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Enhancement of Structural Safety Using Piezoelectric Bimorph

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Abstract : Damping out high frequency low amplitude structural vibrations using PZT bimorph is presented. Static and Dynamic analyses of the piezoelectric bimorph bender were performed. Three layer piezoelectric actuators were modeled with SOLID5 coupled-field elements using ANSYS. Static deflection and modal analyses of the piezoelectric bimorph bender are presented. Proper tuning of the values of the resistor and inductor in the shunt circuit is required for maximum vibration suppression.

Key words: piezoelectric bimorph, structural safety, ANSYS, finite element analysis

1. Introduction

High frequency structural vibrations pose a significant threat to the structural safety of structures [1]. An easy way to eliminate the unnecessary vibration is to damp out the vibration. Passive damping uses its own structural vibration as a damping force without relying on an external power source, guaranteeing the stability of the overall system at the expense of vibration suppression performance [2]. Active damping achieves better vibration suppression but requires an external power source [2]. Piezoelectric material is strained when a voltage is applied and vice versa. This reversible strain-voltage effect is utilized in damping out the structural vibrations. Piezoelectric bimorph bender can be used as a passive and active damper depending on the applications. Piezoelectric damping of the structures to enhance the structural safety of the structure has been comprehensively employed in various engineering fields: mechanical, civil, aeronautical, space, and sports, etc [3-5]. The piezoelectric bimorph bender can be embedded into the structure with superficial increase of mass to the structure and easily tuned to the exact frequency that needs damping with superb efficiency. As a result, the piezoelectric bimorph benders outperform conventional dampers in a more compact package. Most of piezoelectric-based dampers are passive ones, simply a piezoelectric material electrically wired to a resistor. Electrical energy converted by a piezoelectric material from transmitted mechanical vibrations is dissipated into heat energy in the resistor. This kind of damping is called an RC damper which provides fairly broadband damping over about one decade of frequency [8]. At its best performance, RC dampers can damp out 10 % of mechanical vibrations, an efficiency comparable to other conventional passive damping devices [8]. To increase damping efficiency, an inductor is often added in series with the resistor. In active damping piezoelectric material works as an actuator. A voltage is applied to the piezoelectric material to counteract and eliminate the vibration. Active damping offers up to 10 times more damping than passive damping with more complicated and expensive peripheral devices [2]. In this study, static and dynamic characteristics of the piezoelectric bimorph are investigated. Numerical simulation of a three layer bimorph with a center metal shim was performed with a commercial FEA software package ANSYS. Simulation results revealed great potential of piezoelectric bimorph as an efficient mechanical damper.

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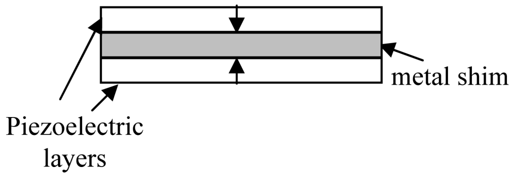
2. Theoretical analyses

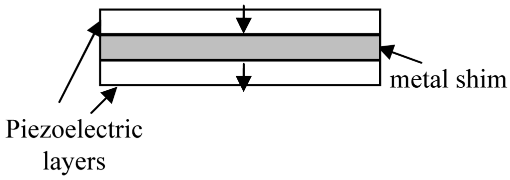
A piezoelectric bimorph is comprised of two thin outer piezoelectric plates and a metal center shim bonded together with adhesives as shown in Figs. 1 and 2.

The dynamic tip deflection of the cantilever bimorph without a center shim is given as [6, 7]:

$$\delta = \frac{3d_{31}V\sin\Omega L\sinh\Omega L}{4t_p^2\Omega^2(1+\cos\Omega L\cosh\Omega L)} \tag{1}$$



(a) X-poled for parallel operation



(b) Y-poled for series operation

Fig. 1. Cross-sectional view of PZT bimorph (↑, ↓ : polling direction)

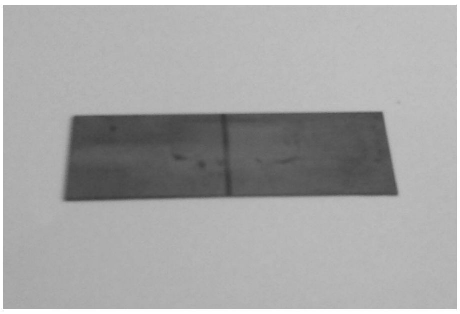


Fig. 2. A picture of PZT bimorph

where,
δ: dynamic tip deflection of cantilever,
d_{31}: piezoelectric constant,
L: length of cantilever,
t_P: thickness of PZT layer,
V: applied voltage.

In general a center shim is embedded between the outer PZT layers to enhance the mechanical strength of a bimorph. This makes the bimorph a three-layer structure. The analytical expressions for the fundamental resonance and static tip deflection of a cantilever bimorph are [6]

$$f_r = \frac{3.53t}{4\pi L^2}\sqrt{\frac{E_P}{3\rho_P}\left[\frac{1+3(1+2B)^2+4AB^3}{4(1+B)^2(BC+1)}\right]} \tag{2}$$

$$\delta_s = \frac{3L^2}{2t}\frac{(1+B)(1+2B)}{AB^3+3B^2+3B+1}d \tag{3}$$

where,
f_r: the fundamental resonance frequency,
δs: static tip displacement,
δ_{31}: piezoelectric constant,
L: length of the beam.
$A = E_m/E_p$, $B = t_m/2t_p$, $C = \rho_m/\rho_p$
where,
E_m: Young's modulus of metal,
ρ_m: density of metal,
t_m : thickness of metal,
E_p: Young's modulus of PZT,
ρ_p: density of PZT,
t_p : thickness of PZT

At resonance dynamic tip deflection is estimated with Eq.1 and procedures suggested by Wu et. al. [1]. The constitutive equations for piezoelectricity are [9]

$$\{T\} = [c]\{S\} - [e]\{E\} \tag{4}$$

$$\{D\} = [e]^T\{S\} - [\varepsilon]\{E\} \tag{5}$$

where,
T : 6 components of stress,
C : stiffness matrix(diagonal),
S : 6 components of strain,
e: piezoelectric matrix,
E: 3 components of electric field,
D: 3 components of electric flux density,
ε: dielectric matrix relating electric field to electric flux density.

The material properties of Eqs.2 and 3 are not easily measured. But, the properties in the inversed of the matrices are easier to obtain. Therefore, Eqs.1 and 2 are modified as follows [9]:

$$\{S\} = [c^E]\{T\} + [d]\{E\} \tag{6}$$

$$\{D\} = [d]^T\{T\} + [P]\{E\} \tag{7}$$

where,
c^E: compliance matrix,
d: dielectric matrix relating electric field to strain
P: permittivity matrix.
Manipulating Eqs.1-4 gives [9]

$$[c] = [c^E]^{-1} \tag{8}$$

$$[e] = [c^E]^{-1}[d] \tag{9}$$

$$[e]^T = [d]^T[c^E]^{-1} \tag{10}$$

$$[\varepsilon] = [P] - [d]^T[c^E]^{-1}[d] \tag{11}$$

It is assumed that all material properties excluding the PZT layer are isotropic. Eqs.6-9 are used to produce the matrices in Eqs.2 and 3 for ANSYS simulation. The reduced-order analysis option in ANSYS was used to calculate the modal response.

3. FEM Results and Discussions

For simulation, materials data from the bimorph manufactured by Piezo Systems(Cambridge, MA, USA) were used. Detailed materials data are shown in Table 1.

The piezoelectric layers were modeled with 3D coupled-field solid elements SOLID5 and the center brass shim was modeled with SOLID45. The system was free-meshed. Reduced-order solver was used for modal analysis. Table 2 shows the first ten natural frequencies of the PZT bimorph.

Table 1. Material properties

PZT type	PSI-5H-S4
d_{31} (10^{-12} m/V)	-320
d_{33} (10^{-12} m/V)	650
d_{15} (10^{-12} m/V)	750
S^E_{11} (10^{-12} m^2/N)	13.8
S^E_{33} (10^{-12} m^2/N)	17.2
$\varepsilon^T_{11}/\varepsilon_o$	1000
$\varepsilon^T_{33}/\varepsilon_o$	3800
width (mm)	21
density (kg/m^3)	7800
Young's modulus(Nm^{-2})	6.6×10^{10}
Poisson's ratio	0.31
Length (mm)	63
Thickness of PZT(mm)	0.191
Thickness of brass shim(mm)	0.127
density of brass (kg/m^3)	8800
Poisson's ratio of brass	0.35
Young's modulus of brass (Nm^{-2})	11×10^{10}

Table 2. First 10 natural frequencies of bimorph

Mode no.	Frequency, Hz
1	61.5
2	377.2
3	387.9
4	1115.3
5	1199.7
6	2222.8
7	2278.3
8	2475.0
9	3592.0
10	3667.7

PZT bimorphs are suitable for eliminating bending vibrations. If the frequency at which vibration occurs has a non-bending mode shape such as longitudinal and torsional vibrations shown in Fig. 3. Then, other measures of vibration suppression should be employed.

To investigate the static deflection characteristic of PZT bimorph, 100 V was applied to the bottom PZT and its deflection is shown in Fig. 4. The PZT bimorph is bended upward. If the polarity of the voltage applied were reversed, the PZT bimorph would be curved downward. These upward and downward motions counter and eliminate unnecessary high frequency vibra-

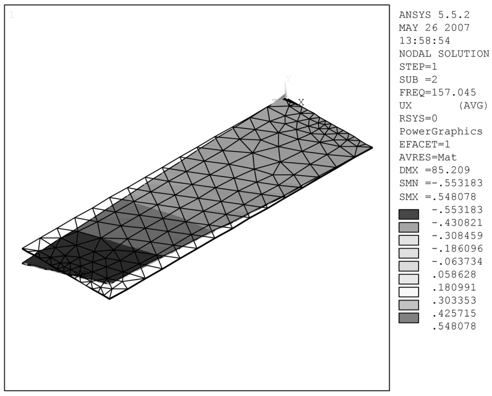


Fig. 3. Torsional Mode of PZT bimorph(ANSYS simulation result)

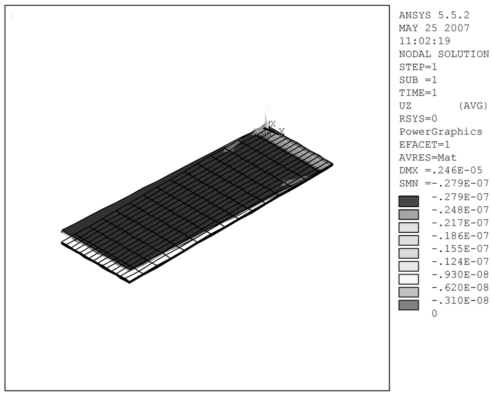


Fig. 4. Static deflection of PZT bimorph(ANSYS simulation result)

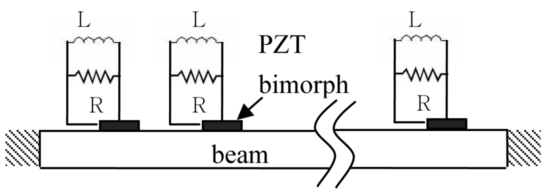


Fig. 5. Vibration suppression using multiple PZT bimorphs

tions, thereby enhancing the structural safety of the structure. A maximum deflection of 2.5 microns at the tip of the PZT bimorph is observed.

Multiple PZT bimorph can be placed on the structure that requires damping of high frequency vibrations as shown in Fig. 5. A series of bimorph can be either individually or collectively tuned to eliminate the specific frequency of vibration.

Procedures for tuning the values of the resistor and inductor are detailed in [1] and can be summarized as follows:

1. Obtain fo and fs where fo: peak frequency(PZT open), fs: peak frequency(PZT short)
2. Calculate the generalized transverse electro-mechanical coupling coefficient of the mode, K_{31}
3. Determine the PZT capacitance at constant strain C^S
4. Calculate the optimum normalized tuning frequency, α^*, $\alpha^2 = (1 - K_{31}^2/2)^{0.5}$
5. Calculate the optimum tuning inductance, L^*, $L^* = 1/[C^S(2\pi f_s\alpha^*)^2]$
6. Calculate the optimum shunt resistant, R^*, $R^* = 1/[2.828\pi f_S C^S K_{31}]$

4. Conclusions

Damping of high frequency low amplitude vibration using PZT bimorph is presented. To input PZT material data into ANSYS, material data supplied by PZT manufacturers need to be modified. Single and multiple PZT bimorph can be attached on the structure requiring vibration absorption. Following Wu's method, the values of the resistor and inductor can be tuned for maximum vibration suppression.

Acknowledgements

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