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High power characteristics at antiresonance frequency of piezoelectric transducers

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Abstract

First in this paper, the loss in piezoelectric ceramics is described. Antiresonance is the vibration under constant D (electric displacement) driving, and therefore electro-mechanical loss becomes almost zero; resonance is the vibration under constant E (electric field) driving, and then there exists large electro-mechanical loss. The relations between antiresonance and the constant D driving are explained. Next, a method of measuring the high-power characteristics is described for antiresonance frequency. Experimental results for the quality factor and temperature rise and other equivalent constants are then shown as high-power characteristics obtained at the antiresonance frequency. Finally, some considerations for the stable-state driving of the high-power piezoelectric devices are described.

Keywords: High-power characteristics; Antiresonance; Constant current driving

1. Introduction

There exist two kinds of electrical resonance in piezoelectric transducers. One is the so-called resonance and the other is antiresonance, and both resonances are mechanical ones. The former represents the mechanical resonance vibrating under the electric short-circuit condition, while the latter represents the mechanical resonance vibrating under the electric open-circuit condition. In this paper, losses at the resonance and antiresonance are described, and the measuring method and experimental results of the high-power characteristics at antiresonance are given.

First in this paper, losses in the piezoelectric ceramics are described. Under constant D (electric displacement) driving, electro-mechanical loss becomes almost zero, while under constant E (electric field) driving, there exists large electro-mechanical loss. The former situation is related to antiresonance, and the latter situation is related to the resonance.

Next, methods of measuring the high-power characteristics – that is, the vibrational level dependence of the equivalent circuit constants – are described for the antiresonance frequency. Some experimental results are then shown. Furthermore, some considerations on the stable-state driving of the high power piezoelectric devices are given.

2. Antiresonance as a vibration under constant electric displacement

In the case of piezoelectric transverse coupling, the fundamental equations of the piezoelectric transducer under constant electric displacement are given by

\[ S = s_{11} T + g_{31} D, \]

\[ E = -g_{31} T + \beta_{33} D, \]

where \( S, T, E \) and \( D \) are the strain, stress, electric field and electric displacement, respectively. \( s_{11}, g_{31} \) and \( \beta_{33} \) are the elastic compliance, piezoelectric constant and dielectric impermeability, respectively.

By using following boundary conditions,

\[ u(x = 0) = u_0, \quad u(x = \ell/2) = 0, \]

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longitudinal displacement $u$ is given by
\[ u = u_0 (\cos(kx) - \cot(kx/2) \sin kx), \]  
where $x$ is the horizontal coordinate, $l$ is the length of the transducer and $k$ is the wave-number. Stress $T$ is represented, as follows, by using the strain $S (= \partial u/\partial x)$,
\[ T = S/s_{31}^0 - g_{33} s_{31}^0 D \]
\[ = -k/s_{31}^0 u_0 (\sin kx + \cot(kx/2) \cos kx) - g_{33} s_{31}^0 D. \] 
At $x = 0$, stress $T$ equals to zero, then
\[ u_0 = -(g_{33}/k) D \tan(k \ell/2). \] 
By substituting Eqs. (5) and (6) into Eq. (2), electric field $E$ is given by
\[ E = \left[ - g_{33}^2/s_{31}^0 (\cos kx + \tan(k \ell/2) \sin kx) + \beta_{33}^T (1 - k_{33}^2) \right] D. \] 
Here, we consider a certain value $E_0$, which is constant over the whole length, and then the induced electric displacement $D'$ is obtained as
\[ D' = E_0 - (g_{33}/k) D \tan(k \ell/2). \] 
This electric displacement refers to the movement of charge when the electrode is fabricated on the whole surface, and then the electric field $E$ becomes $E_0$ (constant) over the whole length. When $E_0$ is put as
\[ E_0 = (2 - k_{33}^2)/(1 - k_{33}^2) D_0 \]
the integral of $D'$ with respect to $x$, that is, $\int_0^x D' dx$, becomes zero. From this relation, the following equation is derived,
\[ \tan(k \ell/2)/k \ell/2 = -(1 - k_{33}^2)/k_{33}^2. \] 
Eq. (10) gives the antiresonance frequency. Hence, it is concluded that the antiresonance is the vibration under constant $D$ and, after fabricating the electrode over the whole transducer surface, because of the piezoelectric reaction, the induced charge is cancelled; the electric field then becomes constant over the whole length.

3. Loss in piezoelectric ceramics

The Gibbs free energy $G$ is given by
\[ G = -\frac{1}{2} PE - \frac{1}{2} ST, \]  
where $P$ is the polarization.

3.1. At resonance frequency

Under $E$ constant driving, from each term in Eq. (11), loss $W$ in the piezoelectric ceramics is given by
\[ W = \frac{1}{2} \varepsilon E^2 \tan \delta + \frac{1}{2} s T^2 \tan \phi \]
\[ + \frac{1}{2} (d^2/s) E^2 \tan \theta + \frac{1}{2} (d^2/s) T^2 \tan \theta, \]  
where $\varepsilon$, $s$ and $d$ are the dielectric constant, elastic compliance and the piezoelectric constant. The first term in Eq. (12) represents the dielectric loss due to $P-E$ hysteresis with the loss angle $\delta$. The second term is the mechanical loss due to $S-T$ hysteresis with the loss angle $\phi$. The third term is the electro-mechanical loss due to $S-E$ hysteresis with the loss angle $\theta$. Under such a driving condition, the domain moves easily, and therefore the hysteresis loop between $S$ and $E$ is fairly large. Resonance is the vibration under $E$ constant driving; therefore, at resonance, all the losses in Eq. (12) must be considered. In particular, the electro-mechanical loss increases markedly with increasing vibrational displacement amplitude.

3.2. At antiresonance frequency

Under $D$ (almost equal to $P$) constant driving, loss $W$ in the piezoelectric ceramics is given by
\[ W = \frac{1}{2} (P^2/s) \tan \delta + \frac{1}{2} s T^2 \tan \phi \]
\[ + \frac{1}{2} (d^2/s) E^2 \tan(\theta - \delta) + \frac{1}{2} (d^2/s) T^2 \tan(\theta - \delta). \]  
Each term in Eq. (13) coincides with each one in Eq. (12). However, in this case, electro-mechanical losses, represented as the third and fourth terms, become almost zero because $\theta$ almost equals $\delta$, since $\varepsilon \approx \varepsilon_0$ in piezoelectric ceramics. Under $D$ constant driving, the domain cannot move so easily, therefore the hysteresis loop between $S$ and $D$ (or $P$) is small. Antiresonance is the vibration under $D$ constant driving, therefore the loss at the antiresonance frequency becomes lower than that at the resonance frequency.

4. Measurement method at the antiresonance frequency

Fig. 1 shows the improved, advanced equivalent circuit, which is called the impedance-type equivalent circuit.
Here, the conductance $G_b$ means only mechanical loss. $G_d$ is the conductance resulting from the electro-mechanical loss, and written as: $G_d = \omega C_d \tan \theta$. $C_r$ is called the free capacitance and written by using the damped capacitance $C_d$ and the coupling coefficient $k$ as follows: $C_r = C_d/(1 - k^2)$.

4.1. Measuring procedure

(1) Quality factor $Q_B$.

Using the frequency perturbation method [2], the quality factor at antiresonance frequency $Q_B$ can be obtained by

$$Q_B = \frac{2f_B}{f_2 - f_1} \sqrt{\frac{K_p(1 - K_p)}{1 - 2K_p}},$$

(14)

where $f_1$ and $f_2$ are frequencies very close to the antiresonance frequency $f_B$, and have the relation $f_1 < f_B < f_2$. In addition, $K_p$ is the perturbation ratio, which is given by the following equation under the constant velocity control,

$$K_p = \frac{(1 - I_0)/I_0}{1 - K_p},$$

(15)

where $I_0$ is the terminal current at the antiresonance frequency $f_B$, and $I$ is that at the frequency $f_1$ or $f_2$. These values are measured by the digital voltmeters and transferred to the micro-computer through GP-IB.

(2) Electro-mechanical loss factor $\tan \theta$.

By using resonance frequency $f_A$ and quality factor $Q_A$ at resonance, and antiresonance frequency $f_B$ and $Q_B$ and the capacitance ratio $C_B/C_f$ at antiresonance, the electro-mechanical loss factor $\tan \theta$ (=$\tan \delta$) can be given as follows:

$$\tan \theta = C_B/C_f(1/Q_A - f_B/f_A)k_1/Q_B).$$

(16)

The measuring method for the other equivalent constants is shown in Ref. [3].

5. Experiments [4]

Quality factors $Q_A$ and $Q_B$, temperature rises, capacitance ratio $C_B/C_f$ and force factor $A_B$ at the antiresonance frequency have been investigated on a PZT ceramic rectangular bar. The vibrational mode considered here is the fundamental longitudinal mode. The experimental results of $Q_B$, $Q_A$, and the temperature rises are illustrated in Fig. 2 as functions of vibrational velocity $v_0$, which was measured at the end of the ceramic bar using a 'Fotonic Sensor'. In addition, the temperature rise was measured at the center of the ceramic rectangular bar by using a thermocouple. In Fig. 2, the configuration and the dimensions of the test sample are illustrated.

From Fig. 2, it can be seen that $Q_B$ is higher than $Q_A$ over the whole vibrational velocity range investigated here; from $v_0 = 0.02$ to about $0.3$ m s$^{-1}$, and the difference between $Q_A$ and $Q_B$ becomes greater with increasing vibrational velocity. The temperature rise of antiresonance is less than that of resonance because $1/Q_B$ is smaller than $1/Q_A$. These facts are caused by the presence of electro-mechanical loss and its nonlinearity.

In Fig. 3, capacitance ratio $C_B/C_f$, force factor $A_B$ and the electro-mechanical loss factor $\tan \theta$ are shown. $\tan \theta$ was obtained using the experimental results of $Q_A$, $Q_B$, and $C_B/C_f$. For comparison, dielectric loss factor $\tan \delta_1$, which is directly measured at a sufficiently low frequency (1 kHz), is also shown in the figure. $\tan \delta_1$ includes an elastic loss brought by a quasi-static strain [5], therefore it is larger than $\tan \theta$ (=$\tan \delta$) in a small vibrational velocity. $C_B/C_f$ and $A_B$ can be viewed as almost constant over the whole velocity range considered here. However,
tan $\theta$ has become markedly larger in the large vibrational velocity above about 0.2 m s$^{-1}$.

6. Driving frequency and efficiency

The equivalent circuit shown in Fig. 1 can be converted equivalently to the one shown in Fig. 4. This figure shows an equivalent electric circuit including the two resistances $R_d$ and $R_m$. Here, resistance $R_d$ indicating electro-mechanical loss is given by

$$R_d = \tan \theta/(\omega_A C_d),$$

where $\omega_A$ is the resonance angular frequency and $C_d$ is the damped capacitance. $R_m$ is the equivalent resistance indicating mechanical vibration loss, which is given as

$$R_m = (\omega_A L_A)/Q_B,$$

where $L_A$ is the equivalent inductance in the series resonance circuit accompanying the equivalent capacitance $C_A$ in Fig. 4.

Fig. 5 shows the experimental results of $R_d$ and $R_m$ in increasing the vibrational velocity $v_0$ measured at the end of the rectangular bar PZT ceramic transducer. In Fig. 5, $R_A$ includes both mechanical and electro-mechanical loss, and it is obtained by the ratio of driving voltage to driving current.

As shown in Fig. 5, $R_A$ almost equals $R_d + R_m$. At a smaller vibration level, $R_d$ is much smaller than $R_m$. With increasing vibrational level, $R_m$ increases in proportion to $v_0^2$. However, the rate of increase of $R_d$ is larger than that of $R_m$; therefore, at a vibrational level larger than about $v_0 = 0.25$ m s$^{-1}$, $R_d$ becomes larger than $R_m$. As a result, a significant amount of input power will be consumed by $R_d$; therefore, the vibrational velocity cannot be increased further.

Two of mechanical terminals, indicated by $b$ and $b'$ in Fig. 4, are positioned to obtain mechanical power. For simulating the efficiency characteristics, mechanical load resistance $R_L$ is connected to the mechanical terminals $b$ and $b'$. Here, we assume that the vibrational mode of the transducer does not vary before and/or after connection of $R_L$. With the equivalent circuit shown in Fig. 4, efficiency $\eta$ (=mechanical output power/electric input power) can be calculated. Maximum efficiency can be obtained at the antiresonance frequency [3].

7. Conclusions

In this paper, losses in the piezoelectric ceramics have been described. Under constant $D$ driving, electro-mechanical loss becomes almost zero, while under constant $E$ driving, there exists large electro-mechanical loss. The former situation is related to the antiresonance, and the latter situation is related to the resonance. Therefore, it is concluded that the loss at the antiresonance frequency is lower than that at the resonance frequency.

Experimental results of the vibrational level dependence on the equivalent electric circuit constants have been obtained for antiresonance frequency. It has been shown that the quality factor $Q_A$ of resonance is always smaller than that of antiresonance $Q_B$ and the difference between them becomes larger with increasing vibrational velocity, and the temperature rise of antiresonance is less than that of resonance. The electro mechanical loss factor $\tan \theta$ has become markedly larger for the large vibrational velocity above about 0.2 m s$^{-1}$.

By using the experimental results of the equivalent constants, including the electro-mechanical loss, the efficiency of the transducers under high-power use can be calculated. Maximum efficiency can be obtained at the antiresonance frequency. In addition, at this frequency, the temperature rise is very small. It is then concluded that stable-state driving of high-power piezoelectric devices, such as an ultrasonic motor, can be achieved at the antiresonance frequency.
This study was conducted for the design of piezoelectric power devices. In addition, by comparing high-power characteristics on various piezoelectric materials, materials with high performance can be selected.

References


