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Development of an Impedance Matching Layer in an Ultrasound Transducer with Gradient Properties

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Abstract

The piezocomposite transducer is widely used because it is highly efficient in transforming electric energy into mechanical energy, and its frequency range is broader than that of other types of ultrasound transducers. A general piezocomposite transducer is composed of an acoustic lens, impedance matching layers, piezoelectric materials, and backing layers. When an input voltage is applied to a piezoelectric material as an active material, it generates sound waves while vibrating. At that time, an impedance matching layer helps the sound waves to propagate forward while reducing the impedance mismatch that may occur at the interface between the active material and its front material. The impedance mismatch has a negative effect on the signal of an ultrasound transducer; thus, it is important to design a matching layer to overcome the issue. In this study, an optimized feature of a matching layer with gradient properties is studied. An objective function is defined to minimize both the average and the deviation of the reflection coefficients that are functions of the frequencies. As a result, an improvement in the signal characteristics with respect to the sensitivity and bandwidth is reported.

Keywords : Acoustic Impedance, Matching layer, Optimization, Gradient properties, Ultrasound transducer

1. INTRODUCTION

There are many types of ultrasound transducers according to the principles of active materials. A piezocomposite transducer using a piezoelectric material as its active material is widely used in devices such as underwater acoustic cameras, nondestructive probes, and medical ultrasound devices because it can be used in a broad band of frequency and is highly efficient in transforming electric energy into mechanical energy and vice versa. When sound waves generated by an input voltage applied to an active material propagate forward through the medium, most portions of the waves become reflected at the interface between the active material and its front material owing to an acoustic impedance mismatch.

The same principle is repeated when reflected waves propagate backward at the interface between the active material and its backing material. As a result, the sound waves that were initially generated are trapped inside the active material, which cause ringing of the active material. If ringing occurs, it has a negative effect on the signal characteristics while reducing the sensitivity and decreasing the axial resolution of the transducer.

To overcome this issue, Desilets and Fraser [1] reported on a way to design an impedance matching layer by setting a virtual node inside the active material. R.E. McKeighn [2] suggested the concept of a statistical design approach based on experiments. This was practically used to make an ultrasound transducer. However, this approach has limitations in that the sensitivity of the signal decreases as the number of layers increases in order to minimize the impedance mismatch of each layer because the impedance matching layer behaves as a damper. M. I. Haller [3] and S. Sato [4] reported on a matching layer for which the properties are gradually changing achieved by a mixture of silicon, polymer, and tungsten powder. Recently, X. Dongyu[5] reported gradient matching layer using metamaterial and Z. Li[6] reported gradient matching layer using epoxy resin and aluminum powder mixture. However, the optimized internal properties of the matching layers were not considered.

In this paper, the signal characteristics of an ultrasound transducer with a matching layer composed of gradient properties are studied by a numerical analysis approach. The matching layer is described as a function of the volume fraction of the filler, and

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a mathematical model to optimize the layer is established using the relationships between the elastic material properties. Additionally, the optimized features of the matching layer and the improvements of an ultrasound transducer are explained.

2. Concept of Model and Method to Evaluate its Characteristics

2.1 Concept of matching layer with gradient properties

Fig. 1 shows the structures of piezocomposite ultrasound transducers with an acoustic lens, acoustic impedance matching layers, kerf filler, backing layers, and PZT. The impedance matching layer is installed between an acoustic lens and a matching layer to help acoustic impedance matching. While the conventional matching layer has internally uniform properties, the proposed matching layer was designed to have gradient properties for which the internal properties of the matching layer were gradually changing along its thickness. Additionally, it was considered that an acoustic matching layer has limitations in its property ranges because it is generally made up of a polymer matrix and tungsten powder. The gradient properties were achieved by controlling the volume fraction of the filler. An ultrasound transducer of 2-2 piezocomposite was selected to evaluate the effect of the matching layer with gradient properties because it is widely used. The active material for the transducer was chosen as PZT-5H. The backing layer was considered as ILPEA F02-BR4 hard rubber (with a density of $3500\ kg/m^3$, Young's modulus of 4 GPa, and Poisson ratio of 0.45) [7] with kerf filler and acoustic lens as polyurethane (with a density of $1100\ kg/m^3$, Young's modulus of 0.9 GPa, and Poisson ratio of 0.45) Water was considered as the medium through which the sound waves generated by the transducer propagate.

2.2 Method to evaluate signal characteristics of ultrasound transducer

To evaluate the effect of the matching layer with gradient properties, the signal characteristics were calculated in the pulse-echo mode according to the ASTM standard guide [8]. When an impulsive voltage is applied to an ultrasound transducer, the transducer is excited and sound waves are generated. The propagating waves through the medium become reflected by the reflection plate, and the reflected waves excite the transducer back so that it generates a voltage. The characteristics of an ultrasound transducer such as its sensitivity and bandwidth are derived by comparison between the impulsive voltage to excite the transducers and the generated voltage by the echo waves.

Sensitivity is a ratio of the peak of the impulsive voltage initially applied to the active material to the peak of the generated voltage that is generated by the echo waves, and generally it is expressed in decibels.

$$\text{Sensitivity[dB]} = 10\ \log\left(\frac{V_p}{V_{in}}\right)^2 \quad (1)$$

Bandwidth is defined as eq. (3). It is calculated by a frequency spectrum analysis of the generated voltage by the echo waves. When the frequency spectrum is normalized, the two frequencies that intersect with the -6-dB line are defined as f_{low} and f_{high}, which are the low and high frequency, respectively. Then, the average of f_{low} and f_{high} is defined as f_c, and the bandwidth as a ratio of the difference of f_{high} and f_{low} to f_c as follows:

$$f_c = \frac{f_{low}+f_{high}}{2} \quad (2)$$

$$\text{Bandwidth[\%]} = \frac{f_{low}-f_{high}}{f_c} \times 100 \quad (3)$$

3. Optimization of Matching Layer

3.1 Analytic model of gradient composite

As mentioned in Chapter 2.1, a matching layer is composed of a polymer matrix and tungsten powder. There have been many studies to model a composite, including the Voigst model [9], Reuss model [10], and Chamis model [11]. Among these, the Halpin-Tsai model [12] was selected to describe the proposed matching layer because it is known for matching well to particle-reinforced composites with a filler that has a larger bulk modulus and shear modulus than those of the matrix. In addition, its volume fraction is less than 50%. In a matching layer with gradient properties, the bulk modulus K and shear modulus G of the composite are

$$P = \frac{p^m\left[1+\xi\varphi\left(\frac{p^f-p^m}{p^f+\xi p^m}\right)\right]}{1-\varphi\left[1+\frac{1}{2}(1-\varphi^2)\right]\left(\frac{p^f-p^m}{p^f-\xi p^m}\right)} \quad (4)$$

$$\xi = \begin{cases} \dfrac{2(1-2\upsilon^m)}{1+\upsilon^m} & \text{for P} = K \\ \dfrac{7-5\upsilon^m}{8-10\upsilon^m} & \text{for P} = G \end{cases}$$

where the superscripts m and f are the matrix and the filler, respectively; υ is Poisson's ratio; and φ is the volume fraction of the filler of the matching layer.

Additionally, other elastic properties to be used for the numerical analysis and optimization process were derived using the relationship with the elastic material properties [13] as eq. (5)–eq. (8):

$$E = \frac{9KG}{3K+G} \tag{5}$$

$$\upsilon = \frac{3K-2G}{6K+2G} \tag{6}$$

$$\rho = \rho_m\varphi_m + \rho_f\varphi_f \tag{7}$$

$$c = \sqrt{\frac{K}{\rho}} \tag{8}$$

where E is Young's modulus, ρ is the density, and c is the sound speed.

3.2 Design of objective function

The matching layer was described in terms of the volume fraction of the filler φ along the axial thickness to design an objective function, where the distance from the surface of the active material was set to be x along the direction to the acoustic lens shown in Fig. 1.

It is expected that the acoustic impedance mismatch will be minimized if the thickness of the matching layer L is as long as possible because it decreases the gradient of the property changes. However, a matching layer is also a kind of damping material, and it also needs to be optimized. Therefore, the thickness L was considered as a design parameter, and it was limited not to be oversized in the optimization process.

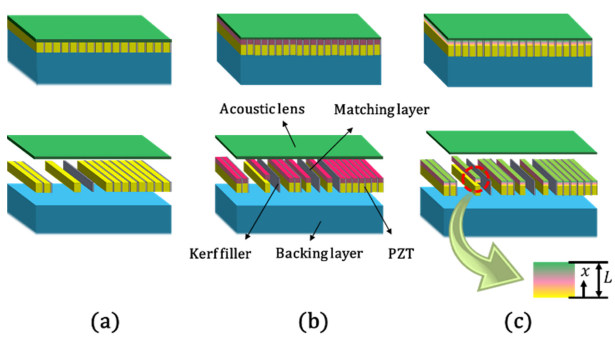


Fig. 1. Scheme of piezocomposite with (a) no matching layer, (b) conventional single matching layer, and (c) proposed matching layer.

In addition, the fraction of the filler in the matching layer at the active material side was limited to 0.5 with respect to the applicable range of the Halpin-Tsai model. The other side was set to zero because only polymer without the filler are closest to the material properties of the medium, water. Then, the matching layer with gradient properties was assumed to be a third-order curve of the volume fraction of the filler along x, and the coefficients a, b, c, and the thickness L were chosen as design variables.

$$\varphi(x) = ax^3 + bx^2 + cx^2 + d \tag{9}$$

$$\varphi(0) = d = 0.5 \tag{10}$$

$$\varphi(L) = aL^3 + bL^2 + cL^2 + d = 0 \tag{11}$$

First, K and G of the matching layer were calculated at a position x by using eq. (4) and eq. (9). After that, they were converted to acoustic impedance Z by eq. (7) and eq. (8) because the acoustic impedance is a product of the density and sound speed.

According to transmission line theory [14], the reflection coefficient can be expressed as a function of the acoustic impedance. When the acoustic impedance at x is $Z(x)$, the total reflection coefficient Γ from $x = 0$ to $x = L$ is expressed in terms of the wave frequency f:

$$\Gamma(f) = \frac{1}{2}\int_{x=0}^{x=L} e^{-2j\frac{2\pi f}{c(x)}x} \frac{d}{dx} ln\left(\frac{z(x)}{z(0)}\right) dx \tag{12}$$

where $c(x)$ is the wave speed at x.

To improve the signal sensitivity of an ultrasound transducer, it is essential to make the generated waves propagate while minimizing the reflection at the interface between the active material and its front material. On the other hand, if the reflection coefficient is low at a certain frequency and is not at frequencies near the certain frequency, then the frequency spectrum is expected to have a shape like a stiff mountain near the peak, which means a low bandwidth. As a result, the deviation of deflection should be low enough to get a broadband signal.

To express these requirements, the frequency interval was set from 0.5 f_c to 1.5 f_c and was divided into n subintervals. Then, each reflection coefficient was calculated at each n frequency, and the average and the deviation were also calculated from the reflection coefficients. Both the average and the deviation of the reflection coefficients should be minimized. If these numerical scales are different, they can cause problems when finding optimum values. Therefore, the objective function α was defined as a harmonic average of the two shown in eq. (16).

$$f_1(=0.5f_c)\,,\ f_2\,,\ f_2\,,\ \ldots\,,\ f_n(=1.5f_c) \qquad (13)$$

$$\mu = \frac{1}{N}\sum_{k=1}^{N}\Gamma(f_k) \qquad (14)$$

$$\sigma^2 = \frac{1}{N}\sum_{k=1}^{N}[\Gamma(f_k)-\mu]^2 \qquad (15)$$

$$\alpha = \frac{2\mu\sigma}{\mu+\sigma} \qquad (16)$$

3.3 Optimized feature of matching layer

The optimum value of this process is the local optimum rather than the global optimum. That means the result of the optimization can be different up to the initial values of *a*, *b*, *c*, and *L*. One of the optimized volume fractions of the filler and its characteristic impedance curve are shown in Fig. 2.

Fig. 2 shows that the characteristic impedance has a maximum value at the closest position to the active material ($x = 0$), and it monotonically decreases in the shape of a high-order curve. It was expected that the volume fraction of the filler decreases linearly over the thickness while it also makes the characteristic impedance decrease linearly. It seems that this curve shape comes from the matching layer thickness. If the thickness is large enough to ignore the change in the characteristic impedance, there will be theoretically no reflection at the interface when the waves propagate forward. However, the thickness was limited in the optimization process not to be oversized. It is thought that the optimization process found solutions while reducing the thickness of the matching layer and the curve shape in which the acoustic impedance decreases rapidly was derived.

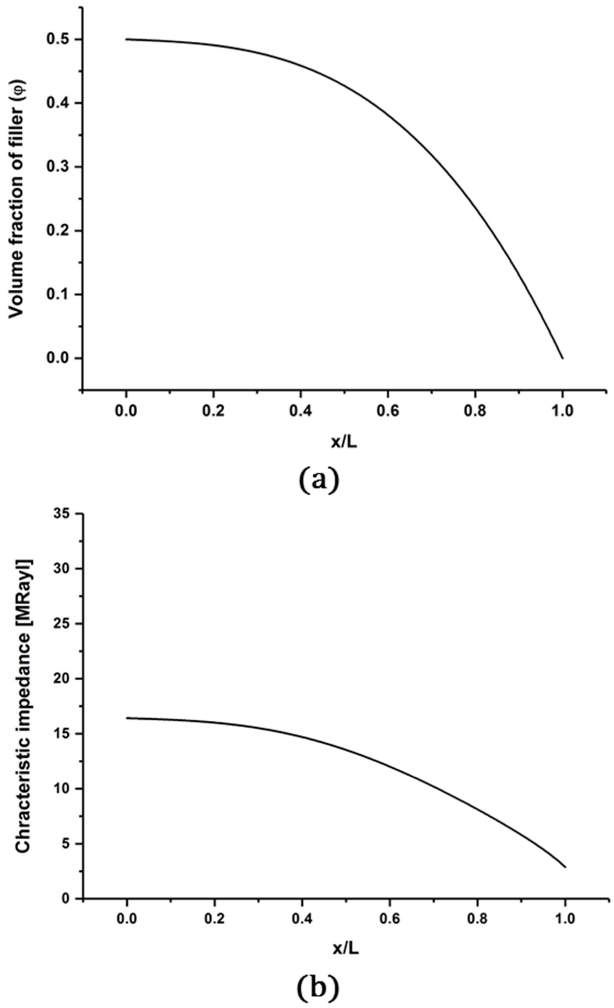
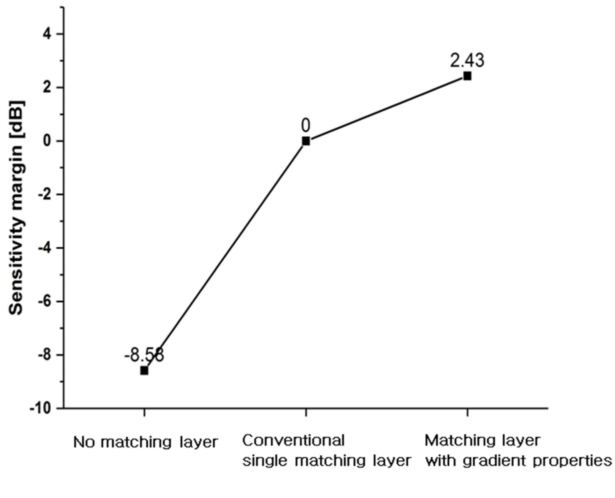


Fig. 2. (a) Volume fraction of filler, and (b) Characteristic impedance along /*x*/*L*.

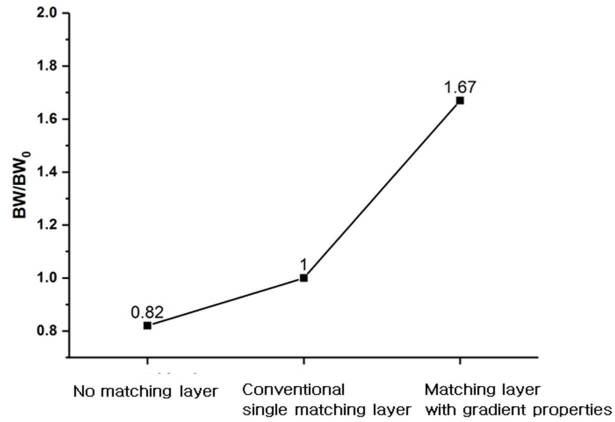
4. Evaluation of Signal Characterisitics of Ultrasound Transducer with Matching Layer

The ultrasound transducer in this paper behaves as an actuator when generating waves by an input voltage, and it also behaves as a sensor when it is excited by the reflected wave. It is not easy to describe the piezoelectric behaviors in a sequence; thus, the actuator mode and sensor mode were analyzed separately. In the actuator mode, an impulse voltage was applied to the piezoelectric material, and the sound pressure at the medium was calculated. Then, the sound pressure was used as input data to excite the sensor, and the voltage by the echo waves was calculated again.

The sensitivity and bandwidth results are shown in Fig. 3, which compares transducers with no matching layer (left), conventional single matching layer (middle), and proposed matching layer with gradient properties (right). This indicates that the optimized matching layer with gradient properties improved the signal characteristics of the ultrasound transducer with respect to both the sensitivity and bandwidth. The conventional single matching layer was evaluated and showed that it has an 8.58 dB improvement, while the optimized matching layer has about an 11 dB improvement in sensitivity compared to an ultrasound transducer without a matching layer. In terms of the bandwidth (BW), the transducer with the proposed matching layer has a 67 % percent improvement compared to the transducer with the conventional single matching layer (BW_0).



(a)



(b)

Fig. 3. The sensitivity and bandwidth results for transducers with (a) no matching layer, (b) conventional single matching layer, and (c) proposed matching layer.

In a conventional approach to designing a matching layer, the sensitivity becomes lower as the number of matching layers increases to get a signal with a broad band. However, the proposed matching layer in this study showed that both the sensitivity and bandwidth were improved at the same time. The reason for this result could be because the optimization process considered the thickness of the matching layer and the surrounding frequencies as well as the center frequency to find the optimum feature of the matching layer.

5. CONCLUSIONS

In this paper, an impedance matching layer with gradient properties was studied. A conventional matching layer has limitations in improving the signal characteristics of an ultrasound transducer because it should increase the number of layers to make the bandwidth large. As an alternative, an impedance matching layer with gradient properties was proposed, and its features were optimized. The matching layer was mathematically described as a particle-reinforced composite. To optimize the features of the matching layer, it was expressed as a third-order curve using the volume fraction of the filler along the thickness direction. Then, the material properties at each position were calculated by the relationship between the elastic material properties. The objective function was set to minimize both the averages and deviations of the reflection coefficients at each surrounding frequency as well as the center frequency.

As a result of this study, an optimized matching layer can improve both the sensitivity and the bandwidth of an ultrasound transducer, even though they usually conflict with each other in a transducer with a conventional matching layer.

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