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Consideration of Feedback Mechanism in Depolarizing Field in Dielectric Material and Piezoelectric Transducer

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1. Introduction

The depolarizing field strongly affects the characteristics of dielectric and piezoelectric materials and devices.

The permittivity ε of a dielectric material should be measured in the environment in which the depolarization coefficient is maximal. In this study, firstly, a feedback system to estimate the permittivity is considered, and by comparing a similar feedback system to estimate the permeability μ of a magnetic material, it is clarified that appropriate estimates of ε and μ can be obtained when no feedback is provided and that what is called E-B correspondence is more essential than E-H one.

In a piezoelectric transducer, the depolarizing field causes another effect on the characteristics of mechanical wave, and the behavior of the transducer is classified into two different types: that with longitudinal (L-) effect and that with transverse (T-) effect. In this study, another type of 'feedback effect' of depolarizing field is considered, which gives a more reasonable explanation for the characteristics of piezoelectric transducer.

2. Feedback system for measurement of permittivity and permeability

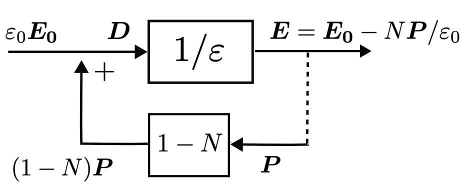

Fig. 1: Feedback diagram for measuring $1/\varepsilon$. N ($0 < N < 1$) is an (averaged) depolarizing coefficient, which affects the measurement via the feedback of depolarizing field from the output (electric field) to the input (dielectric flux density). $N \to 0$ for an infinitely long rod, and $N \to 1$ for an infinitely thin plate.

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Figure 1 shows the effect of feedback of depolarizing field on measuring $1/\varepsilon$, where $\boldsymbol{E_0}$ is an input electric field, N ($0 < N < 1$) is an (averaged) depolarizing coefficient, $\boldsymbol{P}$ is a generated polarization, and a dielectric flux density $\boldsymbol{D}$ is related with a total electric field $\boldsymbol{E}$ as $\boldsymbol{D} = \varepsilon\boldsymbol{E} = \varepsilon_0\boldsymbol{E} + \boldsymbol{P}$. A portion of the output is fed back into the input as $(1-N)\boldsymbol{P}$.

From the closed-loop characteristic, in which the output $\boldsymbol{E}\left(= \frac{\boldsymbol{D}-\boldsymbol{P}}{\varepsilon_0}\right) = \boldsymbol{E_0} - N\frac{\boldsymbol{P}}{\varepsilon_0}$ and the input $\boldsymbol{D} = \varepsilon_0\boldsymbol{E_0} + (1-N)\boldsymbol{P}$, an estimated value of $1/\varepsilon$ is obtained as a function of N:

$$\frac{1}{\varepsilon}(N) = \frac{E_0 - N\frac{P}{\varepsilon_0}}{\varepsilon_0(E_0 + (1-N)\frac{P}{\varepsilon_0})}, \tag{1}$$

which provides a correct value of $1/\varepsilon$ when $N \to 1$; that is, when no output is fed back into the input.

For comparison, the effect of demagnetizing field on the measurement of a permeability μ is schematized in Fig. 2, where $\boldsymbol{H_0}$ is an input magnetic field strength, N ($0 < N < 1$) is an averaged demagnetizing coefficient, $\boldsymbol{M}$ is a generated magnetization, and a magnetic field $\boldsymbol{B}$ is related with a total magnetic field strength $\boldsymbol{H}$ as $\boldsymbol{B} = \mu\boldsymbol{H} = \mu_0(\boldsymbol{H} + \boldsymbol{M})$, where $\boldsymbol{H} = \boldsymbol{H_0} - N\boldsymbol{M}$ due to the feedback of $\boldsymbol{M}$ by $-N\boldsymbol{M}$. From Fig. 2, μ is estimated as

$$\mu(N) = \frac{\mu_0(H_0 + (1-N)M)}{H_0 - NM}, \tag{2}$$

in which a correct estimate of μ can be obtained when $N \to 0$ without any feedback effect.

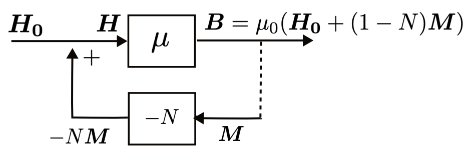

Fig. 2: Feedback diagram to estimate μ.

The comparison of the above feedback systems endorses the correspondence of $\boldsymbol{E} \leftrightarrow \boldsymbol{B}$, rather than that of $\boldsymbol{E} \leftrightarrow \boldsymbol{H}$, which has often been discussed in the interpretation of electromagnetic theory.

3. Influence of depolarization field on piezoelectric transducers

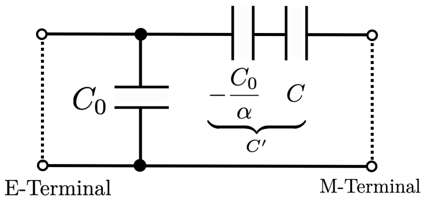

Fig. 3: Equivalent circuit of a piezoelectric transducer at $\omega \to 0$. $\alpha = 1$ for L-effect and $\alpha = 0$ for T-effect.

Figure 3 shows the equivalent circuit of a piezoelectric transducer at low frequency limit, $\omega \to 0$, in which C_0 and C are the dielectric capacitance and the 'intrinsic' elastic equivalent capacitance, respectively. The electromechanical coupling coefficient, $k^2 = C'/(C_0 + C') = (1/C_0)/(1/C_0 + 1/C')$, is calculated as

$$k^2 = \frac{C}{C_0 + (1-\alpha)C} \qquad (0 \leq k^2 < 1), \tag{3}$$

where $\alpha = 1$ for L-effect, and $\alpha = 0$ for T-effect.

The characteristics of piezoelectric transducers can schematically be classified into four patterns by considering whether L- or T-effect works and whether the E-terminal in Fig. 3 is opened or shorted, as shown in Fig. 4.

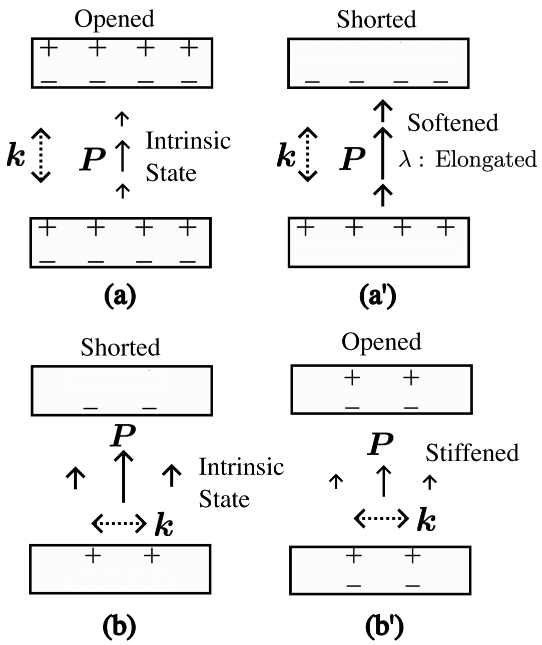

Fig. 4: Schematic diagram of the relationship among the surface charges on electrodes, polarization $\boldsymbol{P}$, and wavenumber vector $\boldsymbol{k}$. (a), (a') L-effect ($\boldsymbol{P} \parallel \boldsymbol{k}$) for opened and shorted states, respectively. (b), (b') T-effect ($\boldsymbol{P} \perp \boldsymbol{k}$) for shorted and opened states, respectively.

In the L-effect ($\boldsymbol{P} \parallel \boldsymbol{k}$), the opened state is regarded as the intrinsic state, as shown in Fig. 4(a), due to the continuity of $\boldsymbol{D}$ normal to $\boldsymbol{k}$-planes that are perpendicular to $\boldsymbol{k}$. In the shorted state, Coulomb's force from the residual charges on the electrodes elongates the wavelength of polarization wave λ , and the elasticity is softened, as shown in Fig. 4(a′), which is represented by $-C_0$ ($\alpha = 1$) in Fig. 3.

In the T-effect ($\boldsymbol{P} \perp \boldsymbol{k}$), the shorted state is regarded as the intrinsic state, as shown in Fig. 4(b), due to the continuity of $\boldsymbol{E}$ tangential to $\boldsymbol{k}$-planes. In the opened state, Coulomb's force from the surplus charges on the electrodes condenses $\boldsymbol{P}$ and the elasticity is stiffened, while λ is invariant, as shown in Fig. 4(b′), which is represented by a series connection of C_0 in Fig. 3.

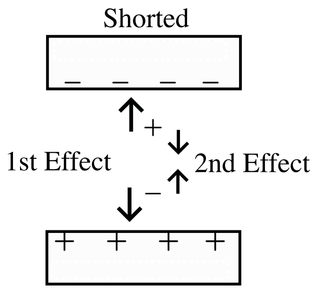

Fig. 5: Primary Coulomb interaction between the surface charges and $\boldsymbol{P}$, and secondary Coulomb interaction inside $\boldsymbol{P}$ as a negative feedback process.

As $\boldsymbol{P}$ becomes larger, a negative feedback process is expected to occur, as shown in Fig. 5, moderating the decrease of elastic stiffness, especially in the case of a high-k^2 material. This process is represented by (I) the depression of the effect of negative capacitance $-C_0$ in the L-effect and (II) the addition of another positive capacitance in series in the T-effect, represented in common as

$$\alpha \to \alpha + \Delta\alpha \qquad (\Delta\alpha < 0) \tag{4}$$

In the L-effect ($\alpha = 1$), unnaturally, the wavelength $\lambda \to \infty$ as $C \to C_0$ at the electrical resonance (shorted state), and $k^2 > 1$ in eq. (3) if $C > C_0$. Nature is self-consistent, and the above negative feedback effect keeps the value of λ and k^2 appropriately. (In addition, while the total elastic capacitance is depressed by the effect of $\Delta\alpha (< 0)$, the inertial inductance is expected to be enhanced by way of compensation.)