G_{E\,vacuum}$, under vacuum condition, and the conductance, $G_{E\,water}$, in water are obtained as:

$$G_{Evacuum} = \frac{1}{R_0} + \frac{1}{R_{vacuum}}. \tag{3}$$

$$G_{Ewater} = \frac{1}{R_0} + \frac{1}{R_w}. \tag{4}$$

where $R_w = \frac{R_m + R_r}{\phi^2}$ at ω_0 .

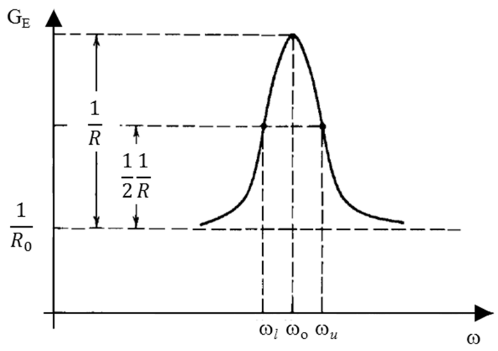

Figure 2: Conductance response curve of an ultrasonic transducer [2, 3].

From Eqs. (3) and (4), R_{vacuum}, R_w and R_r are obtained as followings:

$$R_{vacuum} = \frac{1}{G_{Evacuum} - (1/R_0)} . \quad (5)$$

$$R_w = \frac{1}{G_{Ewater} - (1/R_0)} . \quad (6)$$

$$\frac{R_r}{\phi^2} = R_w - R_{vacuum} . \quad (7)$$

From Eqs. (1) to (7), the efficiency of the ultrasonic transducer, η , is obtained as:

$$\eta = \eta_{EM} \cdot \eta_{MA} = \frac{R_0}{R_0 + R_w} \cdot (1 - \frac{R_{vacuum}}{R_w}) . \quad (8)$$

where R_0 is a resistance at DC condition or at low frequency condition as following:

$$\frac{1}{R_0} = \frac{G_{E0vacuum} + G_{E0water}}{2} (@ \omega \approx 0) . \quad (9)$$

where $G_{E0\,\mathrm{vacuum}}$ and $G_{E0\,water}$ are initial conductances in vacuum and water condition, respectively. The conductance in water, R_{w} and that in vacuum, R_{vacuum}, are substituted as $G_{E\,water}$ and $G_{E\,\mathrm{vacuum}}$ into Eqs. (5), (6), and (9) to get the efficiency of the transducer. Finally, the efficiency of the ultrasonic transducer, η, is obtained from Eq. (8) with $G_{E\,\mathrm{vacuum}}$ and $G_{E\,water}$ as following:

$$\eta = \eta_{EM} \cdot \eta_{MA} = \frac{2(G_{Ewater} - G_{Evacuum})}{G_{Ewater}(1 + G_{Ewater}(G_{Ewater} + G_{Evacuum}))} . \quad (10)$$

2.2 Theoretical impedance of matching layer

When the medium of a transducer is water, the impedance of matching layer, Z_{ML}, for 1-3 piezocomposite transducer made of PMN-PT and epoxy is obtained as following:

$$Z_{ML} = \sqrt{(Z_{PMN-PT} * Vol\%_{PMN-PT} + Z_{301} * (1 - Vol\%_{PMN-PT})) * Z_{water}} . \quad (11)$$

where Z_{PMN-PT}, and Z_{301}, are impedances of PMN-PT and epoxy, and $Vol\%_{PMN-PT}$ is the volume percent of the PMN-PT.

The basic acoustic parameters of the materials of a 1-3 piezocomposite transducer are shown in Table 1. The polyoxymethylene (POM), also known as acetal or polyacetal, is chosen as a base material of the matching layer of the transducer. EPO-TEK 301 and 353ND made by Epoxy technology, Inc. are materials for filling epoxy between 1-3 piezocomposite element and for matching layer of the 1-3 piezocomposite transducer[5]. The base material of the piezoelectric ceramic is PMN-30PT made by Ceracomp Co.[6].

Table 1: Impedance parameters of the transducer material.

Material	Density (kg/m^3)	Speed of sound (m/sec)	Impedance (Mrayls)
POM	1400	2,310	3.23
EPO-TEK 301	1148	2,630	3.02
EPO-TEK 353ND	1240	2,770	3.43 [7]
PMN-PT[6]	7300	1,476	10.8

The theoretical impedances by volume% of PMN-PT that are in water condition and EPO-TEK 301 is filling material are calculated from Eq. (11) as shown in Table 2. The best matched materials for the matching layer of the 1-3 piezocomposite transducer are EPO-TEK 301 (Z=3.02) for 44 vol%, POM (Z=3.23) for 56 vol%, and EPO-TEK 353ND (Z=3.43) for 66 vol%, respectively.

Table 2: Theoretical impedance by the volume% of PMN-PT

Volume % of PMN-PT (%)	Z_{ML} (Mrayls)	Remarks (best matched material)
44	3.09	EPO-TEK 301
56	3.3	POM
66	3.47	EPO-TEK 353ND

2.3 Conductance Measurements

The measurement mode of the Agilent technologies 4294A impedance analyzer, is selected with parallel mode because the mathematical model of the ultrasonic transducer is parallel type as shown in Fig. 3. Based on the measurement parameter data, Gp (parallel conductance) and Bp (parallel susceptance) are selected as parameters of the 1-3 piezocomposite transducer and measured in air and water environment condition, respectively to calculate the efficiency of the 1-3 piezocomposite transducer[1, 4].

Figure. 3 shows the schematic diagram for experimental setup of 1-3 piezocomposite transducer. The diameter and thickness of the 1-3 composite transducer are 30 mm and 2 mm. The POM matching layers with 1.3 ~ 1.5 mm thickness of the 1-3 composite transducer are tested by cutting off each 0.1 mm thickness from the original thickness of POM matching layer. The tested volume% of the 1-3 piezocomposite are 56/64/66 vol% each.

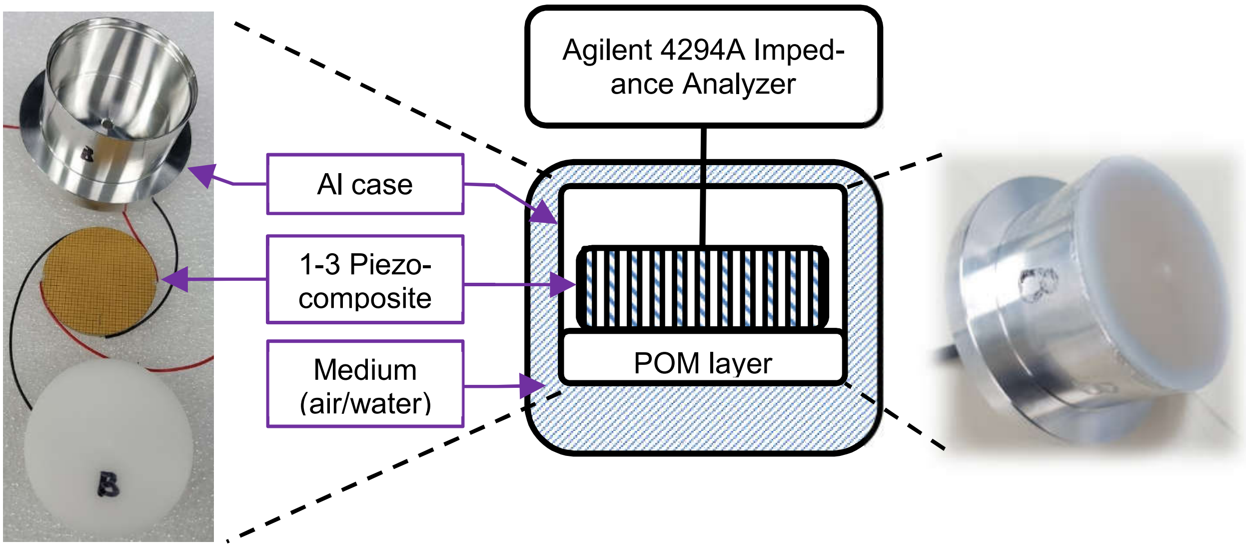

Figure 3: Schematic diagram of the impedance measurement for 1-3 piezocomposite transducer.

3. Results

The maximum efficiencies of the 1-3 composite transducer are 82.3 % and 81.6 % at 64 vol% and 82.7% at 56 vol% with 1.1 mm thickness of POM layer and 79.3% at 66 vol%, with 1.0 mm thickness of POM layer as shown in Fig. 4-5. The best efficiency among them is obtained at 56 vol% of PMN-PT as predicted Eq. (11) because the impedance of the POM, Z_{POM} = 3.23 is the nearest among those of the other materials to the predicted impedance of the matching layer based on Eq. (11), Z_{ML} = 3.3 as Table 2.

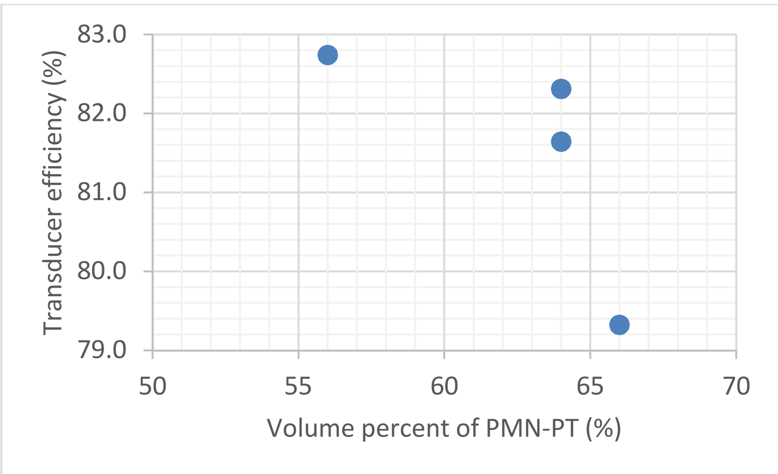

Figure 4: Experimental results of the max. efficiency of 1-3 piezocomposite transducer by PMN-PT vol% with POM matching layer

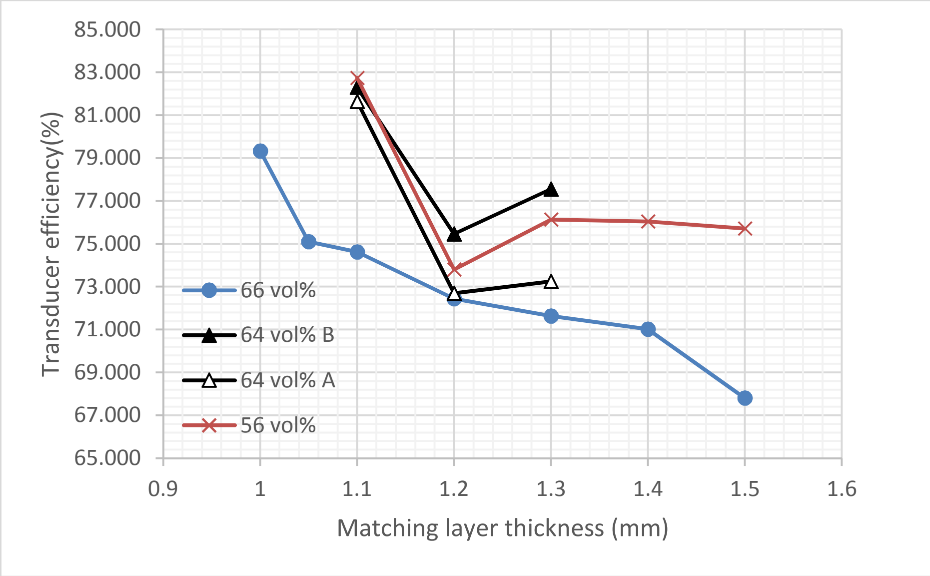

Figure 5: Experimental results of the efficiency of 1-3 piezocomposite transducer with POM matching layer thickness and PMN-PT vol%.

Figure 6 shows the typical experimental results of conductance (G) with 1.1 mm thickness of POM layer with 56 vol% and 64 vol% of PMN-PT. There are two peaks of the conductance graph measured in air and one peak with long plat shape in water as shown in Fig. 6. These two peaks are merged to one peaks and the values at the peak are lowered when it is measured in water. Under water environment condition, the natural frequency range of the transducer is wider natural frequency range than that in air.

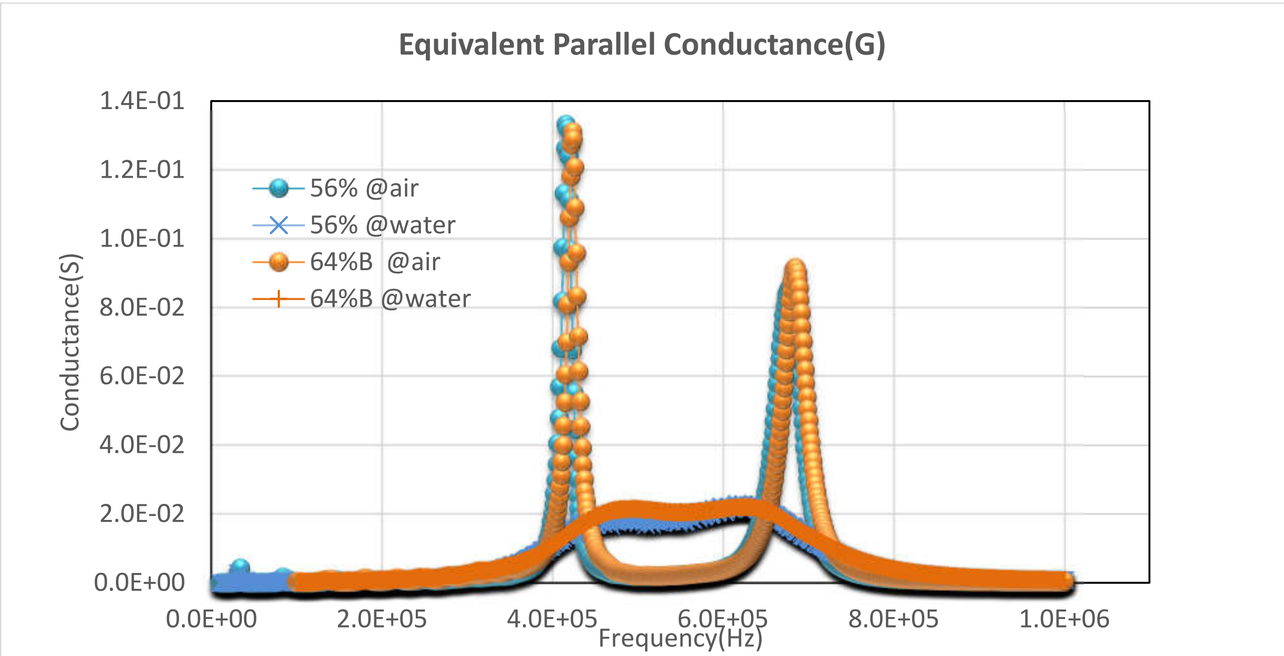

Figure 6: Experimental results of the conductance of 1-3 piezocomposite transducer with POM layer.

4. Conclusions

This paper is focused on the matching layer design of ultrasonic 1-3 composite transducer for high energy conversion efficiency considering the volume fraction of the piezo ceramic, PMN-30PT and impedance of materials. The efficiency of the transmitter with matching layer is calculated based on the acoustic impedance theory, and tested to get the optimal matching layer of the ultrasonic transmitter with the 1-3 composite piezoelectric ceramic structure of 30 mm diameter, 2 mm thickness. The tested 1-3 composite piezoelectric ceramics is PMN-30PT. The polyox-ymethylene (POM), also known as acetal and polyacetal, is chosen as a material of the top layer on the 1-3 composite transducer for impedance matching. The maximum energy conversion efficiency of the transmitter are 82.7 % at 1.1 mm thickness of matching layer and 56 vol% of PMN-PT.

5. Acknowledgements

This work was supported by the R&D Program of MOTIE/KIAT, South Korea [N0000897, Development of sustainable power module for implantable medical devices based on ultrasonic wireless power transfer], and the ICT R&D program of MSIP/IITP [2017-0-00052, Omni-sensory smart physical sensor original technology for human body sensing and diagnosis]. We would like to thank them for their financial assistance.

REFERENCES

1 Hwang, G., Youm, W. and Lee, S., Development of matching layer for ultrasonic wireless power transmitter, *Proceedings of the 44th International Congress and Exposition on Noise Control Engineering,* California, U.S.A., 9 -12 August, (2015).

2 Kinsler, L. Ed., *Fundamentals of Acoustics*, John Wiley & Sons, Hoboken, NJ (2000).

3 Sherman, C. and Butler, J., *Transducers and Arrays for Underwater Sound*, Springer, Cohasset, MA (2007).

4 *Agilent 4294A Precision Impedance Analyzer Operation Manual*, Agilent Technologies, (2003).

5 Epoxy technology, Inc., http://epotek.com

6 Ceracomp, Co., Ltd., http://www.ceracomp.com/

7 Jonathan M. Cannata, et al., Design of Efficient, Broadband Single-Element (20–80 MHz) Ultrasonic Transducers for Medical Imaging Applications, *IEEE Tr. on Ultrasonics, Ferroelectronics, and Frequency control,* pp. 1548~1557, vol. 50, No.11, Nov. 2003.