Effects of Piezoelectric Material Constants on the Performance of Ultrasonic Transducers

초음파 탐촉자 성능에 미치는 압전재료 물성의 영향

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ABSTRACT

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

요 약

초음파 탐촉자의 개발에 필요한 압전재료의 선택을 위하여 탐촉자의 성능에 영향을 미치는 탄성, 유전, 압전 상수의 영향을 알아보았다. 해석 방법으로는 등가회로를 통한 두께 모드 발신기, 수신기, 펄스 반사기의 전달함수를 구하였으며, 이로부터 압전재료의 각 물성치가 가져야 할 바람직한 특성을 제시하였다. 본 연구의 결과는 재료의 선택시와 더불어 세라믹 공학자들이 초음파용 압전소자를 개발함에 있어 적절한 지침이 될 수 있을 것이다.

Ⅰ. Introduction

The piezoelectric element of a transducer determines fundamental characteristics of the unit. Piezoelectric trasducer materials have held a key position as electroacoustic transducers in the sonic and ultrasonic range for some sixty years [1]. There has been no serious challenge to this position for sonic transducers into dense media, or for ultrasonic transducers up to about a gigacycle. The recent development of transducer materials with low acoustic impedance and relatively high coupling constant has opened up new possibilities for transducer improvements in NDT and other applications. These new materials offer intrinsically wide bandwidth, high piezoelectric constants d and g, and interesting mechanical properties, such as flexibility and resistance to shock. However selection of materials suited to a particular application is tricky. The choice will be based on parameters that will depend upon the application. In some cases, the electromechanical coupling coefficient is of primary importance ; in other cases, other parameters are more significant [2].

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 an ultrasonic transducer operating in thickness mode oscillation. The investigation employs equivalent

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circuit analysis techniques. 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. Appropriate transfer functions are obtained and discussed for each purpose, i.e., a transmitter, a receiver, and a pulse-echo transducer. The transfer functions suggest optimum selection guides of piezoelectric materials. Some general brief guides are available already [3]. The criteria developed in this paper differ from them in that full analysis is performed with an equivalent circuit. 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.

II. 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 [4,5], and this study focuses on the behavior of the piezoceramic element itself.

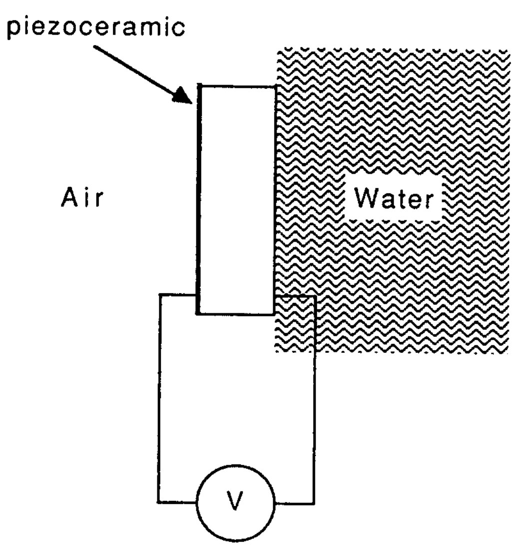

Fig 1. A schematic diagram of piezoceramic element configuration

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 acoustic impedance that 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, a and C_0 contain properties of the piezoceramic. With the circuit, the transmitting voltage ratio 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. $\sqrt{C_{33}^D \rho}$, C_{33}^D is elastic stiffness constant measured at constant electric displacement field, 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, ϵ_{33}^S is the permittivity measured at constant strain, and $C_0 = \frac{\varepsilon^S_{33} A}{t} = 2\varepsilon^S_{33} f_0 \sqrt{\frac{\rho}{C^D_{33}}}$ for the 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 is f_0 that is determined by the specific application. When material constants of piezoceramics replace the lumped parameters, the TVR changes to

$$4 i\pi \sqrt{\rho}\sqrt{\varepsilon^S_{33}}\,\frac{f\, k^t_{33}\,\mathrm{Sin}^2[\frac{a}{2}]}{\alpha\,\mathrm{Sin}[a](a-2k^{t2}_{33}\mathrm{Tan}[\frac{a}{2}])+i(k^{t2}_{33}\mathrm{Sin}[a]-a\mathrm{Cos}[a])} \quad (2)$$

where k^t_{33} is an electro-mechanical coupling factor, $k^2_t = \frac{h^2_{33}\,\varepsilon^S_{33}}{C^D_{33}}$, and α is the ratio Z_0/Z_L. Equation 2 reveals the effect of ε^S_{33} on the performance of a transmitter in a clear fashion. The TVR is proportional to $\sqrt{\varepsilon^S_{33}}$.

When a piezoelectric element works as a transmitter, it is known that the resonant frequency lowers to [6]

$$f_S = f_0\sqrt{1-\frac{8\varepsilon^S_{33}h^2_{33}}{\pi^2 C^D_{33}}} = f_0\sqrt{1-\frac{8k^{t2}_{33}}{\pi^2}} \quad (3)$$

due to the negative compliance $-C_0$ in Fig.2 which can be confirmed with the Eq. 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. The shifted resonance frequency f_S is substituted into Eq.2 and the TVR takes the following form.

$$4 i f_0 \sqrt{\rho}\sqrt{\varepsilon^S_{33}}\,\frac{a\, k^t_{33}\,\mathrm{Sin}^2[\frac{a}{2}]}{\alpha\,\mathrm{Sin}[a](a-2k^{t2}_{33}\mathrm{Tan}[\frac{a}{2}])+i(k^{t2}_{33}\mathrm{Sin}[a]-a\mathrm{Cos}[a])} \quad (4)$$

where $a = \frac{\pi f_S}{f_0} = \sqrt{\pi^2 - 8k^{t2}_{33}}$. In the equation, the term $4 i f_0\sqrt{\rho}$ is assumed to be constant because fluctuation of density is almost negligible within each family of piezoelectric ceramics, such as PZT, $BaTiO_3$ and so on. Then TVR $/\sqrt{\varepsilon^S_{33}}$ is a function of the coupling factor k^t_{33} and the impedance ratio α, not of individual material constants. Figure 3 is the variation of TVR $/\sqrt{\varepsilon^S_{33}}$

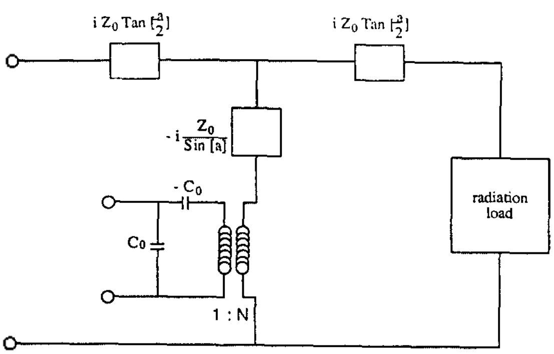

Fig 2. An equivalent circuit for a thickness mode vibrator

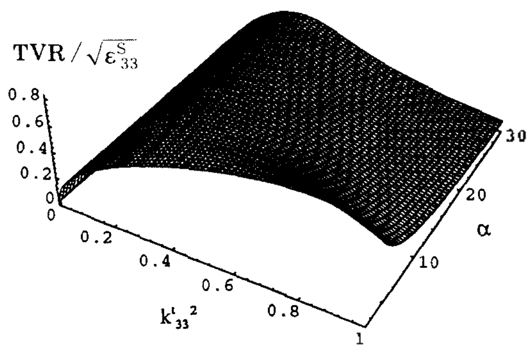

Fig 3. Variation of TVR with $k^{t\,2}_{33}$ and α

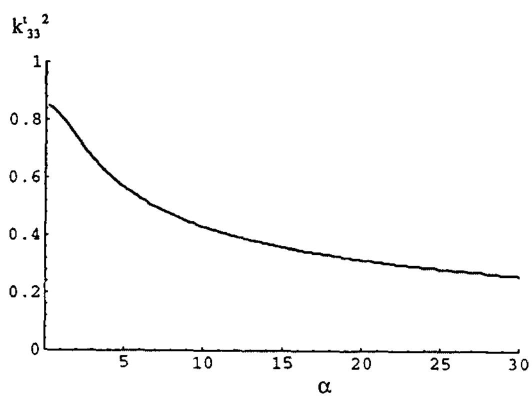

Fig 4. The relationship between α and $k^{t\,2}_{33}$ for the maximum TVR corresponding to the peak line in Fig. 3

with ${k^t_{33}}^2$ and α at the frequency f_s. The author arbitrarity selects the calculation range that is from 0 to 1 for ${k^t_{33}}^2$ and from 1 to 30 for α. The global maximum occurs when α is 1 and ${k^t_{33}}^2$ is 1. In Fig. 3, $TVR/\sqrt{\varepsilon^S_{33}}$ decreases with the increase of the ratio α. 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 gets closer to that of a radiation load, the efficiency of a transmitter gets higher. However, with ${k^t_{33}}^2$, there is a certain local maximum in $TVR/\sqrt{\varepsilon^S_{33}}$, abover or below which the transmitter efficiency decreases. Figure 4 is the curve showing the relationship between ${k^t_{33}}^2$ and α, which corresponds to the connection of local peaks at specific pairs of ${k^t_{33}}^2$ and α in Fig. 3. The curve is interpolated by a third order polynomial as

$$k^{t2}_{33} = -0.47\cdot10^{-4}\alpha^3 + 0.30\cdot10^{-2}\alpha^2 - 0.68\cdot10^{-1}\alpha + 0.86 \quad (5)$$

that is accurate with its standard deviation less than 1 %. For a certain α, when ${k^t_{33}}^2$ gets the value given by the equation, we can get the locally maximum TVR. Even though not exact, as ${k^t_{33}}^2$ gets closer to the curve in Fig. 4, the TVR will increase. Generally it is believed that the higher is the k^t_{33}, the better is the performance of a transmitter. This is true in a practical sense because currently commercially available piezoceramics have quite low ${k^t_{33}}^2$'s, at most 0.26 [7]. Usually the radiation load reflected to the piezoelectric element is modified by several matching layers. With the total equivalent radiation load Z_L including the effects of matching layers, the ratio α is not larger than 10 for most transducers. Even for the piezoceramic, for example PZT, directly exposed to water, α is less than 25. Equation 6 gives ${k^t_{33}}^2$ of 0.3 for the α of 25. The smaller α requires the larger ${k^t_{33}}^2$. Hence, just saying that higher k^t_{33} improves the performance of a transmitter does not violate the guide rule of Eq. 5 for the present time. However, if material scientists are to be able to develop the piezoceramics having much larger ${k^t_{33}}^2$, we should select the one meeting the condition of Eq. 5. In that situation, too large ${k^t_{33}}^2$ would not be beneficial any more. Even for now, in selecting piezoceramics, we should find the one that has a coupling factor closest to the curve in Fig. 4 for a given value of α.

The above discussion is summarized as follows. At the beginning, we have four material parameters involved in the transducer, such as ρ, ε^S_{33}, C^D_{33} and h_{33}. Of the four, the density ρ of each kind of piezoceramics is assumed to be constant within its family. To get the highest TVR, we should determine the ratio α, first. Determining α means selecting C^D_{33} of the element. As shown in Fig. 3, smaller α gives a higher $TVR/\sqrt{\varepsilon^S_{33}}$ in addition to a larger bandwidth. Hence, the piezoceramic with a smaller C^D_{33} should be selected. Then we should find the one having the ${k^t_{33}}^2$ closest to the value calculated with the equation 5. ${k^t_{33}}^2$ is a function of remaining two variables, h_{33} and ε^S_{33}. What we actually want to obtain is TVR that is proportional to $\sqrt{\varepsilon^S_{33}}$ for a certain value of ${k^t_{33}}^2$ and α. Therefore for the same ${k^t_{33}}^2$, the ceramic with a larger ε^S_{33} should be chosen. In consideration of bandwidth, smaller ε^S_{33} and larger h_{33} for the same ${k^t_{33}}^2$ is 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. This procedure defines all the destinations the three parameters should reach.

III. 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) $= V_0/2F =$

$$\frac{\mathrm{Tan}^2[\frac{a}{2}]\, h_{33}}{2\pi f[(2Z_0\,\mathrm{Tan}[\frac{a}{2}] + iZ_L(\mathrm{Tan}^2[\frac{a}{2}]-1)]} \qquad (6)$$

For a receiver, the maximum response occurs at f_0 [6]. At this frequency, the Eq. 6 simplifies to

$$\frac{h_{33}}{2i\pi f_0 Z_L}. \qquad (7)$$

It is independent of the coupling factor and the characteristic impedance of piezoceramics. The only variable involved is h_{33}. However it should be emphasized that the Eq. 7 is valid only at the resonance. Below or above resonance, all the other parameters will be coupled in the RFR as shown in Eq. 6. What is meant by Eq. 7 is that the higher is h_{33} of a piezoceramic, the better is the sensitivity of a receiver. In consideration of bandwidth, the criteria applied to a transmitter is still valid for a receiver, lower Z_0 and higher ${k^t_{33}}^2$. Therefore for an efficient receiver, we should select the piezoceramic with small C^D_{33} and large ${k^t_{33}}^2$. For the same ${k^t_{33}}^2$, large h_{33} and small ε^S_{33} is desirable.

Ⅳ. Puls-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** =

$$\frac{2{k^t_{33}}^2\alpha\,\mathrm{Sin}^2[\frac{a}{2}]\,\mathrm{Tan}[\frac{a}{2}]\,\mathrm{Tan}[a]}{\{\alpha(a\,\mathrm{Sin}[a]-4{k^t_{33}}^2\,\mathrm{Sin}^2[\frac{a}{2}])+i({k^t_{33}}^2\,\mathrm{Sin}[a]-a\,\mathrm{Cos}[a])\}(1+i\alpha\,\mathrm{Tan}[a])} \qquad (8)$$

It is a function of coupling factor k^t_{33} and impedance ratio α, which means that overall performance of a transducer is not influenced by individual characteristics of a piezoceramic. When

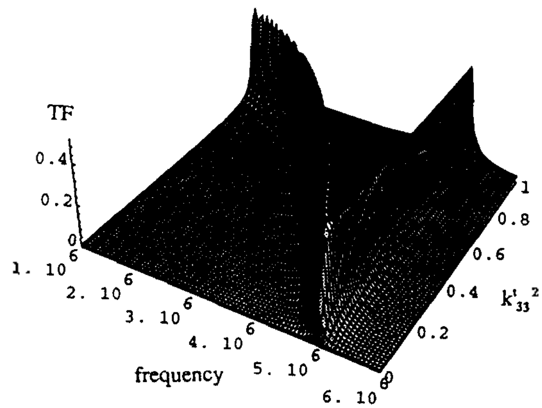

Fig 5. Variation of overall transfer function of a transducer with ${k^t_{33}}^2$ for α of 22

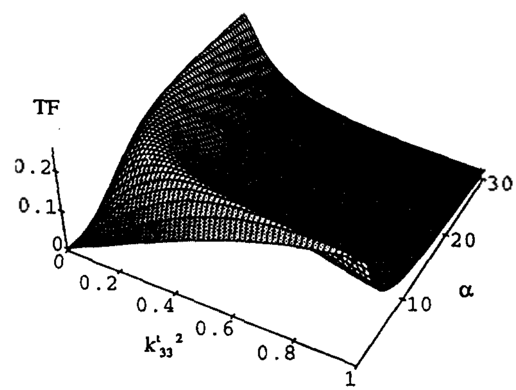

Fig 6. Variation of the TF of a transducer at the frequency of $(f_s+f_0)/2$

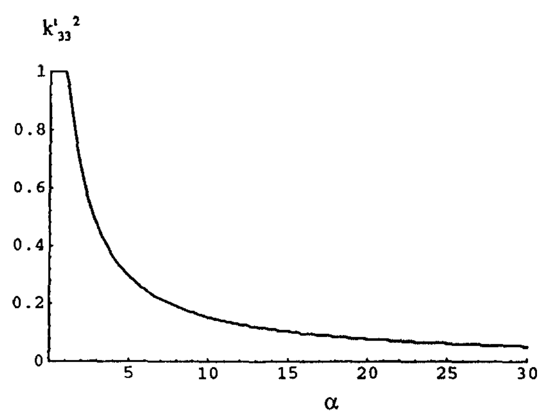

Fig 7. The relationship between the ${k^t_{33}}^2$ and the α for the maximum TF corresponding to the peak line in Fig. 6

the effect of the ${k_{33}^t}^2$ on the performance is checked, the result is as shown in Fig. 5 that shows the TF variation with respect to ${k_{33}^t}^2$ for an exemplary value of α, 11. The f_0 is set to be 5 MHz. As ${k_{33}^t}^2$ increases, the bandwidth increases, too. The TF at f_0 keeps constant after a certain value of ${k_{33}^t}^2$ while the TF at the frequency f_s decreases slowly. Generally the TF at f_0 is always not less than that f_s. The highest TF in Fig. 5 occurs at the point where the two peaks at f_0 and f_s 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 ${k_{33}^t}^2$ and α is shown in Fig. 6. The TF increases with the increase of α and with the decrease of ${k_{33}^t}^2$, while it shows local maximums at specific pairs of ${k_{33}^t}^2$ and α. What interests us is the peak line in the figure and it is separated into Fig. 7. The curve in Fig. 7 is interpolated as Eq. 9 with its standard deviation less than 3 %.

$$k_{33}^{t2}=0.12\cdot10^{-4}\alpha^4-0.84\cdot10^{-3}\alpha^3-0.22\cdot10^{-1}\alpha^2-0.24\alpha+1.09 \quad (9)$$

The curve indicates that we can get the locally highest TF if we select a piezoceramic having ${k_{33}^t}^2$ on the curve for its corresponding α. The global maximum is obtained when α is 1 and ${k_{33}^t}^2$ is 1.

The above discussion is summarized as follows. For a given value of Z_L, we can determine the ratio α, which means determining the value of C_{33}^D. From the Fig. 7, we can define a corresponding value of ${k_{33}^t}^2$ for the α to get a local maximum of TF. The local maximum of TF for each pair of ${k_{33}^t}^2$ and α increases with ${k_{33}^t}^2$, 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 ${k_{33}^t}^2$ available.

V. Discussion

So far, all the analyses have been performed with the assumption that all the non-linear effects and the loss terms are negligible for piezoceramics. Their properties are not linear functions of electrical and mechanical stress. The inherent nonlinear nature of piezoelectric ceramics or ferroelectric crystals leads to considerable difficulty in characterization. With very low electric or mechanical drive the piezoelectric ceramics may be considered strictly linear in their behavior, even though reversible domain wall motion enhances the piezoelectric and dielectric constants and increases compliance [8]. With increasing electric or mechanical drive, there is a disproportionate increase in piezoelectric response. High electric drive also results in a more than linear increase in dielectric displacement and an increase in dielectric loss. High mechanical drive similarly produces a disproportionate increase in mechanical displacement and an increase in mechanical loss. Aging effects also cause the properties to change with time. These effects are frequency dependent, being most severe under very low frequency and static conditions. The limits of linear behavior vary widely for different piezoelectric ceramics, being roughly related to the coercive force. Therefore the investigations performed in this paper are valid in strictly linear range of a piezoceramic. In the same sense, the analysis results do not hold good for piezo-polymers which inherently include fairly large elastic, dielectric and piezoelectric loss terms. However, the method is still valid for the piezo-polymers if complex material constants are plugged into the equivalent circuit.

The piezoceramics meeting all the conditions developed in this paper are not available at the present time. However the criteria in the previous sections can still do two important roles. First, among presently available piezoceramics, we can select the one that has the meterial parameters closest to the conditions. Second, ceramic engineers can take them as a guide rule to proceed with in development of ultrasonic transducer materials. Material parameters of piezoceramics can be optimized for specific applications by a controlled doping as shown in the

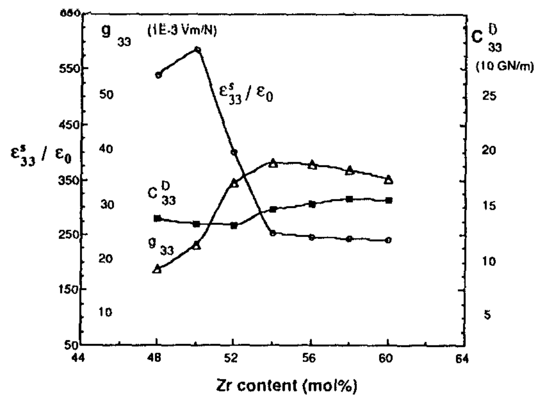

Fig 8. Variation of material constants C_{33}^D, g_{33} and ε_{33}^S of PZT with the addition of Zr

exemplary data of Fig. 8. As an example, for PZT, there exists a multitude of different doping ions that can be classified into four groups :

(1)Donor dopants, e.g., La, Nb, Sb, or W, which are incorporated at a lattice site of lower valence (e.g., La^{3+} at Pb^{2+} sites). These donor dopings lead to increased dielectric constants and coupling factor(up to 0.7) but also decreased mechanical Q and coercive field. The elastic modulus is significantly reduced [9].

(2)Transition metals, e.g., Fe, Mn, Ni, Co, which are incorporated at a lattice site of higher valence (e.g., Fe^{3+} at Ti^{4+} sites), thus showing acceptor character. These acceptor dopants have an effect just opposite to that of the above donors [10].

(3)Transgressing the solubility limit of the doping species which allows a second phase to be formed at the grain boundaries and this, by means of space-charge effects, also increases the stability of ceramics [11].

(4)Softeners or hardeners used in doping concentrations of 2% at most which allows the boundary between tetragonal and rhombohedral phases to extend from a mid horizontal axis upward and lead to a region of maximum piezolectric modulus and permittivities [12].

Ⅵ. 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 the coupling factor on the performance of a thickness mode transducer. The investigation employed equivalent circuit analysis techniques. Appropriate transfer functions were derived for each purpose, i.e., a transmitter, a receiver, and a pulseecho transducer. They suggest optimum selection guides of piezoelectric ceramics. The guides can also help ceramic scientists find the direction to proceed in new material developmemt.

References

1. H. Jaffe and D. A. Berlincourt, "Piezoelectric transducer materials," Proceedings of the IEEE, vol.53, No.10, p.1372-1386, 1965.
2. G. J. Posakony, "Engineering aspects of ultrasonic piezoelectric transducer design," Proceedings of Ultrasonics Symposium, p.1-9, 1975.
3. J. Callerame, H. Tancrell and D. T. Wilson, "Transmitters and receivers for medical ultrasonics," Proceedings of Ultrasonics Symposium, p.407-411, 1979.
4. G. Kossoff, "The effects of backing and matching on the performance of piezoelectric ceramic transducers," IEEE Transactions on Sonics and Ultrasonics, vol.13, No.1, p.20-30, 1966.
5. J. H. Goll, "The design of broad-band fluid-loaded ultrasonic transducers," IEEE Transactions on Sonics and Ultrasonics, vol.26, No.6, p.385-393, 1979.
6. T. M. Reeder and D. K. Winslow, "Characteristics of microwave acoustic transducers for volume wave excitation," vol.17, No.11, p.927-941, 1969.
7. B. Jaffe, W. R. Cooke, Jr., and H. Jaffe, Piezoelectric ceramics, Academic press, New York, 1971.
8. M. E. Lines and A. M. Glass, Principles and applications of ferroelectrics and related materials, Clarendon Press, Oxford, 1977.
9. K. H. Hardtl, "Defect structure of PLZT doped with Mn, Fe and Al," Ferroelectrics, vol.12, p.9, 1976.
10. F. Kulcsar, "Electromechanical properties of PZT

ceramics modified with certain three or five valent additions," Journal of Americal Ceramic Society, vol.42, No.7, p.343-349, 1959.

11. H. Thomann, "Stabilization effects in piezoelectric lead titanate zirconate ceramics," Ferroelectrics, vol.4, p.141-146, 1972.
12. W. Heywang and H. Thomann, "Tailoring of piezoelectric ceramics," Annual Review of Material Sciences, vol.14, p.27-47, 1984.

▲Yongrae-Roh : Vol.11 No.1E

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