PASSIVE VIBRATION CONTROL OF PLATE-LIKE STRUCTURES USING SHUNTED PIEZOCERAMICS

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Abstract

Application of piezoceramic materials in actuation and sensing of vibration is of current interest in active vibration control. The objective of this work is to investigate the effect of shunted piezoceramics as passive vibration control devices when bonded to a host structure. The effect of orientation of the piezoceramic bonded onto the plate is also investigated. Analytical studies are presented along with experimental results.

Introduction

Piezoceramic materials are transformers that convert mechanical energy to electrical energy and vice-versa. When these piezoceramics are bonded to a structure, the mechanical strain energy generated in the piezoceramic is converted to electrical voltage across the poling direction of the piezoceramic device. This voltage or electrical energy is dissipated or shunted to another frequency band using electrical networks connected to the terminals of the piezoceramic as shown in Fig.1. The mechanical energy of motion of the structure is thereby controlled. Passive vibration absorbers, or controllers, are well known in vibration engineering [1,2]. Piezoceramic materials with tunable passive electrical networks are essentially passive vibration controllers that can be tuned to cope with varied operating conditions. The tunable passive electrical networks connected to the piezoceramic can modify the frequency selective vibration transmission properties of the structure itself.

Electrical passive shunting of piezoceramics bonded to beams has been investigated in the recent past [3,4]. These studies have focused on experimental investigation of the additive damping, and change in resonance frequencies. The analytical vibration models represent the damping and stiffness due to electrical shunting of the piezoceramic as a complex frequency dependent modulus similar to that used in viscoelastic solids [3]. The optimum shunting parameters for the piezoceramic vibration absorber is also derived and experimentally verified. The present work focuses on added damping due to resistive shunting of piezoceramics bonded to plates.

Modeling of Shunted Piezoceramic Materials

The modeling of shunted piezoceramics bonded to structures has been dealt with elsewhere [3], and here we present the essential steps. The mechanical impedance of the shunted piezoceramic can be obtained, in non-dimensional form, for uniaxial loading in the j^{th} direction, as,

$$Z_{jj}^{ME}(s) = \frac{A_j}{C_{jj}^{SU} L_j s} \tag{1}$$

In the above, A_j is the area of the piezoceramic element whose normal is in the j^{th} direction, L_j is the length of the piezoceramic, $C_{jj}^{SU} = (1 - k_{ij}^2 \bar{Z}_i^{EL})\, C_{jj}^{E}$ is the mechanical compliance of the shunted piezoceramic where in C_{jj}^{E} is the mechanical compliance with short-circuit electrical boundary conditions, and s is the Laplace variable. One can non-dimensionalize this as the ratio of the mechanical impedance of the shunted piezoceramic to the mechanical impedance of the piezoceramic with open circuit electrical boundary condition :

$$\bar{Z}_{jj}^{ME} = \frac{Z_{jj}^{SU}(s)}{Z_{jj}^{OC}(s)} = \frac{(1 - k_{ij}^2)}{\left[1 - k_{ij}^2 \bar{Z}_i^{EL}(s)\right]} \tag{2}$$

where k_{ij} is the electromechanical coupling coefficient, $\bar{Z}_{jj}^{EL}$ is the total electrical impedance of the PZT with the shunt impedance non-dimensionalized to its open-circuit values. The mechanical impedance, $\bar{Z}_{jj}^{ME}$, is in general

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complex and frequency dependent and can be represented as :

$$\bar{Z}_{jj}^{ME} = \bar{E}_{jj}(\omega)\left[1 + i\eta_{jj}(\omega)\right] \tag{3}$$

Shunting devices such as resistors, as shown in Fig.1, act as an energy dissipater on the electrical side. Electrical resistive shunting of a piezoceramic bonded to a host structure is equivalent to a viscoelastic damping treatment of the same host structure [3]. The non-dimensional mechanical impedance of a resistively shunted piezoelectric is given by

$$Z_i^{SU}(s) = R_i,\ \bar{Z}_i^{EL}(s) = \frac{Z_i^{EL}(s)}{Z_i^{OC}(s)} = \frac{sC_{pi}R_i}{1 + sC_{pi}R_i},\ \bar{Z}_{jj}^{ME}(\omega) = 1 - \frac{k_{ij}^2}{1 + i\rho_i} \tag{4}$$

where C_{pi} is the capacitance of the piezoceramic, R_i is the resistance of the shunt resistor, and $\rho_i = R_i\, C_{pi}\, \omega$ is the non-dimensional frequency. The loss factor and the frequency dependent storage modulus are

$$\eta_{jj}^{ME}(\omega) = \frac{\rho_i k_{ij}^2}{(1 - k_{ij}^2) + \rho_i^2},\ \bar{E}_{jj}^{ME}(\omega)$$

$$\bar{E}_{jj}^{ME}(\omega) = 1 - \frac{k_{ij}^2}{(1 + \rho_i^2)} \tag{5}$$

In order to study the effectiveness of piezo-resistive shunting in controlling the dynamics of a vibrating system, the dynamics of the host structure is modeled by a single vibration mode. The piezoceramic is then coupled in parallel to this one degree-of-freedom (1-DOF) system as shown in Fig.2. The modal velocity of the vibrating system with piezoceramic can be expressed in the Laplace domain as

$$v(s) = \frac{F(s)}{Ms + (K/s) + Z_{jj}^{ME}(s)} \tag{6}$$

where Ms is the impedance associated with modal mass of the structure, K/s, is the impedance associated with the modal stiffness of the host structure, and $Z_{jj}^{RES}(s)$ is the impedance associated with the resistively shunted piezoceramic. The above modeling of the resistively shunted

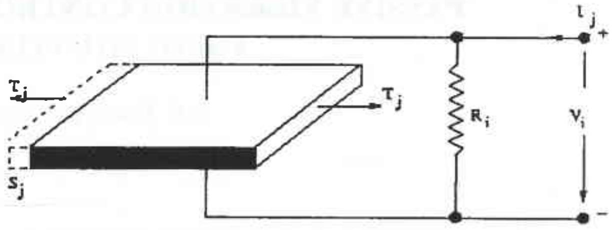

Fig. 1 Electrical network analog for resistive shunting

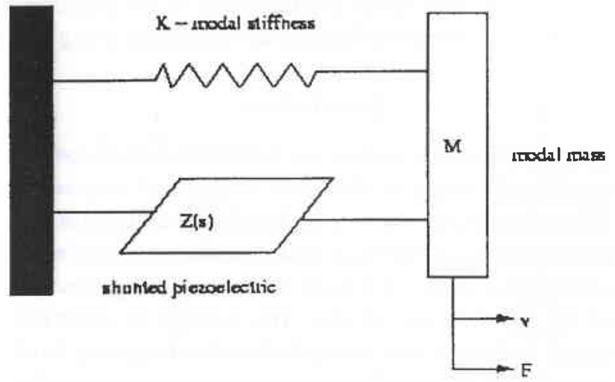

Fig. 2 Sdof system model with shunted piezoelectric element in parallel with system modal mass

piezoceramic bonded to the host structure assumes a linear electro-mechanical coupling leading to a linear visco-elastic model of the overall structural dynamics.

Results and Discussion

In order to investigate the dynamic behaviour of the resistively shunted piezoceramic bonded to a structure, dynamic tests were conducted on a duralumin cantilever plate specimen with surface bonded piezoceramic patches. SP-5H actuators manufactured by Sparkler Ceramics Pvt Ltd., Pune, India were used. The piezoceramic patches were bonded to the plate, near the fixed end, with a very thin layer of epoxy. The material properties of the plate and piezoceramic are listed in Table-1.

The plate was excited at its first and second resonance frequency using Derritron VP2MM exciter, 25W Derritron power amplifier, and A&D AD-3525 signal generator as shown in the Fig.3. Input force was measured using B&K 8200 force transducer and amplified by B&K 2626 conditioning amplifier. Both, sine-sweep as well as random excitation tests were conducted to determine resonance frequencies. The acceleration response of the plate was picked up near the tip by B&K 4344 accelerometer and amplified by B&K 2635 charge amplifier. These signals were acquired by National Instruments ATMIO 16 data acquisition card using LabView (Version.5.0) Software.

The results of the experiment are summarized in Table-2. Note that the first resonance frequency of the plate with piezoceramic attached to it, and in short and open circuit conditions, are almost the same. The frequency response of the system to white noise excitation, as shown in Fig.4, confirms this too. Short-circuiting the PZT implies that the electric field across it is effectively zero. On the other hand, an open circuit termination of the PZT implies that the impedance across the PZT is infinite. In Fig.4, the frequency response of the plate with PZT resistively shunted at an optimum resistance value of 140 kΩ, is also shown. The optimum value of resistance was obtained by varying the terminal resistance and solving for the poles of the transfer function given by Eq.(6). The real part of the poles of this transfer function denotes the added damping to the single-mode approximation of the vibrating beam. The variation of added damping due to resistive shunting is shown in Fig.5. Note that the experimental and analytical trends are similar to that of a viscoelastic solid [1] represented by a complex modulus denoted by Eq.(3).

The effect of orientation of the piezoceramic patch with reference to the plate was also investigated. For the experiments, we considered two configurations. The first referred to as 0^{o} orientation of the piezoceramic is when the PZT longitudinal axis is aligned with that of the plate.

Table-1 : Cantilever Plate and PZT Dimensions and Properties

Material	Duralumin	PZT
Length (mm)	155	50
Width (mm)	155	25
Thickness (mm)	0.5	0.5
E (GPa)	70	69
Poisson's ratio	0.3	0.35
Capacitance (μF)	-	0.058
Density (Kg/m^3)	2700	7500
Coupling coefficient (k_{31})	-	0.36

Table-2 : Experimentally Measured Parameters for Resistive Shunting (I-mode)

Cantilever Plate	Natural freequency without PZT (Hz)	15
	Natural freequency with PZT (Hz)	18.5
	Natural freequency (shorted) Hz	18.5
	Natural freequency (open) Hz	18.5
	Loss factor (without PZT)	0.0051
	Loss factor (with PZT short circuited)	0.0082
	Generalized coupling coefficient (measured) K_{ij}	0.043
Resistive Shunting	Capacitance (μF)	0.058
	Optimal resistance (I-mode) kΩ	140
	Non-dimensional resistance	0.94

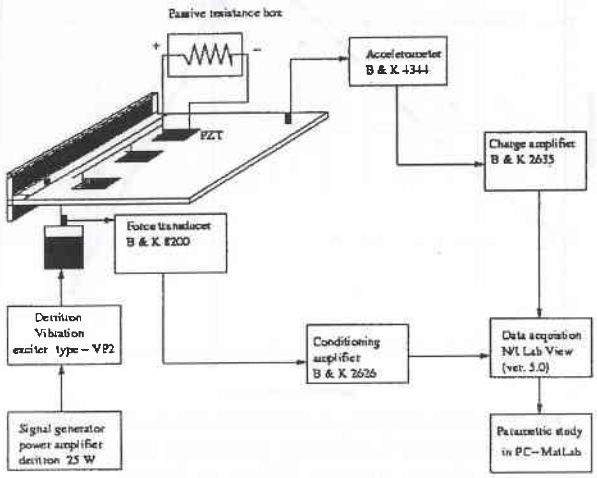

Fig. 3 Experimental setup

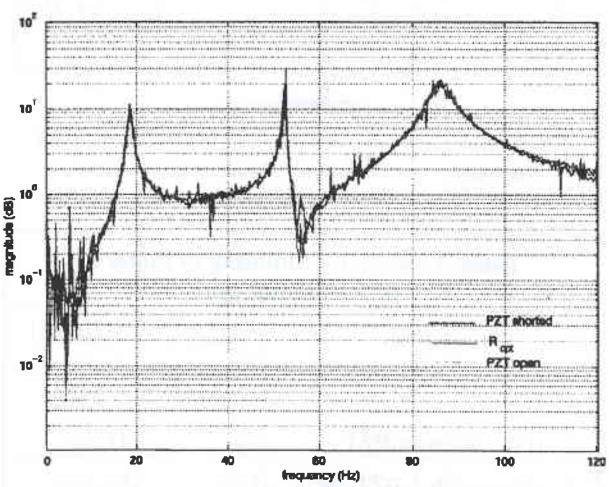

Fig. 4 Frequency response of plate with resistive shunted piezoceramic

The second is when the PZT longitudinal axis is inclined at 45^{o} to that of the plate. Table-3 summarizes the resonance frequencies of these two configurations as well as the base configuration of the plate without the PZTs. The PZTs were short-circuited when these measurements were made. Figs.5-8 summarize the results of experiment on the effect of orientation of additive damping through resistive termination of PZT. Modes 1 and 2 of the plate plus PZT configuration were considered. If we compare the additive damping for mode 1 for the 0^{o} and 45^{o} PZT orientations, it is observed that additive damping for the 0^{o} PZT orientation plate is more. This is as expected since the first plate is a predominant bending mode, and the 0^{o} PZT orientation strains the maximum resulting in maximum voltage drop across the resistive termination relative to the 45^{o} PZT orientation plate. Fig.6 and 8, on the other hand, for mode 2 of the plate-piezo combination, shows that the 45^{o} PZT orientation plate results in more additive damping. This result is also in keeping with expectation since the second plate mode is a predominant torsion mode and the 45^{o} orientation is angle of maximum shear stress. The

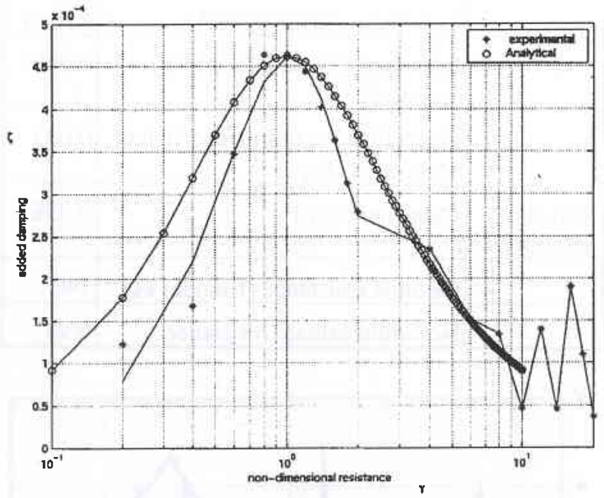

Fig. 5 Added damping as a function of non-dimensional resistance for a resistively shunted piezoceramic Plate-1, Mode-I (PZTs at 0 degree)

Table-3 : Resistive Shunting of Plates : Results Summary

Sl. No.	Plate	Mode-I Frequency (Hz)	Mode-II Frequency (Hz)
1	Plate without PZT	15	41.75
2	Plate with 3-PZTs at 0^{o}	18.5	52.375
3	Plate with 3-PZTs at 45^{o}	19.125	48.75

45^{o} orientated PZT thus strains more and generates a greater potential drop across the resistive termination as compared to that of the 0^{o} PZT orientation plate. Note that the optimum resistance values differ for the plates with different PZT orientations, as well as different plate modes.

Conclusions

The effect of resistive shunting of a piezoceramic material bonded to a duralumin cantilever plate is investigated with reference to its vibration control effectiveness.

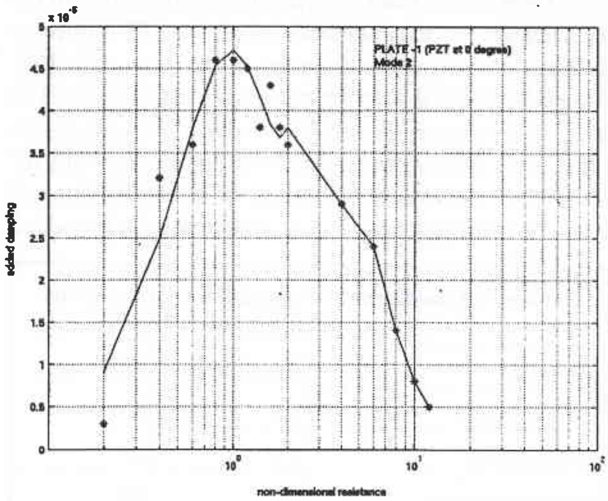

Fig. 6 Added damping as a function of non-dimensional resistance for a resistively shunted piezoceramic Plate-1, Mode-II (PZTs at 0 degree)

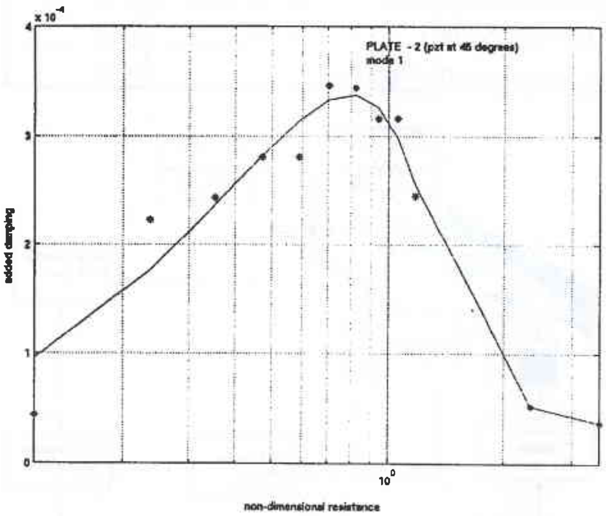

Fig. 7 Added damping as a function of non-dimensional resistance for a resistively shunted piezoceramic Plate-2, Mode-I (PZTs at 45 degree)

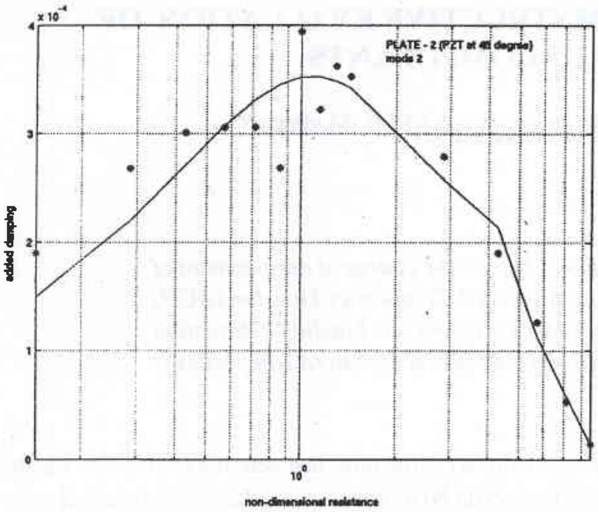

Fig. 8 Added damping as a function of non-dimensional resistance for a resistively shunted piezoceramic Plate-2, Mode-II (PZTs at 45 degree)

Specifically, we have focused on the increase in additive damping as a function of terminal resistance. The effect of orientation of the PZT relative to the plate and its effect on additive damping for the first and second vibration modes is also investigated. The analytical and experimental values of the added damping closely agree indicating the validity of the modeling of the shunted PZT.

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