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Technical Notes

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Behavior of Piezoelectric Transducer on Energy-Recycling Semiactive Vibration Suppression

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Introduction

A NOVEL method of semiactive vibration suppression based on an energy-recycling approach has been proposed and investigated.[1–3] The energy-recycling method uses a piezoelectric transducer connected to a passive electric circuit and reverses the polarity of electric charge and voltage for the purpose of vibration suppression by exploiting the first half-period of an electrical vibration mechanism. The electrical energy converted from mechanical energy is reused to suppress the vibration of the structure, instead of simply being dissipated. Therefore, the energy loss would crucially deteriorate the vibration suppression performance of the method, and we pay the highest attention to preventing the energy loss caused by electrical resistors. In Ref. 1 there were some quantitative differences between numerical and experimental results, and this discrepancy has not been resolved. It is, therefore, the objective of this Note to identify the source of the discrepancy. From careful investigations, we discovered an unexpected phenomenon of the electrical resistance of the piezoelectric transducer in the energy-recycling method. We found that the piezoelectric transducer had a larger effective resistance value with respect to the method's performance than its measurement by using a common measuring instrument, an LCZ meter. This large resistance value deteriorated the method's performance and led to the aforementioned discrepancy.

Previous Procedures to Construct Mathematical Models

A 10-bay truss structure with an attached piezoelectric transducer was used for a vibration suppression experiment. For the energy-recycling semiactive method, a passive electric circuit composed of an inductor (inductor A), a resistor, two diodes, and a switch was connected to the piezoelectric transducer (Fig. 1). The mathematical model of the piezoelectric transducer was derived from constitutive equations of piezoelectric materials.[1] After several characteristic experiments,[1] we determined the coefficients in the mathematical model of the piezoelectric transducer. By the use of an LCZ meter, the inductance L was determined to be 2.23×10^{-3}H, and the resistance R, except for the piezoelectric transducer, was determined to be 1.00 Ω. The resistance of the piezoelectric transducer cannot be directly measured, but it corresponds to the dielectric loss.[4] Its dielectric loss is written as

$$\tan\delta = R_e \omega_c C_p^S \tag{1}$$

where R_e is the effective resistance, ω_c is the angular frequency of sinusoidal voltage applied to the transducer, and C_p^S is the constant-elongation capacitance of the transducer. The value of $\tan\delta$ was measured with the LCZ meter. R_e was 0.42 Ω because $\tan\delta = 0.03$, $\omega_c = 6.17 \times 10^3$ rad/s, and $C_p^S = 1.17 \times 10^{-5}$ F. The damping ratio of the first mode was obtained from the free vibration experiment of the structure with the attached transducer. During the free vibration, electric terminals of the transducer were opened so that its electrical status could not be changed. This damping ratio included the energy loss of the piezoelectric transducer caused by its mechanical properties, such as nonlinearity. Therefore, its mechanical properties were ruled out as a source of the discrepancy.

Comparison of Experimental and Numerical Results in Vibration Suppression

Figure 2 shows the comparison between the experimental and numerical results of single-mode vibration suppression using the energy-recycling semiactive method. After the first modal velocity was given to the structure, the subsequent transient vibration was suppressed. The vibration of the structure was suppressed more slowly in the experiment than in the numerical simulation. The two frequencies of mechanical vibration were almost the same, and both switching timings agreed well. It can, therefore, be concluded that there is no major difference in the mathematical models for both the structure including the transducer and that including the controller. However, there are differences in voltage at each switching, indicating that there may be some discrepancies in the mathematical model of the electric circuit.

Measurement of Detailed Behavior of the Piezoelectric Transducer

For a detailed investigation into the characteristics of the circuit including the piezoelectric transducer, the free electrical vibration

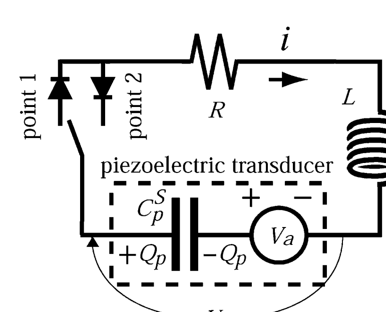

Fig. 1 Electric circuit for energy-recycling semiactive vibration suppression.

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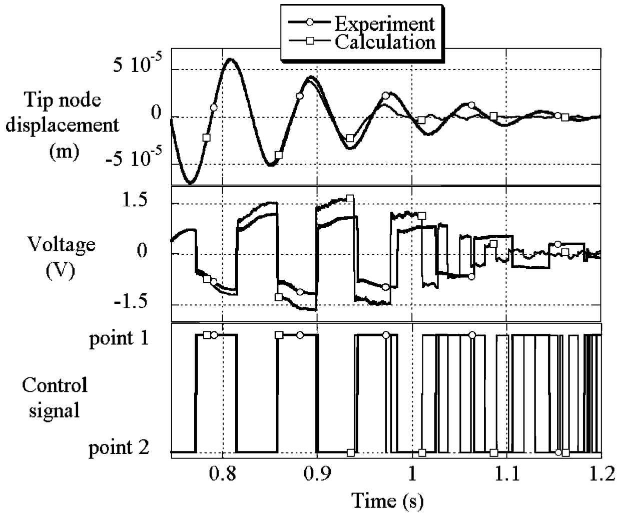

Fig. 2 Time histories obtained in experiment and simulation ($R = 1.40$ Ω and $L = 2.23 \times 10^{-3}$ H).

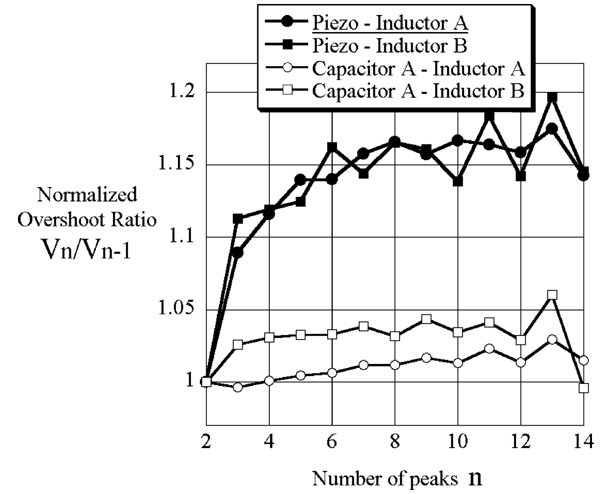

Fig. 3 Normalized overshoot ratio as function of number of free electrical vibration cycles.

in the circuit was measured. Because the resistance of diodes[1] (0.022 Ω) was much smaller than that of total resistance (R and R_e, at least 1.42 Ω), the diodes were removed from the circuit to evaluate the free electrical vibration. First, the switch was opened so that the capacitor element in the piezoelectric transducer was charged by a constant-voltage supplier. Next, the switch was closed so that the electric current flowed. Then, during the free electrical vibration, voltage V_p across the piezoelectric transducer was measured.

Let n be the ordinal number of the half-cycle of electrical vibration. Let t_n be the peak time and V_n the voltage at $t = t_n$. Then, $t_n - t_{n-1}$ is the half-period of the electrical vibration, and $-V_n/V_{n-1}$ is the overshoot ratio. A normalized overshoot ratio is defined as the overshoot ratio divided by that of the first half-period. The normalized overshoot ratio is calculated as a function of the number of peaks and is marked with filled circles (piezo–inductor A) in Fig. 3. The normalized overshoot ratio increases with the number of peaks until the eighth peak. The duration of the half-periods is almost constant in the measurement. For comparison, three more measurements were carried out using combinations of another inductor (inductor B) and another capacitor (capacitor A). Only when using the piezoelectric transducer does the normalized overshoot ratio increase significantly with the number of peaks. Because the duration of the half-periods of the electrical vibration is almost constant, it is unlikely that the inductance and capacitance will vary with the cycle number. The resistance variation of the circuit can be contributed by the variation in the effective resistance R_e of the piezoelectric transducer because the overshoot ratio increases significantly only for circuits with the piezoelectric transducer. Therefore, we conclude that the effective resistance of the piezoelectric transducer decreases with the number of electrical vibration cycles until the eighth peak, and, after that, it converges to a low constant value.

Redetermination of Electrical Parameters

Because the energy-recycling semiactive method[1–3] exploits the first half-period of free electrical vibration, the experimental data obtained from the first half-cycle of electrical vibration are indispensable to obtain a meaningful resistance value. We carried out an experiment of free electrical vibration to obtain $R + R_e$. In the experiment, the piezoelectric transducer had one free end. When the mathematical model[1] of the piezoelectric transducer is applied under the free-end condition, $Q_p = C_p^T V_p$ is obtained, where C_p^T is the constant-force capacitance. By characteristic experiments,[1] $C_p^T = 1.32 \times 10^{-5}$ F is obtained. The equation for the circuit (Fig. 1) is

$$L\ddot{V}_p + (R + R_e)\dot{V}_p + V_p\big/C_p^T = 0 \tag{2}$$

where R_e is regarded as additional resistance. Assuming that $V_p(0) = V_1$ and $\dot{V}_p(0) = 0$, by solving Eq. (2), we obtain

$$V_p(t) = V_1 \exp\{-[(R + R_e)/2L]t\} \times \cos\left((1/2L)\sqrt{\left\{\left[4L - (R + R_e)^2 C_p^T\right]\big/C_p^T\right\}}t\right) \tag{3}$$

where $t_1 = 0$. Because the measured duration of the first half-cycle is 5.80×10^{-4}s, from Eq. (3),

$$t_2 - t_1 = 2\pi L\sqrt{C_p^T\big/\left[4L - (R + R_e)^2 C_p^T\right]} = 5.80 \times 10^{-4} \tag{4}$$

is obtained. The measured overshoot ratio of the first half-cycle is 0.647. Then, from Eq. (3),

$$-V_2/V_1 = -V_p(t_2)/V_p(t_1) = \exp\left\{-\pi(R + R_e)\sqrt{C_p^T\big/\left[4L - (R + R_e)^2 C_p^T\right]}\right\} = 0.647 \tag{5}$$

is obtained. The resistance and inductance are determined by solving Eqs. (4) and (5) as $R + R_e = 3.80$ Ω and $L = 2.53 \times 10^{-3}$H. Compared to the previously estimated value for the total resistance (1.42 Ω), the new value (3.80 Ω) is much larger.

To verify the redetermined electric parameter, by using the redetermined electric parameters, we again performed a simulation corresponding to the vibration suppression experiment. Figure 4 shows that the new numerical simulation agrees well with the experimental result. In conclusion, the redetermination of the electrical parameters greatly contributes to the agreement of the experimental and numerical results.

Discussion of Discovery of Piezoelectric Phenomenon

The energy-recycling semiactive method[1–3] uses the first half-period of the electrical vibration mechanism. We must use the experimental data obtained from the first half-cycle of electrical vibration to obtain an accurate resistance value for the method. However, a common measuring instrument, such as an LCZ meter, measures electrical parameters after inputting sinusoidal voltage for a long time. Thus, it provides parameter values after the convergence (Fig. 3) and leads to the discrepancy in the method. Comparing Figs. 2 and 4, we find that the suppression performance significantly depends on the resistance value. Our procedure to obtain the accurate resistance value is quite useful to evaluate the energy loss. Consequently, it is possible to evaluate the vibration suppression performance accurately and to design a controller system properly.

Our discovery and discussion can be applied not only to the energy-recycling semiactive method,[1–3] but also to other vibration suppression methods exploiting the electrical vibration mechanism,

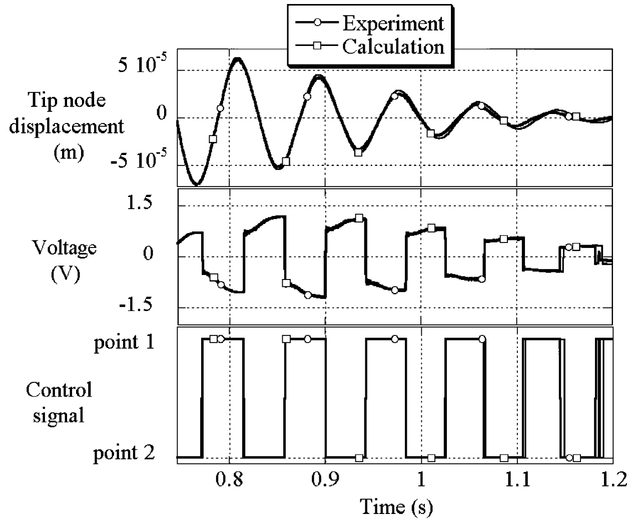

Fig. 4 Time histories obtained in experiment and simulation using refined parameters ($R = 3.80\ \Omega$ and $L = 2.53 \times 10^{-3}$ H).

for example, a hybrid active method.[5] This electrical vibration mechanism is always subject to the energy loss caused by resistors, and the accurate estimation of the resistance value is essential to evaluate method's performance. However, the reason why the overshoot ratio of the piezoelectric transducer is dependent on the number of electrical vibration cycles is still unknown at this stage. The investigation of this is an interesting subject for future research.

Conclusions

The behavior of the piezoelectric transducer was scrutinized to find the reasons for the quantitative discrepancy between the experimental and numerical results in the energy-recycling semiactive method. We discovered that the effective resistance of the piezoelectric transducer decreases significantly with the number of free electrical vibration cycles. Therefore, when the energy-recycling method is used, it is essential to use the experimental data obtained from the first half-cycle of free electrical vibration for obtaining an accurate resistance value, which contributes to the accurate performance evaluation. On the other hand, measurements with a common measuring instrument may lead to the wrong evaluation of the method's performance. This Note provides the proper method to measure the effective resistance of the piezoelectric transducer for the purpose of an accurate controller design with vibration suppression methods exploiting the electrical vibration mechanism.

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