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Sensitivity analysis of damping performances for passive shunted piezoelectrics

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ABSTRACT

A shunted piezoelectric is a device to suppress vibration consisting of a piezoelectric material and a shunt circuit connecting between two electrodes of the piezoelectric material. The sensitivity of damping performances is analyzed for passive shunted piezoelectrics: a resistive, a series resonant, and a parallel resonant shunted piezoelectric. The parameters that affect their damping performances are Young's moduli of a base structure and a piezoelectric material, a piezoelectric coupling coefficient, an electric permittivity of a piezoelectric material, and resistance and inductance of a shunt circuit. A loss factor is selected as a performance index for the damping and formulated for each type of shunted piezoelectric. For an aluminum beam with symmetrically bonded piezoelectric patches, the sensitivity of the loss factor is evaluated with respect to the system parameters. For a resistive shunted piezoelectric, a piezoelectric coupling coefficient has the largest effect on the damping performance. For resonant shunted piezoelectrics, an increasing electric permittivity of the piezoelectric material has the greatest effect on the damping performance. As a whole, the sensitivities for both resonant shunted piezoelectrics are in the similar level and they are much larger than that for a resistive shunted piezoelectric. Using the sensitivities to parameter values, the estimation method for the sensitivity with respect to varying operating conditions such as the temperature change is presented.

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1. Introduction

Vibration reduction or suppression is a very important issue for various structures in human life such as buildings, bridges, automobiles, and aircrafts. A shunted piezoelectric is one of popular damping devices to control vibrations in a variety of applications. This device consists of a piezoelectric material bonded on a vibrating structure and a shunt circuit connecting between two electrodes of the piezoelectric material. Piezoelectric materials transform mechanical energy into electrical energy, and *vice versa*, due to their electromechanical coupling effect [6]. The shunted piezoelectric technique has been widely studied because of its simplicity, lightness, and small size compared to other dampers such as a viscoelastic material or a tuned-mass damper. Passive shunted piezoelectrics, in specific, resonant shunted piezoelectrics, have good damping performances with a simple device so that they have been actively applied to control vibrations of diverse structures such as helicopters blades, turbo machine blades, aircraft panels, and snowboards [19].

Forward showed electronic damping can be a powerful control method for low-level vibrations occurred in optical systems [8]. He used piezoelectric materials as electromechanical transducers and brought analogies between electrical circuits and mechanical structures to explain the damping principles. A conventional electrical system with inductors, capacitors, and resistors has an analogical dynamics to a mechanical system with masses, springs, and dampers [15]. In a similar way, Hagood and von Flotow applied analogies to a resistive shunted piezoelectric with a viscoelastic material and a resonant shunted piezoelectric with a tuned-mass damper [10]. A mechanical impedance concept was, then, used to derive the system dynamics model combining a mechanical structure and an electrical shunt circuit. They mathematically formulated and characterized the damping performances in a frequency domain for a resistive shunted piezoelectric and a series resonant shunted piezoelectric. In addition, optimization methods for resistance and inductance values of shunt circuits were developed and verified to produce the maximum damping at a resonant frequency by simulations and experiments. Wu applied the same analysis methods to a parallel resonant shunted piezoelectric [26]. He derived mathematical expressions for optimal resistance and inductance of the shunt circuit and demonstrated that the optimally tuned circuit can successfully reduce the resonant peaks of an aluminum cantilevered beam. Park and Inman [21] compared the damping performances between a series resonant shunted piezoelectric and a parallel resonant shunted piezoelectric. They showed that both had the same level of performance and the parallel connection required larger resistance value than the series connection.

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On top of the basic passive shunted piezoelectrics, a variety of advanced types have been developed by adopting various control algorithms or circuits types. LQG, H_2, H_∞, neuro-adaptive, and μ-synthesized control laws are representative modern control theories that have been actively used for piezoelectric actuators to suppress vibrations [12,27]. These various control theories have been applied to shunted piezoelectrics for higher damping performances [16]. A negative capacitor shunt circuit was studied for an advantage in its simpler implementation [17], and switching controls with voltage sources are studied to increase the electromechanical coupling [14,22]. The other types are switched shunts and adaptive shunts, which have an effect of changing structural properties or electrical resistance values [3,7,20,23,24]. However, most of these advanced shunting methods have drawbacks including the complexity in the implementation and the need for additional power source. The long-term reliability and the robustness with respect to the environmental conditions are still considerable issues. Therefore, basic passive shunted piezoelectrics are the preferred approach in many practical applications.

This paper is to address the sensitivity issue: how much the damping performance of the passive shunted piezoelectrics is degraded when the system parameters are changed. Some previous studies [10,21,26] have dealt with mistuned shunt circuits, showing how transfer functions were changed when electrical resistance or inductance is slightly different from the nominal values. De Marneffe [4] presented that the damping of a resonant shunted piezoelectric was much more sensitive than that of a resistive shunted piezoelectric when the structural resonant frequency was changed from the original value. Niederberger [18] experimentally demonstrated that the damping of the standard resonant shunted piezoelectric decreased as the temperature increased. However, a systematic sensitivity analysis of the damping characteristics of the shunted piezoelectrics has not been published.

In this paper, the sensitivities of the damping performances for passive shunted piezoelectrics are mathematically derived with respect to varying material and electrical properties. A beam with symmetrically bonded piezoelectric patches connected to a resistive, a series resonant, and a parallel resonant shunt circuit is analyzed. A loss factor is selected as a performance index for the damping and formulated for each type of shunted piezoelectrics. The sensitivity of the loss factor is obtained with respect to each system parameter variation from the nominal values at the optimally tuned condition. By integrating all the effects of the system parameters, the damping performance degradation under varying temperature condition is evaluated. The analysis results provide a proper guideline to determine which types of shunted piezoelectrics are most suitable for a specific application considering the variations in the environment.

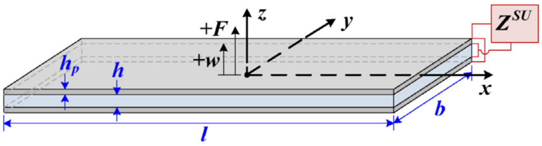

Fig. 1. Structural model for sensitivity analysis.

2. Mathematical modeling

2.1. Modeling of structure with shunted piezoelectric

A beam with symmetrically bonded piezoelectric patches as shown in Fig. 1 is chosen as a structure to be analyzed. The sandwiched beam is made of aluminum and the piezoelectric material is C-82 which is one of typical soft ceramics manufactured by Fuji Ceramics Corporation. Z^{SU} is the electrical impedance of the shunt circuit. Two piezoelectric patches are connected in parallel because the optimal resistance value becomes smaller by doubling the capacitance of the piezoelectric material. This structure has a free–free boundary condition and the damping for the first bending mode is mainly analyzed. Because this structure is lengthwise uniform and symmetric with respect to the xy-plane, the beam can be modeled as an Euler–Bernoulli beam so that the analytical solution for the modal characteristics are provided. When more complex geometries, such as the one with partially bonded piezoelectric patches, need to be considered, the finite element analysis can be applied to obtain the modal characteristics [11]. The specification and the properties of the analysis structure are shown in Table 1. Material properties of the piezoelectric material are taken from the manufacturer [13]. The piezoelectric electromechanical coupling coefficient k_{31} is calculated from the provided values of $Y^{\mathrm{E}}_{p,11}$, d_{31}, and ε^T_3 using Eq. (1). The meanings of the symbols are presented in Table 1.

$$k_{31} = |d_{31}|\sqrt{\frac{Y^{\mathrm{E}}_{p,11}}{\varepsilon^T_3}} \tag{1}$$

The generalized electromechanical coupling coefficient K_{31} is obtained using the natural frequencies at open circuit and short circuit states of the piezoelectric material as Eq. (2), which was suggested way by Hagood and von Flotow [10].

$$K_{31} = \sqrt{\frac{(\omega^D_n)^2 - (\omega^{\mathrm{E}}_n)^2}{(\omega^{\mathrm{E}}_n)^2}} \tag{2}$$

The mechanical structure in Fig. 1 can be modeled as a single degree-of-freedom (SDOF) system because the first bending mode is assumed to be dominant. Therefore, the structure connected

Table 1
Specification of the beam with symmetrically bonded piezoelectric patches.

	Beam		Piezoelectric patch		Unit
Length	l	150	l	150	(mm)
Width	b	20	b	20	(mm)
Thickness	h	1	h_p	0.4	(mm)
Material		Al.		C-82	
Density	ρ_b	2700	ρ_p	7500	(kg/m^3)
Elastic Modulus	Y_b	70	$Y^{\mathrm{E}}_{p,11}$	62	(GPa)
Piezoelectric coupling coefficient			d_{31}	266e–12	(C/N)
Electric permittivity			ε^T_3	3650	(ε_0)
Piezoelectric E–M coupling coefficient			k_{31}	0.369	
Capacitance of piezoelectric material			$C^T_{p,3}$	480	(nF)
Short-circuited first natural frequency			ω^{E}_n	1871	(rad/s)
Open-circuited first natural frequency			ω^D_n	1987	(rad/s)
Generalized E–M coupling coefficient			K_{31}	0.357	

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