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Active Vibration Control of Smart Structure using PZT Patches

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Abstract

The assembly that serves an engineering function is called as structure and structure that exhibits intelligence, efficiency, adaptability, accurate response and optimum performance is termed as a smart structure. Though, due to these advantages smart structures are used in many high end applications like aerospace engineering, microelectronics productions, precise positioning and automation industries, active vibration control of these structures is extremely important. This is because; mechanical vibrations in the structure can have detrimental effects as they can damage sensitive components of the structure or even the whole structure. Vibration control basically suppresses the effect of external disturbances and keeps the structure in its equilibrium position. In this paper, vibration control analysis of the structure for forced vibrations is carried out. The smart structure considered here, is a finite and flat beam-like fiber cantilever structure with PZT patches attached to its surface. Along with vibration control analysis effect of changing positions of PZT patches on this analysis is also discussed in this paper.

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Keywords: Active Vibration Control; Piezoelectricity; Robust Control; Smart Structure.

1. Introduction

Any structure that carries out specific engineering function must be intelligent, efficient and smart. It must have ability to respond adaptively in a pre-designed and scientific manner to changes in environmental conditions, along with any changes in its own condition. In addition to this, it must have optimum performance. The structure that exhibits all these features is termed as smart structure. Operation of such structures is featured with four basic parts 'sensors', 'actuators', 'control mechanism' and 'timely response'. Hence, Specific definition of smart structure can be given as 'A system which has built in or intrinsic sensors, actuators and control mechanism whereby it is capable of sensing a stimulus, responding to it in a predetermined manner in a short/appropriate time so as to revert to its original state as soon as the stimulus is removed'[1,4]. These features make smart structures extremely suitable for wide range of applications spanning from microelectronics productions to large applications like aerospace engineering. To meet such severe performance smart structures are implemented considering active control strategies which deals with shape control and vibration control. In vibration control, effect of external disturbances is suppressed to keep the structure in its equilibrium position, while the shape control deforms the structure to a desired shape, position and maintains the structure in the proper shape[2].

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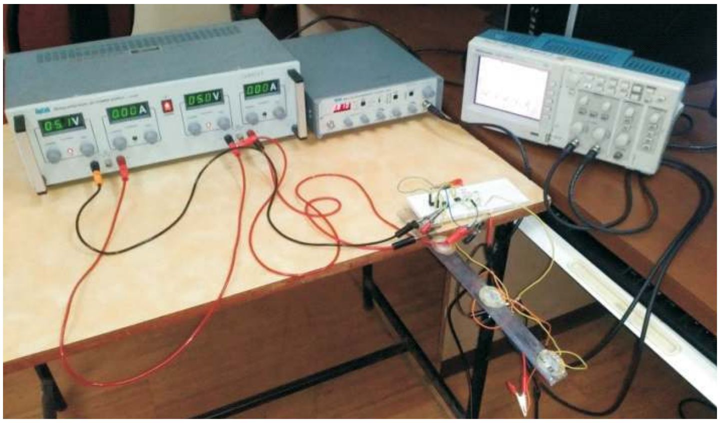

Fig. 1. Experimental Setup of the System.

As mechanical vibration resonance in the system gives rise to detrimental effects, suppression of such vibrations is very crucial and many control mechanisms are designed for the same. Basics of smart structures and their applications is explained by V. K. Wadhvan.[1] Neda Darivandi Shoushtari has explained optimal active control of flexible structures which deals with shape control and vibration control strategies.[2] Vibration control analysis of a cantilever beam using of piezoelectric patches is discussed by Hamed Mohammadi and Sallehuddin Mohamed Haris.[3] Martin Pohl and Michael Rose have investigated application of piezoelectric shunt damping of a circular saw blade for noise and vibration reduction. In this application authors have used autonomous power supply in which the required energy for the electronics is taken from the rotation by a generator, so that no change of the machine tool is required.[4] Further, some applications of smart structures for active vibration control is given by Melin Sahin, Fatih Mutlu Karadal and Yavuz Yaman.[5] Piezoelectric material exhibits reversibility property, which makes it suitable to use as sensor as well as an actuator. This technique, called as self sensing can also be used for vibration suppression. Kenta Seki and Makoto Iwasaki have explained this phenomenon.[6]

Vibrations here refer to the repeating motion or deformations of an elastic structure. From Structural engineering point of view, vibrations are defined based on the 'restoring force' present in the system. In presence of a restoring force the mass of a system gets excited and is disturbed from its rest or equilibrium position which in turn initiates vibrations. For modeling of the vibrating system, four types of forces are taken into account. Those are inertial force, spring force, damping force, total external force. Generally, conventionally engineered structures are over-designed, for meeting safety requirements. But ideally, designed system should work passively for purpose and adaptively for crises. Moreover, practically conventional approach gives rise to higher costs due to over-designing. Hence, smart configuration would be that in which normal loads are taken care of in normal conditions, and suitable actuation systems are activated to tackle abnormal loads. This paper deals with implementation of active control strategy, specifically active vibration control[1,3].

2. Experimental Setup

Figure 1 shows an experimental setup of the designed system.

Block diagram of the system setup is given in Fig. 2. The smart structure considered here, is a finite and flat beam-like fibre cantilever structure with PZT patches attached to its surface. In order to analyze response of structure to forced vibrations vibrator is attached to a structure. A simple function generator is used to generate forced vibrations. Further PZT patches are used as a vibrations sensor, structural vibrations sensor and as an actuator as shown in the Fig. 2. Vibration sensor is subjected near a vibrator to sense vibrations of a structure. It senses vibrations in the beam the output voltage signal of the sensor is sent to the actuator after passing through controller. The signal sent to the actuator counteracts the motion of the beam and damps out its vibrations. Middle sensor senses overall vibrations in the structure.

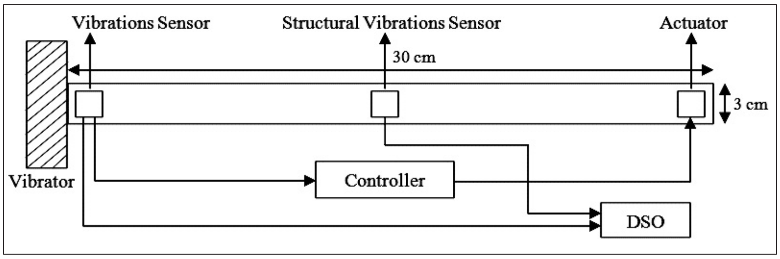

Fig. 2. Block Diagram of Experimental Setup.

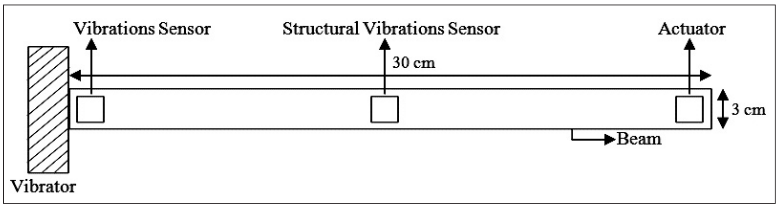

Fig. 3. Block Diagram of Cantilever beam with PZT Patches.

3. Controller Design

3.1 Modeling of beam with piezoelectric patch

Figure 3 illustrates a cantilever beam with PZT patches as vibration sensor, structural vibration sensor and an actuator.

The governing equation for PZT material is given as:

$$\sigma = C_E S + eE \tag{1}$$

$$D = eS - \varepsilon E \tag{2}$$

where, σ is the stress vector, C_E is the matrix of elastic constants under constant electric field (dependent on modulus of elasticity and Poisson's ratio), E is the electric potential, S is the strain vector, ε is the electric permittivity matrix under constant mechanical strain, e contains the piezoelectric coupling constants and D is the electric displacement vector[2].

Further modelling of the beam with PZT patches for forced vibration is carried out using differential equations as follows:

$$\frac{\partial^2}{\partial x^2}\left(EI(x)\frac{\partial^2 w(x,t)}{\partial x^2}\right) + c\frac{\partial w(x,t)}{\partial t} + m(x)\frac{\partial^2 w(x,t)}{\partial t^2} = F_d \tag{3}$$

Here, ω is the beam deflection, m is the mass, c is the damping constant, and Fd is an external force[3]. Above equation models beam considering spring force, damping force, inertial force and external force.

3.2 Design of vibration sensor

In the system, output of basic 30 mm piezoelectric disk due to presence of vibration is sensed through vibration sensing circuit as shown in Fig. 4. National Instrument Circuit Design Suit Multisim 14.0 is used for simulation of a designed circuit.

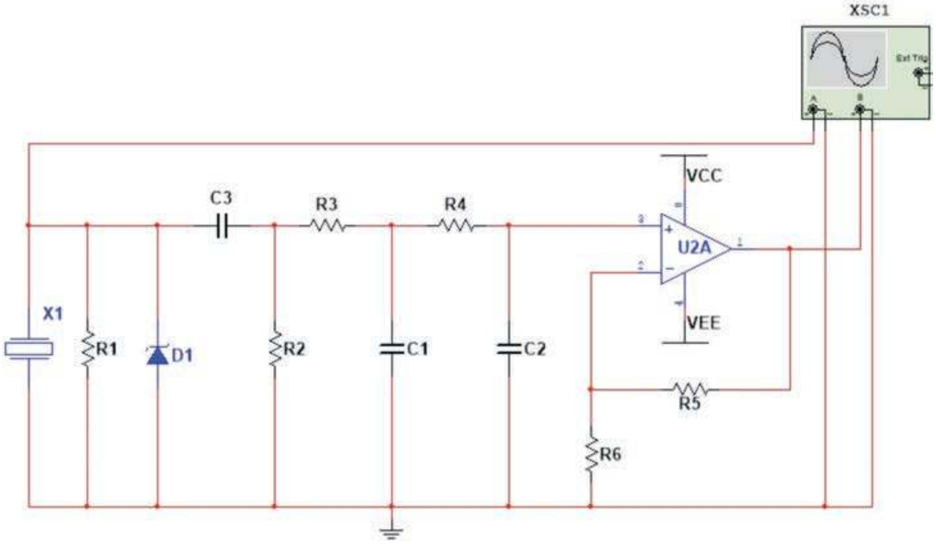

Fig. 4. Vibration Sensor Circuit.

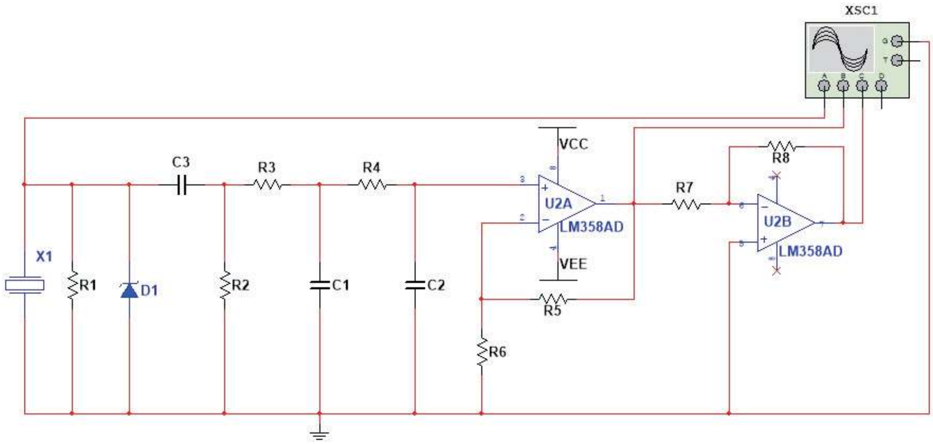

Fig. 5. Vibration Sensor Along with Inverter Circuit.

3.3 Design of an inverter circuit

Figure 5 Shows implementation of an inverter circuit. Output of this circuit is directly fed to the PZT patch that is working as an actuator. When PZT actuator is excited through exactly opposite waveform of that of the vibration sensor waveform, two signals, one due to forced vibrations and other from the actuators get added. If both the waveforms have same magnitude but are 180 degree out of phase their vector addition results into waveform of zero amplitude and frequency. Hence, basic mechanical vibrations present in the smart structure system are suppressed. This very visible phenomenon can be sensed through structural vibration sensor situated in the middle of the vibration sensor and an actuator[3,4].

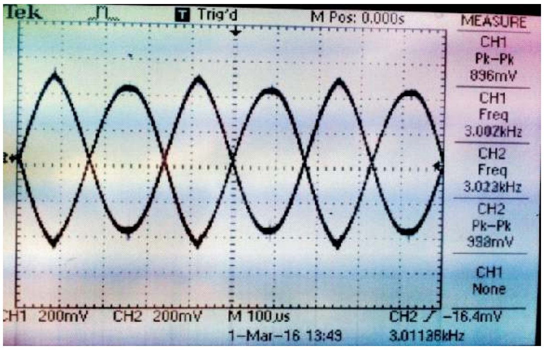

Fig. 6. Output of the Circuit Implemented in Fig. 5.

Mathematical equation for inverter circuit is given as:

$$V_{\text{out}} = -\frac{R2}{R1}V_{\text{in}} \tag{4}$$

To achieve exactly inverted waveform $R1 = R2$.

Even though, this phenomenon works for small structures, practically, for large structures vibration suppression in the system is highly influenced by location of the PZT patches, i.e. sensors and actuators. This is observed by changing positions of the PZT vibrator and PZT actuator patch on the structure. It shows that distance between vibrator and actuator patch is directly proportional to the amplitude of structural vibrations, i.e. as distance decreases amplitude of structural vibrations decreases[2].

$$V = k * D \tag{5}$$

where, V is structural sensor output voltage, k is constant of proportionality that can be defined as a coefficient of transformation from mechanical energy to electrical energy and D is distance between vibrator and an actuator. Concept is explained well below in the Result analysis.

4. Result Analysis

Initially, experiment was performed to analyze response of the system i.e. flat beam-like fiber cantilever structure with PZT patches for different frequency and voltage ranges. In this experiment, it was observed that in the frequency range 2.8 kHz to 3.6 kHz PZT patch working as vibration sensor gives accurate response with maximum vibration amplitude voltage. Outside this range, amplitude of voltage of sensed vibration decreases. Hence, vibrator frequency is taken as 3 kHz. Further, 1 V peak to peak amplitude of vibration voltage is taken. This is because, if vibration amplitude is less, vibration sensor does not sense sufficient amount of vibrations and if vibration amplitude is large it gives rise to mutual vibration sensing that is, two nearly placed PZT patches sense each other's vibrations.

When output of circuit shown in Fig. 5. is given to actuator PZT patch, net vibrations in the structures are suppressed. Results of this experiment were observed on Digital Storage Oscilloscope. Further, effect of changing distance between sensor and actuator is also verified below. Output of the circuit implemented in Fig. 5. is shown below. Here, Channel 1 is input while channel 2 represents output of the circuit.

Further, results were evaluated by varying location of the actuator with respect to vibrator and vibration sensor. Here in DSO, Channel 1 of shows vibration sensors output and channel 2 shows output of the structural vibration sensor.

Case 1: $D = 28$ cm

For $D = 28$ cm, structural vibrations that are sensed by middle PZT structural vibration sensor are 224 mV, i.e. Amplitude of vibration is suppressed from 896 mV to 224 mV.

Case 2: $D = 16$ cm

For $D = 16$ cm, structural vibrations that are sensed by middle PZT structural vibration sensor are 104 mV, i.e. Amplitude of vibration is suppressed from 888 mV to 104 mV.

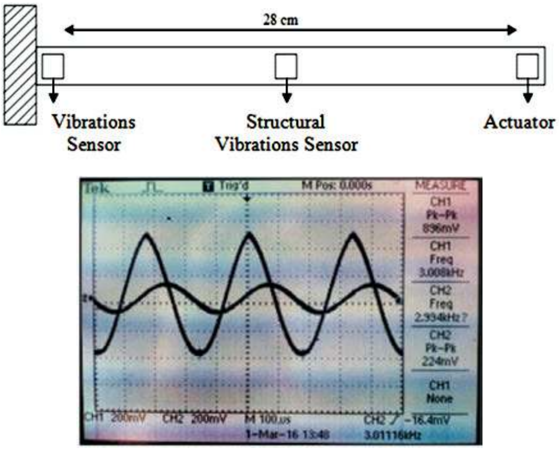

Fig. 7. Output of the System for $D = 28$ cm.

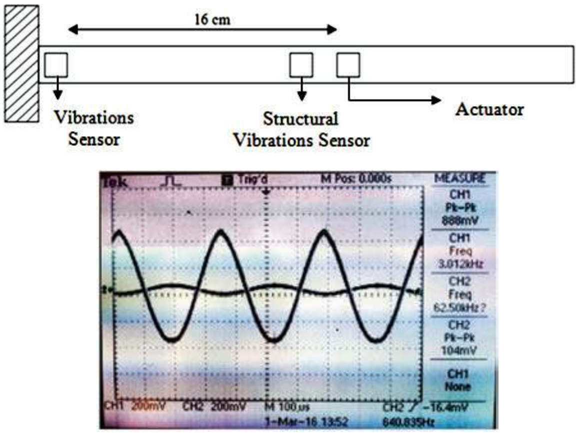

Fig. 8. Output of the System for $D = 16$ cm.

5. Conclusions

This paper presented a vibration suppression approach using the active control strategy. Piezoelectric Patches have high resolution, high bandwidth, rapid response, large force generation and reversibility property. All these advantages make them very efficient in order to use as a sensor and actuator for smart structure. Experimentally it was verified that vibrations in the smart structure can be reduced by applying to an actuator a waveform that is out of phase with that of sensed waveform. Further, relation of distance between vibrator and an actuator with amplitude of vibration was also discussed. It was observed that, distance between vibrator and actuator is directly proportional to amplitude of vibrations.

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