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Optimization of the Structure of 1-3 Piezocomposite Materials to Maximize the Pulse-Echo Response of an Underwater Acoustic Transducer

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1. Introduction

Most of current underwater acoustic transducers utilize piezoceramics as its drive section. However, piezoceramics have such limitations as low electromechanical coupling factor and high acoustical impedance. Hence, 1-3 piezocomposites have been widely tried for the drive section to overcome the limitation of the conventional bulk piezoceramics [1]. The 1-3 piezocomposite consists of piezoceramic pillars embedded in a polymer matrix. In this paper, an underwater acoustic transducer was designed to have excellent performance using the 1-3 piezocomposite material [2]. Transmitting Voltage Response (TVR) and -3dB Fractional Bandwidth (FBW) and Receiving Voltage Sensitivity (RVS) were the performance factors to characterize the piezocomposite transducer. When the piezocomposite vibrates in a thickness mode, inter-pillar resonant modes are likely to occur by the lateral waves reflected at the interface between lattice-structured piezoceramic pillars and polymer matrix [3]. If the inter-pillar resonant mode is coupled with a thickness resonant mode, the efficiency to convert electrical energy to mechanical energy is decreased a lot. So, it is very important for a piezocomposite transducer not to have the inter-pillar mode of vibration [4].

In this work, the structure of a 1-3 piezocomposite plate was designed to avoid the performance degradation by the inter-pillar resonance while maximizing the transmitting and receiving sensitivity as well as the bandwidth of an underwater acoustic transducer. Design variables are volume fraction of the ceramic, elastic modulus of the polymer, and aspect ratio and thickness of the piezocomposite plate. These variables are the most effective variables influential on the acoustic performance [5]. The performance of the piezocomposite transducer was analyzed by presenting the transducer with an equivalent circuit. The structure was optimized by means of the OQ-NLP(OpQuest-Nonlinear program) algorithm and the finite element analysis method using the commercial package ANSYS [6].

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2. Equivalent circuit

Structure of the underwater acoustic transducer under consideration is shown in **Fig. 1**. The region above the 1-3 piezocomposite plate is occupied by water and a matching layer. A backing is attached to the rear face of the 1-3 piezocomposite, and a steel plate supports the backing. Thickness of the piezocomposite plate (t) is a variable while thickness of the matching layer (t_{m}) is fixed to 5 mm, thickness of the backing (t_{b}) to 5 mm, thickness of steel (t_{s}) to 10 mm and radius of transducer (a) to 150mm. To avoid the coupling between thickness and lateral modes of the piezocomposite plate, the lateral dimension of the plate was set to be ten times larger than the thickness.

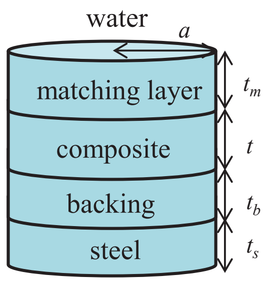

Fig. 1 Schematic structure of the underwater piezocomposite transducer.

Fig. 2 shows the Mason equivalent circuit composed of T-networks to analyze the performance of the transducer. TVR, RVS and FBW were calculated with this circuit. Z is an electromechanical impedance element and R_r is a radiation resistance element.

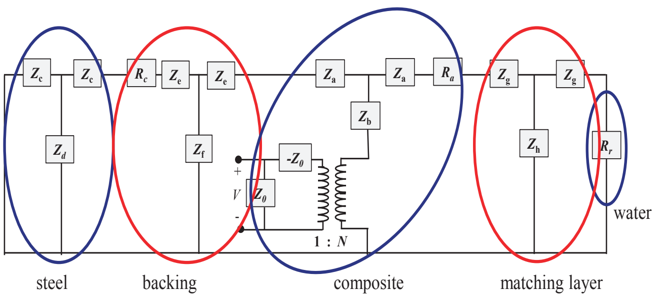

Fig. 2 Equivalent circuit of piezocomposite transducer.

3. Structural optimization of the transducer

The purpose of optimizing the structure of the 1-3 piezocomposite transducer is to maximize the magnitude of object functions while preventing the occurrence of the inter-pillar mode. The object functions considered are transmitting performance, receiving sensitivity and transmitting/receiving performance, respectively. The selected design variables are volume fraction of the ceramic (*VF*), elastic modulus of the polymer (*Y*), thickness of the composite (*t*) and aspect ratio of the composite (*AR*). Variation range of the variables is from 10 to 90 percent, 1.5 to 6 GPa, 10 to 40 mm and 0.3 to 0.5, respectively. The object function TFR shown in equation (1) is to maximize the transmitting /receiving performance while preserving a wide bandwidth. The TVBW in equation (2) is to maximize the transmitting performance while preserving a wide bandwidth. RVS is used to maximize only the receiving performance.

$$TFR = \frac{TVR - TVR_{\min}}{TVR_{\max} - TVR_{\min}} \times \frac{FBW - FBW_{\min}}{FBW_{\max} - FBW_{\min}} \times \frac{RVS_{\min} - RVS}{RVS_{\min} - RVS_{\max}} \quad (1)$$

$$TVBW = \frac{TVR - TVR_{\min}}{TVR_{\max} - TVR_{\min}} \times \frac{FBW - FBW_{\min}}{FBW_{\max} - FBW_{\min}} \quad (2)$$

The object functions were maximized by the OQ-NLP algorithm. After the optimization, the finite element model was utilized to check whether the inter-pillar resonance was coupled with the thickness resonance of the optimized 1-3 piezocomposite plate. The frequency range between 0.8 ~ 1.2 times the thickness mode resonant frequency was analyzed to check the mode coupling. If the inter-pillar resonant mode was coupled with the thickness mode within this range, the minimum values of the design variables were increased to shift the inter-pillar resonant mode away from the thickness mode. The transmitting and receiving frequency was selected to be 40 kHz and 20 kHz, respectively. The result of optimization with each object function is shown in **Table I**. As shown in **Fig. 3**, thickness resonant mode is free from any mode coupling.

Table I Optimized values of the design variables for each object function.

Object	*VF* (%)	*E* (GPa)	*AR*	*t* (mm)
TFR	43.7	1.5	0.5	19
TVBW	40.5	1.5	0.5	19
RVS	30.0	1.5	0.5	19

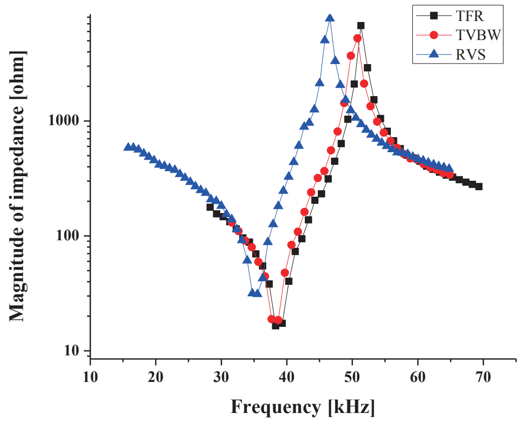

Fig. 3 Impedance spectra of the three piezocomposite transducers optimized with the object functions.

4. Conclusions

We determined the optimal structure of the 1-3 piezocomposite plate to maximize the pulse-echo response of an underwater acoustic transducer while preventing the mode coupling within the frequency range of interest. Results of the optimization with the three object functions TFR, TVBW and RVS showed significantly different structure for each of the object function. Optimal design method proposed in this paper is applicable not only to the structure in **Fig.1** but also to general underwater acoustic transducer of various structures.

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