A frequency variable ultrasonic transducer made of composite piezoelectric vibrator

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1. Introduction

It is known that a resonant frequency of thickness mode piezoelectric vibrator with high electromechanical coupling varies notably depending on electrical impedances connected to the electrical terminals due to the electroelastic effect[1]. In this paper, for an application of this effect, a bolt clamped type frequency controllable piezoelectric transducer is investigated. By a new transmission line model for a thickness mode piezoelectric vibrator which has been recently derived[2] including the electrical impedance connected to electrical terminals, the free admittance characteristics[3] and electro-acoustic efficiencies[4] of the bolt-clamped type frequency controllable transducer are obtained, and these results are confirmed experimentally.

2. Theory

Fig. 1 shows the configuration of the thickness mode PZT vibrator of thickness \( l \) with electrical impedance \( Z_e \) connected to electrical terminals. In this case, the equivalent circuit is obtained by the new transmission line model as shown in Fig. 2. In the figure, \( v_o, v_l, p_o, p_l \) are the particle velocities and forces on both surfaces (\( x=0 \) and \( x=l \)), respectively. The equivalent impedance \( z \) and the equivalent forces \( F_A, F_B \) in Fig. 2 have been derived as follows:

\[
z = -\frac{\sigma C_o h^2}{j\omega}, \quad F_A = zv_l \quad \text{and} \quad F_B = zv_o \tag{1}
\]

where \( \sigma = 1/(j\omega C_o Z_e + 1) \), and \( h \) and \( C_o \) are piezoelectric h-constant[5] and clamped capacity, respectively. From this equivalent circuit, the transmission line equations are derived as Eq. (2).
\[ p_t = \frac{z_o + z}{j \tan \gamma l} p_o + \frac{z^2 - 2z_o(1 - \cos \gamma l)}{j \sin \gamma l} v_o \\
\]

\[ v_t = \frac{1}{z_o + z} + \frac{z_o}{j \sin \gamma l} v_o \]

where \( \gamma \) and \( z_o \) are propagation constant and characteristic impedance of PZT respectively.

The electroelastic effect in thickness mode piezoelectric vibrator is applied for a bolt-clamped type ultrasonic transducer to controlled resonant frequencies. The configuration of bolt-clamped type frequency controllable ultrasonic transducer is shown in Fig. 3. This transducer has three pair of electric terminals, one driving part (b ~ c) and two non-driving parts (a ~ b and c ~ d). PZT layers are sandwiched by a pair of aluminum columns and clamped together by a steel bolt. An electric source is supplied to the driving part and the electrical impedances are connected to non-driving parts. The resonant frequencies are varied depending on the electric impedances. The equivalent circuit of this transducer, based on the new transmission line model, is expressed as Fig. 4. In this figure, a vibromotive force \( F \) is \( hQ \) when \( Q \) is a electric charge supplied by the electric source[6].

Fig. 3 Construction of a bolt clamped type frequency controllable piezoelectric transducer.

Fig. 4 New transmission line model of a bolt clamped type frequency controllable piezoelectric transducer.
3. Results

For an example, a coil of variable inductance $L_e$ is connected as the electrical impedance $Z_e$ to the electrical terminals of non-driving parts. The free admittance characteristics in the case of radiating into water are measured for various values of inductance $L_e$ from $\infty$ mH (open circuit) to 0 mH (short circuit). The results are shown in Fig. 5(a). As seen in the figure, the MODE 2 can be controlled continually from 27 kHz to 60 kHz. This result coincide well with the calculated result of Fig. 5(b), which is obtained for the equivalent circuit given in Fig 4. The electro-acoustic efficiencies of the transducer can be calculated by the following equation.

\[
\eta_{el} = \frac{Y_{m0}}{G_{m0}} \left( 1 - \frac{Y_{m0}}{Y_{m00}} \right),
\]

where $Y_{m0}$: motional admittance at resonant frequency in water
$G_{m0}$: motional conductance at resonant frequency in water
$Y_{m00}$: motional admittance at resonant frequency in air.

The electro-acoustic efficiencies for MODE 2 obtained for various inductances are shown in Fig. 6. The theoretical and experimental results are coincide well and the electro-acoustic efficiencies have a minimum value at 52 kHz.

4. Conclusion

For an application of the electroelastic effect in thickness mode piezoelectric vibrator, a bolt clamped type frequency controllable piezoelectric transducer is proposed. To analyze the characteristics of transducer, a new transmission line model equivalent circuit including the electrical impedance connected to electrical terminals has been employed to investigate the free admittance characteristics and the electro-acoustic efficiencies. The experimental results are coincide well with the theoretical calculations.

The results may be summarized as follows:
(1) The resonant frequency has been controlled continually from the fundamental resonant frequency (27 kHz) to the second harmonic resonant frequency (60 kHz) by varying the values of electrical inductance $L_e$. 

(a) Experimental results
(b) Theoretical results

Fig. 5 Free admittance characteristics in the case of radiating into water.
(2) The characteristics of electro-acoustic efficiency showed a minimum at 52kHz, where the minimum value was above 20%.

We are considering to apply this frequency controllable ultrasonic transducer to ultrasonic power equipments such as ultrasonic cleaners, knifes, etc.

![Graph](image)

Fig. 6 Theoretical and experimental results of electro-acoustic efficiency at various center frequencies (MODE 2) controlled by a variable external inductance.

Reference