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Complete passive vibration suppression using multi-layered piezoelectric element, inductor, and resistor

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ABSTRACT

This paper describes passive technique for suppressing vibration in flexible structures using a multi-layered piezoelectric element, an inductor, and a resistor. The objective of using a multi-layered piezoelectric element is to increase its capacitance. A piezoelectric element with a large capacitance value does not require an active electrical circuit to simulate an inductor with a large inductance value. The effect of multi-layering of piezoelectric elements was theoretically analyzed through an equivalent transformation of a multi-layered piezoelectric element into a single-layered piezoelectric element. The governing equations were derived using this equivalent transformation. The effect of the resistances of the inductor and piezoelectric elements were considered because the sum of these resistances may exceed the optimum resistance. The performance of the passive vibration suppression using an LR circuit was compared to that of the method where a resistive circuit is used assuming that the sum of the resistances of the inductor and piezoelectric elements exceeds the optimum resistance. The effectiveness of the proposed method and theoretical analysis was verified through simulations and experiments.

1. Introduction

Bending vibration of flexible structures such as beams and plates can be suppressed by using piezoelectric elements and a passive electrical circuit. A plate-type piezoelectric element is preferred in such applications because it does not require additional large space. The vibration suppression method using piezoelectric elements has the advantage that the performance is independent of mass of a vibration control device. There are two methods for passive vibration suppression using piezoelectric elements: one method uses an LR circuit [1–5], and the other method uses a resistive circuit [2,6]. These two methods can suppress only a single vibration mode. Hence, multiple vibration mode suppression has been studied [7–10]; however, we refrain from describing it in this paper for simplicity. In addition, many researches have still been reported to increase the feasibility of the vibration suppression using piezoelectric elements [10–12]. Because passive vibration suppression using a resistive circuit is not effective, passive vibration suppression using an LR circuit has been intensively studied thus far. In the LR circuit method, the capacitance of piezoelectric elements and inductance of the LR circuit produces an electrical resonance. The effect of this method is similar to the effect of dynamic vibration absorbers. Both these methods use resonance; however, one is electrical, and the other is mechanical. Optimum values of the inductance and resistance can be formulated by using the two fixed points method similar to dynamic vibration absorbers [13]. This method is categorized as a passive method, in principle; however, an active electrical circuit is generally preferred in practice, except

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when the natural frequency of the targeted vibration mode is sufficiently high. This is because the size of an actual inductor that gives optimum value of the inductance is too large for practical use. Because the optimum value of the inductance is inversely proportional to square of the natural frequency of the targeted vibration mode of the host structure, the optimum value of the inductance is relatively small when the natural frequency of the targeted vibration mode is sufficiently high. However, vibration suppression of low-order vibration modes is more important in practice. Therefore, the active electrical circuit that simulates an inductor with a large inductance value is usually critical for the vibration suppression method using an LR circuit. Operational amplifiers are used in the active electrical circuit that simulates an inductor, and, thus, a DC power supply must be included in the practical devices. The system stability is maintained even if an active electrical circuit is used; however, the necessity of a DC power supply prevents the rise in the practical use of this method. In order to solve this problem, we propose a passive vibration suppression technique using plate-type multi-layered piezoelectric elements instead of plate-type single-layered piezoelectric elements. Using multi-layered piezoelectric elements enables increasing the capacitance value, and decreasing the inductance to a sufficient level, given the fact that optimum value of the inductance is inversely proportional to the capacitance of the piezoelectric elements. The capacitance can be increased by shunting a commonly used capacitor in parallel with the piezoelectric element; however, the performance of vibration suppression degrades with the increase in the total capacitance in this method. Because an inductor and piezoelectric elements have non-negligible resistance, there is a possibility that the sum of the resistances of the inductor and piezoelectric elements exceeds the optimum value of the resistance. Therefore, the performance of vibration suppression when total resistance exceeds the optimum value is theoretically analyzed in this study. The effects of the bonding layer and the margin of the plate-type multi-layered piezoelectric elements are also theoretically analyzed given their importance in accurate estimation of the material properties. The margin of the electrodes of the piezoelectric element is not important for single-layered piezoelectric elements; however, the margin is essential for multi-layered piezoelectric elements because the layers cannot be electrically connected in parallel without it. The effectiveness of the proposed method and theoretical analysis is verified through simulations and experiments.

2. Theoretical analysis

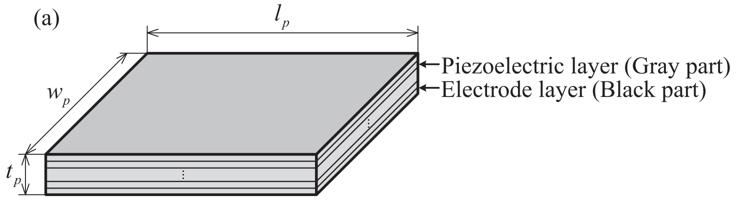
In this section, equivalent transformation from a plate-type multi-layered piezoelectric element into a plate-type single-layered piezoelectric element is described. The knowledge obtained from the previous studies can be utilized by using this equivalent transformation. Similar to the previous studies, a thin cantilever was used as a host structure in this study. There is no essential difference among the beams with other boundary conditions. The governing equations that consist of the equation of motion of the host structure and circuit equation of the electrical system are formulated considering the effect of the bonding layer, quality factor of the inductor, and dielectric loss tangent of the piezoelectric element. Because the margin of the electrode of the piezoelectric element is critical for the theoretical estimation of the material properties of plate-type multi-layered piezoelectric elements, the method to consider the effect of the margin in the theoretical analysis is also described in this section.

2.1. Equivalent transformation from multi-layered piezoelectric element into single-layered piezoelectric element

In this section, the margin of electrodes of the piezoelectric element is neglected to investigate the essential effect of the multi-layering of the piezoelectric element. The thickness of the electrode layers is neglected in this theoretical analysis since the thickness of each electrode layer is usually sufficiently thin compared to the thickness of each piezoelectric layer. Therefore, the effect of the mechanical stiffness of the electrode layers is not considered in this theoretical analysis.

The analytical model of a plate-type multi-layered piezoelectric element is shown in Fig. 1(a). For such a piezoelectric element, the strain in the longitudinal and width directions, and electric flux density in the thickness direction must be considered. The piezoelectric constitutive equations for a single layer are given as

$$S_1 = \frac{1}{E_p}T_1 - \nu_p\frac{1}{E_p}T_2 + d_{31}E_{3s}, \tag{1}$$



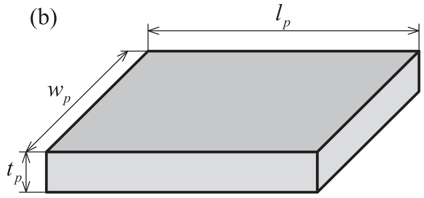


Fig. 1. Analytical model of a plate-type multi-layered piezoelectric element: (a) original model and (b) an equivalent single-layered piezoelectric element.

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