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Active Vibration Control of a Smart Cantilever Beam on General Purpose Operating System

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ABSTRACT

All mechanical systems suffer from undesirable vibrations during their operations. Their occurrence is uncontrollable as it depends on various factors. However, for efficient operation of the system, these vibrations have to be controlled within the specified limits. Light weight, rapid and multi-mode control of the vibrating structure is possible by the use of piezoelectric sensors and actuators and feedback control algorithms. In this paper, direct output feedback based active vibration control has been implemented on a cantilever beam using Lead Zirconate-Titanate (PZT) sensors and actuators. Three PZT patches were used, one as the sensor, one as the exciter providing the forced vibrations and the third acting as the actuator that provides an equal but opposite phase vibration/force signal to that of sensed so as to damp out the vibrations. The designed algorithm is implemented on Lab VIEW 2010 on Windows 7 Platform.

Keywords: Smart cantilever beam, active vibration control, direct output feedback, Lead Zirconate-Titanate

1. INTRODUCTION

The very first analysis of any measured data from a vibrating system is to convert it from time domain into frequency domain so as to find the frequency content of measured data. In a normal engineering system investigation process, a complex physical system or real system is studied as a physical model. It is then mathematically modelled so that further analysis can be carried out on the model instead of the system. This helps in attaining a clear understanding of the system behaviour and is also cost effective. Finally, the physical system is put to the same tests as is its model. The simulated and experimental results from the model are then compared. If they do not match, the assumption made to build the model is re-defined and the entire process is repeated till a satisfactory solution is obtained. The development in piezoelectric materials have motivated many researchers to work in the field of smart structures[9-15]. A smart structure can be defined as the structure that can sense external disturbance and respond to it actively as per the designed control algorithm so as to maintain its dynamics within the desired levels. They comprise of distributed active devices like sensors and actuators that may either be embedded or attached to the structure with integrated processor networks. Smart structures are widely used in place of the traditional structures on account of their ability to adapt according to the prevailing disturbances. Mechanical vibrations of these structures tend to affect their operational efficiency to a great extent and so the need to damp out these vibrations is felt. The simplest control algorithm that can be implemented to suppress the occurring vibrations in the system is direct feedback of the output parameter back into the sytem[1,2,4,15]. Measurable parameters like strain, displacement, velocity, accelaration, etc are the commonly fed signals. This type of control is simple to implement and yet yeilds satisfactory results. In this work, a simple cantilever beam was used as the system whose dynamics was studied and active vibration control technique was applied. The system parameters were analysed through the free vibration test. The setup consisted of one Lead-Zirconate-Titanate (PZT) patch producing the primary disturbance (the exciter), another PZT patch sensing the occurring disturbance (the sensor), and finally the third PZT patch that suppressed the vibration (the actuator). The setup with the embedded PZT patches is as shown in Fig.1a. As reported by Lim[5], *et al.*, presence of the patches shifts the natural frequencies of the passive structure to higher frequencies. Waghulde and Kumar[6] used piezoelectric material on a cantilever beam thereby making it smart. The placement of the piezo sensors and actuators on the beam were determined through modal analysis as reported by Tripathi and Gangadharan[1]. Active control of hybrid smart structures under forced vibrations was investigated by Choi[7], *et al.*

2. DESIGN SIMULATION FOR FREE VIBRATION USING LABVIEW

The entire work was executed on LABVIEW 2010 on a windows platform. The graphical programming nature of LAB VIEW made the design of the algorithm simple and also it was user friendly with respect to debugging. Good reliability, near linear response to the applied voltage and exhibition of excellent response to the applied electric field over very large range of frequencies coupled with low cost of PZT makes it a very popular choice as a sensor and actuator that enables the

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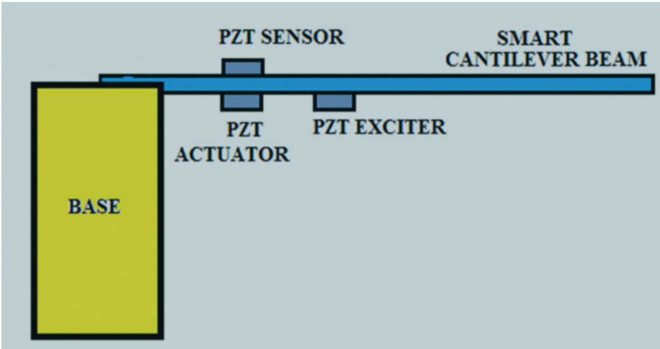

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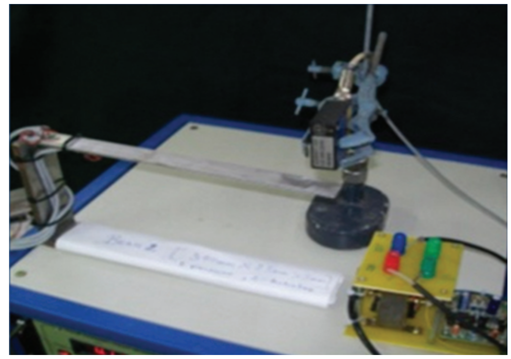


(b)

Figure 1. (a) Schematic of the system under study, (b) The experimental setup.

structure to be smart. The details of the smart beam along with the details of the PZT patches considered in this work are given in Table 1 and Table 2 respectively.

The first step in this work was to find out the system parameters of the smart cantilever beam. This was accomplished by subjecting the system to the free vibration test. This was performed so as to obtain critical parameter values like that of the system's natural frequency, stiffness, damping, transfer function etc. The system response shown in Fig. 2(a) was then validated with its predicted/simulated response as shown in Fig. 2(b). Complete modal analysis of the smart system was achieved as well as analysed by Tripathi[8]. In this work, common parameters of the system were determined theoretically and were validated in through the experimental process.

From the concepts of machine vibrations, the natural frequency of the vibrating beam was determined by the following formula:

$$\omega_n = \sqrt{\frac{k}{m}} \qquad (1)$$

where ω_n = the natural frequency of the beam

(rad/sec) = $2\pi f_n$

k = the beam stiffness *(N/m²)*

m = the modal mass of the beam (kg)

The dimensions of the beam selected include a length (L) = 300 mm; breadth *(*b) = 25 mm; and a height (h) = 3 mm. From the physical dimensions, the beam inertia (*I*) was obtained through the following equation:

$$I = \frac{bh^3}{12} \qquad (2)$$

Using Eqn. (2) along with the known Young's modulus (*E*) of the Al cantilever beam, the beam stiffness was determined as:

$$k = \frac{3EI}{L^3} \qquad (3)$$

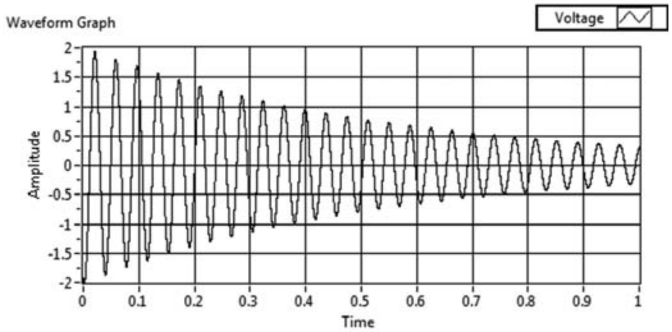
From the free vibration test, the logarithmic decay ratio was determined as per the following formula:

Table 1. Properties of the smart beam

Parameter	Value
Length (L)	0.3 m
Width (b)	0.025 m
Thickness (h)	0.003 m
Modulus (E)	$7.1*10^{10}$ N/m²
Density (ρ)	2700 kg/m³
Mass Density (M)	0.06075 kg/m
Modal Mass (m)	0.015377 kg

Table 2. PZT patch properties

Properties	PZT-5H
Density	7350 kg/m³
Elastic Stiffness Matrix	
C_{11}	12.6×10^{10} N/m²
C_{12}	7.95×10^{10} N/m²
C_{13}	8.41×10^{10} N/m²
C_{33}	11.7×10^{10} N/m²
C_{44}	2.33×10^{10} N/m²
Piezoelectric Strain Matrix	
E_{31}	6.5 C/m²
E_{33}	23.3 C/m²
E_{15}	17 C/m²
Dielectric Matrix	
ε_{11}	1.503×10^{-8} F/m
ε_{22}	1.503×10^{-8} F/m
ε_{33}	1.503×10^{-8} F/m



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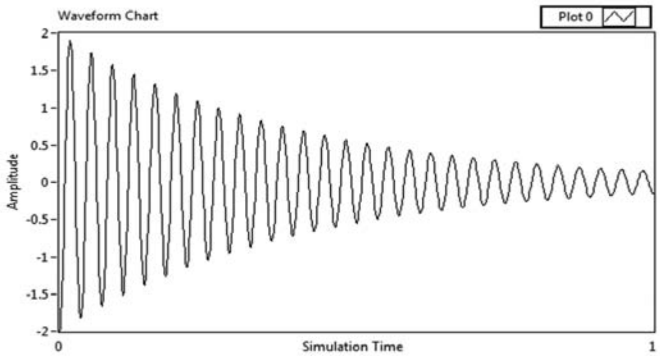


(b)

Figure 2 (a) Experimental free vibration response of the smart cantilever beam, (b) Simulated free vibration response of the smart cantilever beam.

Table 3. System parameters

Parameter	Formula	Value
Natural frequency	$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$	27.05 Hz
Second area moment of the beam cross section	$I = \frac{bh^3}{12}$	5.625×10^{-11} m^4
Beam stiffness	$k = \frac{3EI}{L^3}$	443.75 N/m
Logarithmic decay	$\delta = \frac{1}{n} In\left(\frac{X_n}{X_{n+1}}\right)$	0.06346
Damping coefficient	$c = \frac{2\delta\sqrt{km}}{\sqrt{\delta^2 + 4\pi^2}}$	0.07203 Ns/m

$$\delta = \frac{1}{n} ln\left(\frac{X_n}{X_{n+1}}\right) \tag{4}$$

The logarithmic decay ratio is also written as:

$$\delta = \frac{2\pi\varepsilon}{\sqrt{1-\varepsilon^2}} \tag{5}$$

Upon solving Eqn. (5), the following relation for damping constant (ε) was obtained:

$$\varepsilon = \frac{c}{c_c} = \frac{c}{2m\omega_n} = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \tag{6}$$

Upon further simplification of Eqn. (6), the following relation for damping factor (c) was arrived:

$$c = \frac{2\delta\sqrt{km}}{\sqrt{(\delta^2 + 4\pi^2}} \tag{7}$$

3. EXPERIMENTAL FORCED VIBRATION OF THE SMART STRUCTURE

The smart cantilever beam was subjected to harmonic excitation at its natural frequency. The experimental work reported here formed the basis of implementation of active vibration control in real time as shown by Parameswaran and Gangadharan[2]. The general block diagram adopted in this work to achieve active vibration control through direct output feedback is shown in Fig. 3. The piezo exciter excited the beam at its natural frequency as a result of which maximum displacement of the beam tip was observed at its free end. Also maximum strain was developed at the fixed end. This strain was sensed as a voltage by the piezo sensor. The sensed voltage was then amplified and fed into the LABVIEW domain in the PC through NI C-Series modules mounted on cDAQ-9174 compact data acquisition platform or directly through analog input/output modules. Through software means, the smart beam was subjected to forced vibrations at its first natural frequency (27.05 Hz) through the PZT Exciter patch mounted at the bottom of the beam. The first natural frequency of the smart beam was determined from theoretical calculations as well as through experimental means as indicated by its time Fig. 4(a) and frequency responses Fig. 4(b). In this work, direct strain feedback from the fixed end as well as displacement (sensed at the free end) feedback based closed loop active vibration control of the disturbed smart beam demonstrated the output feedback control algorithm

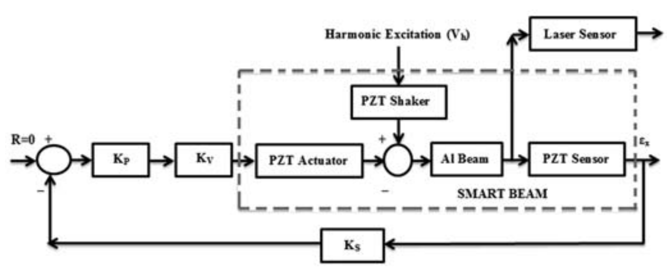
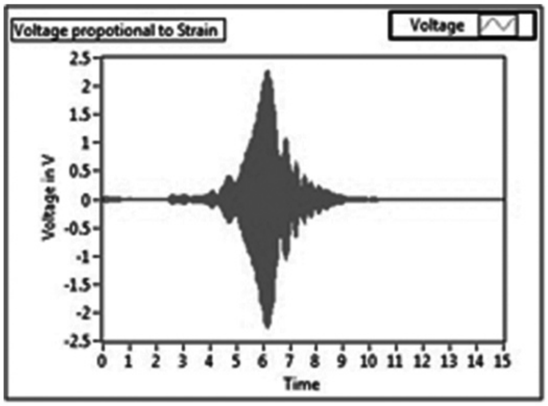


Figure 3. Block diagram of output feedback based active vibration control of the smart cantilever beam.



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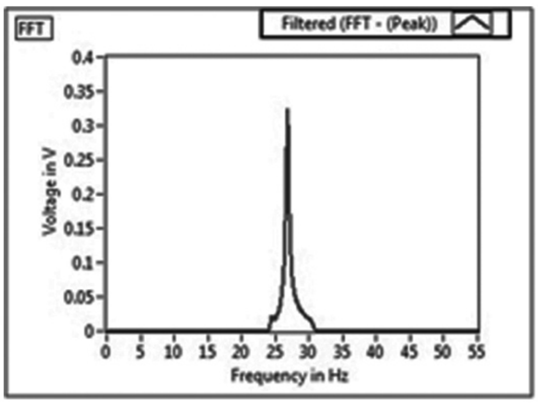


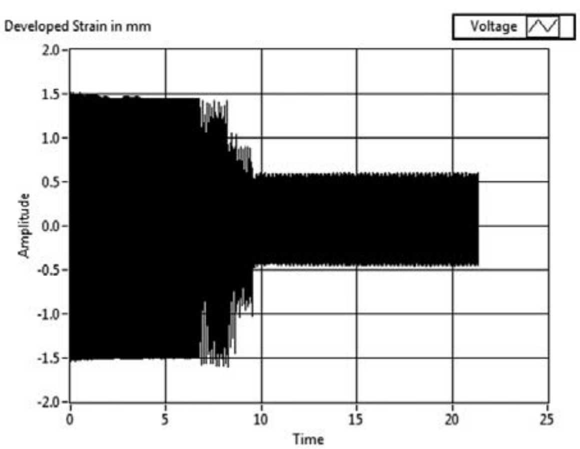
(b)

Figure 4. (a) Time response of the vibrating smart beam, (b) Frequency response of the vibrating smart beam.

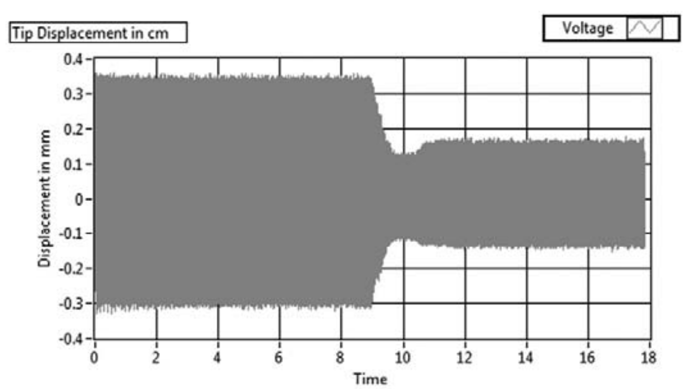
that was successfully implemented to damp out the occurring vibrations in an active manner. Maximum strain was sensed at the fixed end. It was sensed by the PZT patch sensor which converted the resulting charge (corresponding to the strain) to an appropriate voltage.The developed voltage from the PZT sensor was then transmitted through the NI-C series modules into the LABVIEW domain in the PC. The designed control logic ensured that the acquired signal after being conditioned and amplified with a suitable controller gain was fed back into the system with an 180° phase shift through the smart structure instrumentation system before being fed to the PZT actuator patch that was mounted exactly on the opposite side as the PZT sensor. For accurate control, it was very important for the sensed signal to be conditioned appropriately so that it is free from any other unwanted noises. This was achieved by using a band pass butterworth analog filter that allowed a frequency range of 5-50 Hz. The acquired signal was initially filtered before being transferred into the software domain. The same logic was followed in the case of displacement feedback based control too with the sensor being a Laser Doppler Vibrometer placed appropriately at the free tip of the beam.

4. RESULTS AND DISCUSSIONS

The experimental results demonstrated successful implementation of output feedback based active vibration control of a smart cantilever beam by employing three PZT patches that were appropriately placed. The harmonic excitation at the systems first natural frequency ensured maximum tip deflection as well as maximum strain development at the fixed end. Through successful implementation of the control logic in LABVIEW on a Windows 7 platform, active vibration control based on strain feedback as well as tip displacement feedback were obtained as shown in Figs. 5(a) and 5(b) respectively. From the free vibration test, values of critical parameters of the system were determined. The model obtained was tested and validated successfully. It is seen that when the control was initiated (at time *(t)*=7 s and controller gain =10), by employing strain feedback based control logic, the strain developed at the fixed end of the beam dropped from 1.5 mm to around 0.5 mm. This shows nearly a 67% reduction in the strain when active vibration control is applied. Similarly, when displacement feedback based control was applied, for the same controller gain (at t = 9 s), it was observed that displacement of the free tip of the smart cantilever beam reduced from about 0.35 cm to around 0.15 cm. this shows a reduction in the vibration by about 57%. Also, in the frequency response, it was noted that when the control action was applied, the amplitude of vibrations fell drastically at the system's natural frequency.



(a)



(b)

Figure 5. (a) Fixed end strain feedback based active vibration control of smart beam, (b) Tip displacement feedback based active vibration control of smart beam.

5. CONCLUSION

From this experiment work, it was concluded that though active vibration control of the smart system was achieved, it was non-deterministic as well as non-sustained. This was attributed to the time-multiplexed nature of the GPOS (LABVIEW was run on a Windows 7 platform) where in the internal as well as external interrupts are serviced sequentially, Hence, the processor was unable to devote its complete processing time as well as capabilities towards achieving satisfactory vibration control. Thus even though active vibration control was achieved, the results showed inconsistent transient as well as steady state characteristics in the dynamics of the beam. Hence, it was concluded that experimental control of the vibrating smart beam needed to be performed on a real time operating system (RTOS) platform wherein deterministic and reliable control could be achieved.

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