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STUDY ON OPTIMAL VOLTAGE FOR PZT ACTUATOR IN VIBRATION CONTROL OF CANTILEVER BEAM USING ANSYS

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Abstract: In active vibration control the vibration of a beam is reduced by using opposite directional force to the beam. Nowadays active vibration control is frequently being used in aircraft, submarine, automobile, helicopter blade, naval vessel. In this work, we tried to reduce the wave formation for a beam. Piezoelectric materials allow the transformation of electricity constraints into mechanical constraints and vice versa. They are used as controllers or sensors in the industry field. The objectives of this work are the modeling of smart structures and study on dynamic behavior of the beam also the effect of voltage for actuator in the control system. In this work we consider a cantilever beam under loading condition and tried to reduce the vibration of that beam using PZT actuator. The study uses ANSYS software to derive the finite element model of the smart beam. Based on this model, the optimal voltage for actuator is found. Beyond the optimum voltage level, the actuator increased the level of vibration 180 out-of-phase. Modal, harmonic finite element analyses are performed. We found the drastic changes due to use of piezoelectric actuators. The work displayed the role of PZT actuators for the active control of the beam.

Keywords: Cantilever beam, Finite Element Analysis, PZT, Smart structure, Vibration analysis.

I. Introduction

Active vibration control is defined as a technique in which the vibration of a beam is reduced or controlled by applying counter force to the beam that is appropriately out of phase but equal in amplitude to the original vibration. As a result two opposite force cancel each other and beam stops vibrating. Techniques like use of springs, pads, dampers, etc have been used previously to control vibration. These techniques are known as "Passive vibration control technique". They have limitations of versatility and can control the frequencies only within a particular range of bandwidth hence there is a requirement for active vibration control. Active vibration control makes use of smart beam. The system mainly requires actuators, sensors, source of power and a compensator that performs well when vibration occurs. Smart beam are used in the bridges, trusses, buildings, mechanical systems etc. analysis of a basic beam can help in improving the performance of beam under poor working conditions involving beam vibrations. Active smart materials are those materials which possess the capacity to modify their geometric or material properties under the application of electric, thermal or magnetic field, thereby acquiring an inherent capacity to transducer energy. The active smart materials are piezoelectric material, Shape memory alloys, Electro-rheological fluids and Magneto-strictive materials. Being active they can be used as force transducers and actuators. The materials which are not active under the application of electric, thermal or magnetic field are called Passive smart materials. Fiber optic material is good example of passive smart material. Such materials can act as sensors but not as actuators and transducers.[2] Piezoelectric materials like (lead-Zirconium-Titanate) can be used effectively in the development of smart systems. So far a large amount of work has been devoted exploring smart beams with piezoelectric actuation. Some of them suggested strategies have already found in practical applications in vibration control. Materials with piezoelectric properties have been found to exhibit pyroelectric and electro caloric properties for the possible conversion of thermal energy into electrical energy, and vice versa. Conversion of thermal in to mechanical energy and vice-versa by means of thermal expansion together with piezo-caloric effect can be observed in piezo-thermoelectric materials. These effects can be used to increase the efficiency of the control actuation.[1] K.B.Waghulde. et al. presented the FEA results of the modeling of a smart beam for active vibration control. The effect of changes in the mass and the stiffness of the structure combined with control performance index lead to solutions that were independent of initial conditions of the flexible structure. [3] Zhi cheng Qiu. et al. used piezoelectric ceramics patches as sensors and actuators to suppress the vibration of the smart flexible clamped beam. A method for optimal placement of piezoelectric actuators and sensors on a cantilever beam was developed. An experimental setup of piezoelectric smart beam was built up. [4] Yang Y. and Zhang L. studied a simply supported rectangular beam subject to in-plane forces, resting on an elastic foundation and excited by a PZT actuator.[5] The objective of this paper is to find out optimal voltage for PZT actuators in vibration control of aluminum cantilever beam.

II. VIBRATION OF CANTILEVER BEAM

By using Euler's Bernoulli beam theory,

$$\frac{\partial^2 u}{\partial t^2} + \frac{EI}{\rho} \frac{\partial^4 u}{\partial x^4} = 0 \quad (1)$$

To find the response of the system one may use the variable separation method by using the following equation.

$$u(x, t) = \varphi(x)q(t) \quad (2)$$

$\varphi(x)$ is known as the mode shape of the system and $q(t)$ is known as the time modulation. Now equation (1) reduces to

$$\varphi(x) \frac{\partial^2 q(t)}{\partial t^2} + \frac{EI}{\rho} \frac{\partial^4 \varphi(x)}{\partial x^4} q(t) = 0 \quad (3)$$

or

$$-\frac{EI}{\rho} \left(\frac{1}{\varphi(x)} \right) \left(\frac{\partial^4 \varphi(x)}{\partial x^4} \right) = \frac{1}{q} \left(\frac{\partial^2 q}{\partial t^2} \right) \quad (4)$$

Since the left side of equation (4) is independent of time t and the right side is independent of x the equality holds for all values of t and x . Hence each side must be a constant. As the right side term equals to a constant implies that

the acceleration $\left(\frac{\partial^2 q}{\partial t^2} \right)$ is proportional to displacement

$q(t)$, One may take the proportionality constant equal to $-\omega^2$ to have simple harmonic motion in the system. If one takes a positive constant, the response will grow exponentially and make the system unstable. Hence one may write equation (4) as

Hence,

$$\frac{d^2 q}{dt^2} + \omega^2 q = 0 \quad (5)$$

And

$$\frac{\partial^4 \varphi(x)}{\partial x^4} - \frac{\rho \omega^2}{EI} \varphi(x) = 0 \quad (6)$$

Taking

$$\beta^4 = \frac{\rho \omega^2}{EI} \quad (7)$$

The above equation can be written as

$$\frac{\partial^4 \varphi(x)}{\partial x^4} - \beta^4 \varphi(x) = 0 \quad (8)$$

The solution of equation (6) and (9) can be given by

$$q(t) = C_1 \sin \omega t + C_2 \cos \omega t \quad (9)$$

$$\varphi(x) = A \sinh(\beta x) + B \cosh(\beta x) + C \sin(\beta x) + D \cos(\beta x) \quad (10)$$

Hence,

$$u(x, t) = (A \sinh \beta x + B \cosh \beta x + C \sin \beta x + D \cos \beta x) (C_1 \sin \omega t + C_2 \cos \omega t) \quad (11)$$

Here constants C_1 and C_2 can be obtained from the initial conditions and constants A, B, C, D can be obtained from the boundary conditions. Let us now determine the mode Shape of cantilever beam. In case of cantilever beam the boundary conditions are

At left end i.e.,

$$\begin{aligned} \text{At } x = 0 \quad u(x, t) &= 0 & (\text{Displacement} = 0) \\ \frac{\partial u(x, t)}{\partial x} &= 0 & (\text{Slope} = 0) \end{aligned} \quad (12)$$

At the free end i.e.,

$$\begin{aligned} x = L \quad \frac{\partial^2 u(x, t)}{\partial x^2} &= 0 & (\text{Bending moment} = 0) \\ \frac{\partial^3 u(x, t)}{\partial x^3} &= 0 & (\text{Shear force} = 0) \end{aligned} \quad (13)$$

$$\text{At } x=0 \quad \phi(x)=0 \text{ and } \frac{\partial \phi(x)}{\partial x}=0 \quad (14)$$

$$\text{At } x=L \quad \frac{\partial^2 \phi(x)}{\partial x^2}=0 \text{ and } \frac{\partial^3 \phi(x,t)}{\partial x^3}=0 \quad (15)$$

Substituting these boundary conditions in the general solution,

$$\phi(x) = A \cosh \beta x + B \sinh \beta x + C \cos \beta x + D \sin \beta x \quad (16)$$

$$\text{From (Eqn.15)} \quad A = -C \text{ and } B = -D \quad (17)$$

$$\phi(x) = A(\cosh \beta x - \cos \beta x) + B(\sinh \beta x - \sin \beta x) \quad (18)$$

From (15 and 18) one may have

$$\frac{A}{B} = -\frac{\sinh \beta l + \sin \beta l}{\cosh \beta l + \cos \beta l} = -\frac{\cosh \beta l + \cos \beta l}{\sinh \beta l - \sin \beta l} \quad (19)$$

or,

$$\cos \beta l \cosh \beta l = -1 \quad (20)$$

and the root of the equation is,

$$\beta l = \frac{(2n-1)\pi}{2} \quad (21)$$

Hence one may solve the frequency equation $\cos \beta l \cosh \beta l = -1$ to obtain frequencies of different modes. For the first two modes the values of βl are calculated as 1.875, 4.694.

For a simple elastic beam problem with uniform cross-sectional area, a well-known natural frequency can be calculated by,

$$\omega = (\beta l)^2 \sqrt{EI/\rho A L^4} \text{ in rad/sec}^2$$

While natural frequency in Hz,

$$f_n = \frac{\omega}{2\pi} \text{ in Hz}$$

Where, A and L are the area of cross-section and the length of the flexible beam, respectively, E is the Young's Modulus and I is the moment of inertia of beam.

III. VIBRATION ANALYSIS OF CANTILEVER BEAM BY USING FEA

The natural frequency of the aluminum beam is found by the well known Finite Element (FEA) Software. For cantilever beam Solid 45 element type and for PZT patch Coupled field Solid 5 element types are used. Modal analysis and harmonic analysis are carried out using ANSYS software for finding the natural frequencies. The dimensions and material properties of aluminum beam and PZT actuator are listed in Table 1 and Table 2. The first two mode shapes of aluminum beam and beam with PZT actuator are shown in Figure 1 and Figure 2. The first two natural frequencies of aluminum beam and Beam with PZT actuator are shown in the Table 3.

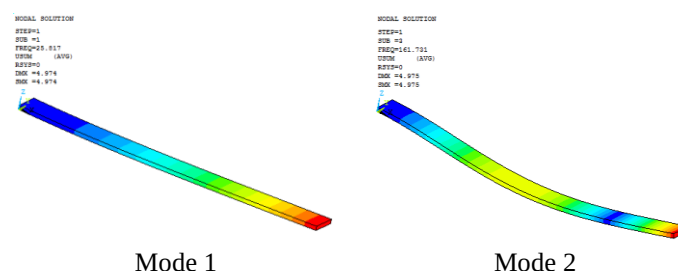


Fig.1 1st and 2nd Mode Shape of Cantilever Beam

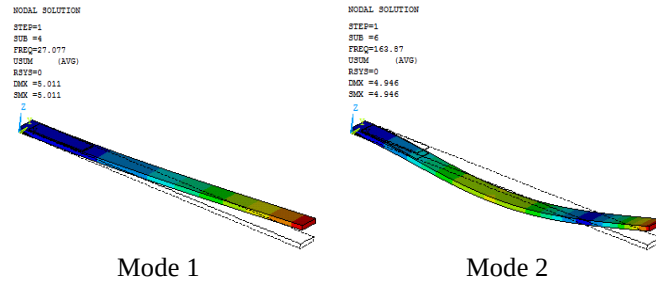


Fig.2 1st and 2nd Mode Shape of Cantilever Beam with PZT Actuators

Table: 1 Material Properties and Dimensions of Aluminium beam

Dimensions/Properties		Aluminum
Length	l	400 mm
Width	b	50 mm
Thickness	t	5 mm
Young modulus	e	70 Gpa
Poisson's ratio	μ	0.3

Table: 2 Material Properties for the PZT patch [6]

PZT 5H Type Actuator	Standard Values
C11 (Pa)	12.6×10^{10}
C12 (Pa)	8.41×10^{10}
C13 (Pa)	7.95×10^{10}
C22 (Pa)	12.6×10^{10}
C23 (Pa)	7.95×10^{10}
C33 (Pa)	11.7×10^{10}
C44 (Pa)	2.33×10^{10}
C55 (Pa)	2.10×10^{10}
C66 (Pa)	2.10×10^{10}
e12 (C/m2)	-6.5
e22 (C/m2)	-6.5
e32 (C/m2)	23.3
e41 (C/m2)	17.0
e53 (C/m2)	17.0
ϵ_{11} (F/m)	15.03×10^{-9}
ϵ_{22} (F/m)	15.03×10^{-9}
ϵ_{33} (F/m)	13.00×10^{-9}
ρ (Kg/m ³)	7800
Length of patch	76.4 mm
Width of patch	25.4 mm
Thickness	0.5mm

IV. EFFECT OF PZT ACTUATOR ON NATURAL FREQUENCY

PZT actuator patch is surface bonded at different locations from the fixed end. The PZT actuator located on the fixed end of the beam had the high stiffness. The seventh segment, located on the free end of the beam had the low stiffness. The beam and the PZT actuator were modeled in ANSYS and were contact together and analyzed for natural frequency with fixing the beam at one end. Due to addition of PZT patch on the aluminum beam the mass and stiffness of the beam gets increased but not proportionally. So the natural frequency of the beam is also gets increased.

Table: 3 First Two Natural Frequencies of Beam

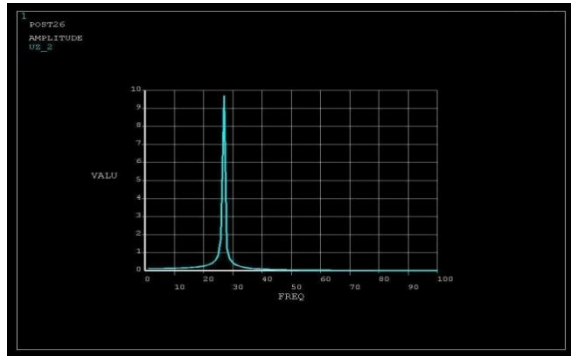
Mode	f_n (Hz) Without PZT Actuators	f_n (Hz) With PZT Actuators
1	25.817	27.07
2	161.731	163.87

V. OPTIMAL VOLTAGE FOR PZT PATCH

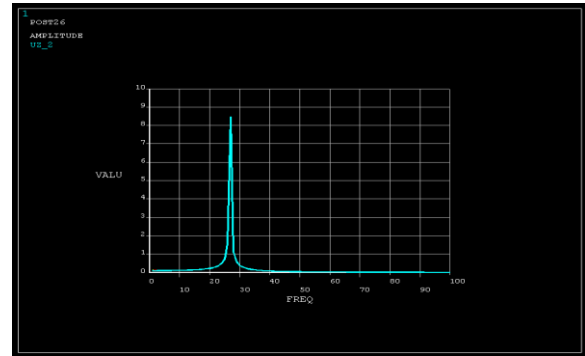
The effectiveness of the optimum voltage active vibration reduction was evaluated for the smart cantilever beam. Fig. 3 shows the mode shape of the first natural frequency, Mode I, at 27.07 Hz when PZT is placed 12mm from

fixed end. Henceforth, the term ‘uncontrolled’ means that only the external load 10 N is being applied to the beam at free end and the actuator voltage is 0V. On the other hand, the term ‘controlled’ means that in addition to the external load, internal load supplied by a non-zero actuator voltage also exists, simultaneously. Graph 1 to Graph 5 shows amplitude responses of the smart aluminum beam tip for various 0 to 100 voltages applied to actuator.

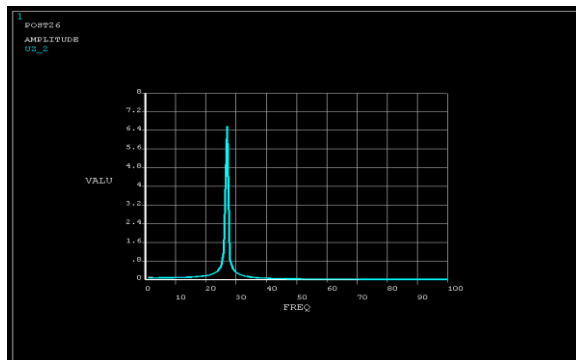
Graph 1: Tip displacement when 0 volt applied to PZT Actuator.



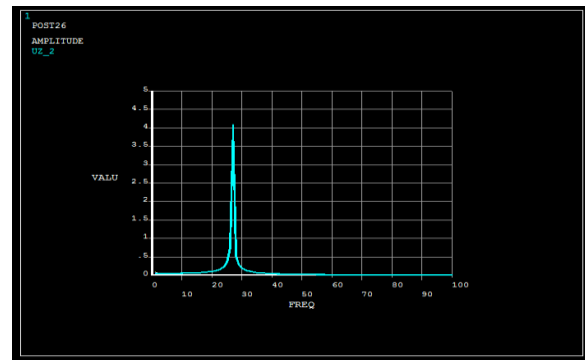
Graph 2: Tip displacement when 25 volt applied to PZT Actuator.



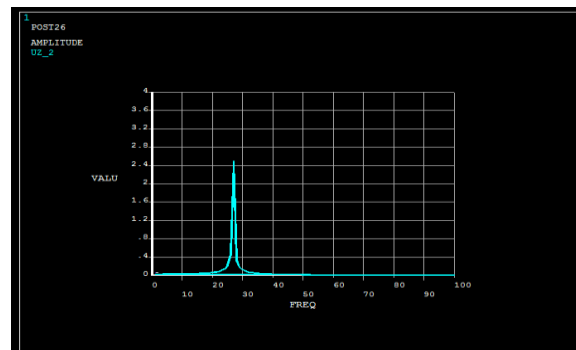
Graph 3: Tip displacement when 50 volt applied to PZT Actuator.



Graph 4: Tip displacement when 75 volt applied to PZT Actuator.



Graph 5: Tip displacement when 100 volt applied to PZT Actuator.



VI. RESULT AND DISCUSSION

It is well known that PZT actuator has a significant affects on vibration control of mechanical host. In order to do so, the PZT actuator was placed near to fixed end. After that, the first two natural frequencies are calculated. The calculated frequency for aluminum beam with surface bonded PZT actuator is listed in Table 3. From the Table 3, it can conclude that the natural frequency of the aluminum beam with PZT actuator increases slightly. Harmonic analysis was carried out to find out effectiveness of PZT actuator. In harmonic analysis, an external load 10 N applied on free end of cantilever beam and 0 to 100V supplied to PZT actuator. It is observed that as we increase voltage then the amplitude of vibration decreases. Graph 1 to Graph 5 shows amplitude responses of the smart

aluminum beam tip for various 0 to 100 voltages applied to actuator. And also it is found that the optimum voltage is about 100V.

VII. CONCLUSION

A simple but efficient analytical approach was proposed to simulate the action of the piezoelectric actuators placed on cantilever beam. In this study, it can be found that the PZT actuators can be used for active vibration control. Finite element analysis of the proposed model is presented. Through the use of that method, the vibration control of the beam subjected to external action can be achieved. By doing harmonic analysis it is observed that the vibrations in a cantilever smart beam were suppressed by applying variable voltage to the piezoelectric actuator.

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