초음파 센서를 위한 압전 세라믹 선택

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Selection of Piezoelectric Materials for Ultrasonic Transducers

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Abstract

We investigate the influence of individual properties of piezoceramics such as elastic, dielectric, piezoelectric constants, and the coupling factor on the performance of the transducer operating in thickness mode oscillation. The investigation employs equivalent circuit analysis techniques. Appropriate transfer functions are obtained and discussed which suggest optimum selection guides of piezoelectric ceramics for each purpose, i.e. a transmitter, a receiver, and a pulse-echo transducer. The guides can help ceramic scientists find the direction to proceed in new material development.

I. Introduction

Selection of ferroelectric compositions suited to ultrasonic transducers is tricky. The choice of a piezoelectric material for a particular application will, of course, be based on parameters which will depend upon the application. In some cases, the electromechanical coupling coefficient is of primary importance; in other cases, other parameters are more significant. In this paper, we investigate the influence of individual properties of piezoceramics such as elastic, dielectric, piezoelectric constants, and the coupling factor on the performance of a transducer operating in thickness mode oscillation. The investigation employs equivalent circuit analysis techniques. Appropriate transfer functions are obtained and discussed for each purpose, i.e. a transmitter, a receiver, and a pulse-echo transducer. Two types of piezoelectric materials are available to choose from, piezo-ceramics and piezo-polymers. They each have specific advantages and disadvantages. This study adapts the piezoceramics as the transducer material because they have a wide selection compared with piezo-polymers. The transfer functions suggest optimum selection guide of piezoelectric materials. Validity of the guide is confirmed with exemplary analyses of currently available materials, especially with PZT, one of the most widely accepted ultrasonic transducer materials. Generally there are two factors to take into account in designing a transducer, bandwidth and efficiency. In this paper, the specific application under consideration is pulse-echo detection of defects in deep locations, which require high power ultrasonics. Thus the authors pursue high efficiency while maintaining the bandwidth as wide as possible. The guides can also help ceramic scientists find the direction to proceed in new material development.

2. Transmitter

Figure 1 illustrates the piezoelectric element configuration under study. In practice, the front and back sides of the element are covered with appropriate thin layers to enhance acoustic impedance matching with a radiation load, and to reduce unnecessary ringing. Often also, an electric tuning circuit is attached to the element to improve the performance of the unit. Numerous literature is available to explain the effects of the other components [2, 3], and this study focus on the behavior of the piezoceramic element itself. Vibrating properties of piezoelectric ceramics are analyzed by the well known Mason's one dimensional equivalent circuit in Fig. 2 where Z_0 is the characteristic impedance, C_0 is the clamped capacitance, N is the turning ratio $C_0 * h_{33}$, h_{33} is the piezoelectric constant, f_0 is the open circuit resonant frequency of the piezoelectric element, and a is $\pi * f / f_0$. The radiation load is represented by a single value of the acoustic impedance which is equivalent to the combination of a true radiation load (water) and matching layers if present. In most transducer designs of practical interest, the assumptions of simple mechanical and electrical boundary conditions are not valid, and in many cases internal losses and nonlinear effects are significant. For the time being, both internal losses and nonlinear effects are neglected. Conducting electrodes in the element are assumed to be so thin that their effects are negligible. In the figure, Z_0, α, C_0 contain properties of the piezoceramic. With the circuit, the transmitting voltage ration of a transmitter is obtained in a simple form as follows.

TVR (transmitting voltage ratio of a transmitter) = F / V_i =

$$\frac{4\, i\, \pi\, f\, Z_0 Z_L \mathrm{Sin}^2[\frac{a}{2}]\, C_0\, h_{33}}{\{ 2\pi f Z_0 (Z_0 \mathrm{Sin}[a] - i Z_L \mathrm{Cos}[a]) - C_0 h_{33}^2 (4 Z_0 \mathrm{Sin}^2[\frac{a}{2}] - i Z_L \mathrm{Sin}[a]) \}} \qquad (1)$$

where Z_0 is the acoustic impedance of the element, i.e. $\sqrt{C^D_{33}\rho}$, ρ is the density, Z_L is the impedance of the radiation load, F is the acoustic force applied to the Z_L, V_i is the input voltage, , and $C_0 = \frac{\varepsilon^S_{33} A}{t} = 2\,\varepsilon^S_{33} f_0 \sqrt{\frac{\rho}{C^D_{33}}}$ for thickness t being $\frac{\lambda}{2} = \frac{1}{2 f_0}\sqrt{\frac{C^D_{33}}{\rho}}$. For a thickness vibrator, we have four material constants involved in the TVR, such as ρ, ε^S_{33}, C^D_{33} and h_{33}. In Eq. 1, the only variable fixed for now in f_0 which is determined by the specific application. When a piezoelectric element works as a transmitter, it is known that the resonant frequency lowers to [4]

$$f_s = f_0 \sqrt{1 - \frac{8\,\varepsilon^S_{33} h^2_{33}}{\pi^2 C^D_{33}}} = f_0 \sqrt{1 - \frac{8\, k^{t\,2}_{33}}{\pi^2}} \qquad (2)$$

due to the negative compliance - C_0 in Fig. 2. We already know that bandwidth of a transmitter is proportional to the coupling factor k^t_{33}. Hence, the only point of remaining interest is the magnitude of a signal at the resonance of the element. Density of piezoceramics is assumed to be constant because variation of density is almost negligible within each family of piezoelectric ceramics, such as PZT, $BaTiO_3$ and so on [5]. Then TVR / $\sqrt{\varepsilon^S_{33}}$ is a function of coupling factor k^t_{33} and impedance ration α not of individual elastic, dielectric, and piezoelectric constants of piezoceramics. Figure 3 is the variation of TVR / $\sqrt{\varepsilon^S_{33}}$ with $k^t_{33}{}^2$ and α at the frequency f_s. The author arbitrarily selects the calculation range which is from 0 to 1 for $k^t_{33}{}^2$ and from 1 to 30 for α. From the figure, for each value of a, corresponding value of $k^t_{33}{}^2$ can be obtained for the case of maximum TVR / $\sqrt{\varepsilon^S_{33}}$. As shown in the Fig. 3, as the ratio is smaller, the TVR / $\sqrt{\varepsilon^S_{33}}$ gets higher. It is the maximum when α is 1 and is the minimum when α is 30. It means that as the impedance of a piezoceramic is closer to that of a radiation load, the efficiency of a transmitter is better, which is a quite predictable result. However, there is a certain maximum in TVR / $\sqrt{\varepsilon^S_{33}}$, above or below which the transmitter efficiency decreases.

The above discussion is summarized as follows. At the beginning, we have four material parameters involved in the transducer. To get the highest TVR, we should determine the ratio α, first. Because density of a kind of piezoceramics is almost constant within its family, determining α means selecting C^D_{33} of the element. As shown in the Fig. 3, smaller α (smaller C^D_{33}) will give a higher TVR in addition to a larger bandwidth. From the figure, we should find the value of $k^t_{33}{}^2$ giving the highest TVR / $\sqrt{\varepsilon^S_{33}}$. $k^t_{33}{}^2$ is a function of remaining two variable, h_{33} and ε^S_{33}. What we want to obtain actually is TVR which is proportional to ε^S_{33} for a certain value of $k^t_{33}{}^2$ and α. Hence for the same $k^t_{33}{}^2$, the ceramic with a larger ε^S_{33} should be selected. In consideration of the bandwidth of the element, smaller ε^S_{33} and larger h_{33}, is more preferable. However, the band shape can be modified by addition of several matching layers to the element, and thus is given a lower priority than a higher TVR.

3. Receiver

Performance of a receiver can be analyzed with the same equivalent circuit in Fig. 2. Radiation load is replaced with an external acoustic force F', and output voltage V_0 is developed across C_0. Losses due to diffraction beam spread and attenuation in the beam path are neglected. Open circuit output is twice the output of the transmitting transducer. In the same manner as for the transmitter, the transfer function is obtained as

RFR (receiving force ratio of a receiver) = V_0 / 2F' =

$$\frac{\mathrm{Tan}^2[\frac{a}{2}]\, h_{33}}{2\pi f [(2 Z_0 \mathrm{Tan}[\frac{a}{2}] + i Z_L (\mathrm{Tan}^2[\frac{a}{2}] - 1)]} \qquad (3)$$

At the resonant frequency f_0 of a receiver, RFR is independent of the coupling factor and the characteristic impedance of piezoceramics. The only variable involved is h_{33}. What the equation means is that the higher is h_{33} of a piezoceramic, the better is the sensitivity of a receiver. However, in consideration of a bandwidth, the criteria applied to a transmitter is still valid for a receiver, lower Z_0 and higher k'^2_{33}.

4. Pulse-Echo Transmitter

Usually a single transducer is used as both a transmitter and a receiver as in pulse echo detection applications. Because the input of the receiving transducer is twice the output of the transmitting transducer, the overall transfer function is $V_0 / 2V_i$.

TF (overall transfer function of a transducer) =
TVR * RFR =

$$\frac{2\, k'^2_{33}\, \alpha\, \mathrm{Sin}^2[\frac{a}{2}]\, \mathrm{Tan}[\frac{a}{2}]\, \mathrm{Tan}[a]}{\{\, [\, \alpha\, (\, a\, \mathrm{Sin}[a] - 4\, k'^2_{33}\, \mathrm{Sin}^2[\frac{a}{2}]\,) + i\, (\, k'^2_{33}\, \mathrm{Sin}[a] - a\, \mathrm{Cos}[a]\,)\,]\, (\, 1 + i\, \alpha\, \mathrm{Tan}[a]\,)\, \}} \tag{4}$$

It is a function of coupling factor k'^2_{33} and impedance ratio α, which means that overall performance of a transducer is influenced not by individual characteristics of a piezoceramic but by its coupling factor and the ratio α. When the effect of the k'^2_{33} on the performance is checked, the result is as shown in Fig. 4 which shows the TF variation with response to k'^2_{33} for an exemplary value of α, 11. As k'^2_{33} increases, the bandwidth increases while the TF at the frequency f_s decreases slowly. The TF at the frequency f_0 keeps constant after certain value of k'^2_{33}. Generally the TF at f_0 is always not less than that at f_s. The highest TF in Fig. 4 is the point where the two peaks emerge to each other and show a single highest peak. The new peak is created at the frequency $(f_0 + f_s) / 2$. Variation of this new peak with k'^2_{33} and α is shown in Fig. 5. Generally the TF increases as α decreases and k'^2_{33} increases while it shows a certain maximum at each k'^2_{33} for its corresponding α.

The above discussion is summarized as follows. For a given value of Z_L, we can determine the ration α, which means determining the value of C^D_{33}. From the Fig. 5, we can define a corresponding value of k'^2_{33} for the α to get a maximum TF. The maximum TF for each pair of (k'^2_{33}, α) increases with k'^2_{33}, and decreases with α. This trend is good in consideration of the bandwidth as well. Thus to get the maximum TF, we should select the piezoceramic having the lowest α for a given radiation load and the highest k'^2_{33} available.

5. Conclusion

Selection of proper piezoelectric materials is a tricky and important problem in developing ultrasonic transducers. In this paper, we investigated the influence of individual properties of piezoceramics such as elastic, dielectric, piezoelectric constants, and coupling factor on the performance of a thickness mode transducer. Appropriate transfer functions were derived for each purpose, i.e. a transmitter, a receiver, and a pulse-echo transducer. They suggested optimum selection guides of piezoelectric ceramics. The guide can also help ceramic scientists find the direction to proceed in new material development.

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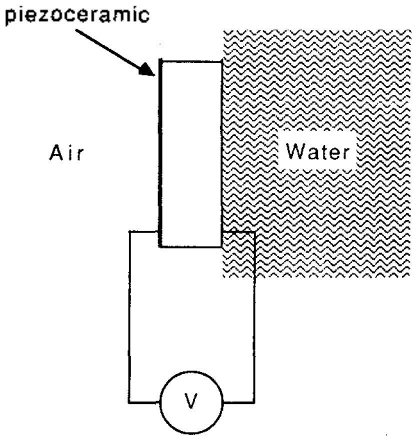

Fig. 1. A schematic diagram of piezoceramic element configuration

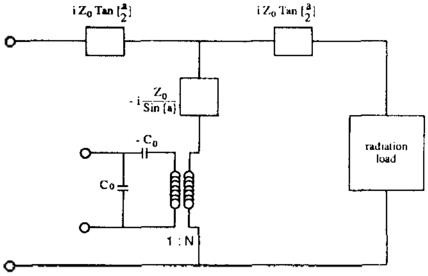

Fig. 2. An equivalent circuit for a thickness mode vibrator

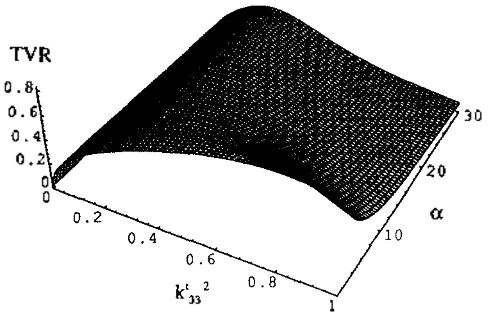

Fig. 3. Variation of TVR with k'^{2}_{33} and α

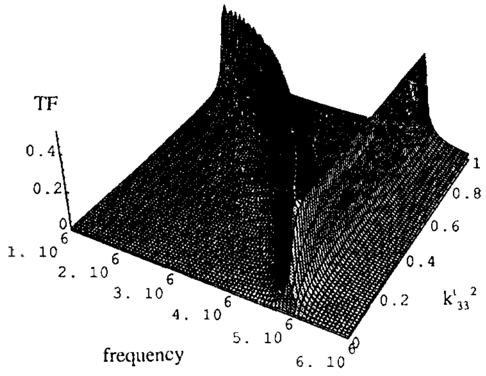

Fig. 4. Variation of overall transfer function of a transducer with k'^{2}_{33} for α of 22

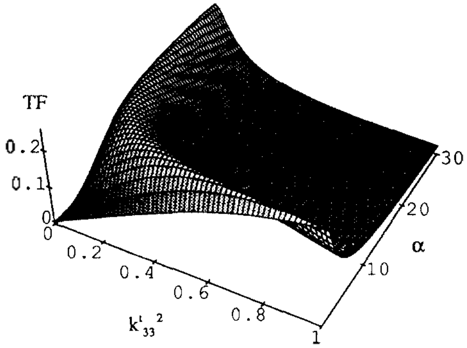

Fig. 5. Variation of the TF of a transducer at the frequency of ($f_s + f_0$) / 2