International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 1, January - 2014

# Strain Feedback Active Vibration Control of Smart Cantilever Beam

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## Abstract

In the present study, active vibration control of a flexible aluminum cantilever beam in single input single output configuration using piezoelectric patches as sensor and actuator is investigated. A linear mathematical model is developed to predict the dynamics of a smart beam using system identification technique. The same model is used to design and simulate stain feedback controller. The feedback control algorithm is analyzed and implemented in real-time using National Instruments cRIO9022 controller in LabVIEW graphical programming environment. The control law has demonstrated 53.91% and 62.5% reduction in vibration for the first and second modes of vibration respectively.

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## 1. Introduction

Vibration control has been a challenging problem for both academic and industrial researchers for many years. Vibrations can be found virtually everywhere, in vehicles, buildings, or machines, and flexible structures. Most vibrations are undesirable because they cause unpleasant noises, unwanted stress in structures, and malfunction or failure of systems. Within the last two decades, much attention has been focused on active control of structures to suppress their structural vibrations [1]. The flexibility nature of the structures results the structure to continuously vibrate for a longer time in less damping situation when it is exposed to wind gust and other exogenic forces. Such kind of vibration will affect the operating accuracy and stability of the entire system and it may cause catastrophic failure to the structure if the vibration persists for longer time. Research results indicates that the maximum order of magnitude of vibration response can be measured and optimal control effect can be achieved by the sensor and actuator allocated at the position with maximum curvature of vibration mode[2]. Crawley and de Luis [3] initially investigated both analytically as well as experimentally that piezoelectric materials can be used as sensor and actuator for predicting the behavior of flexible smart structures for the first time.

A brief review of work on active vibration control of a smart structures shows that most of the work are based on models developed using Finite Element method. S. M. Khot et al.[4], presented PID based output feedback for active vibration control of cantilever beam using a reduced model extracted from a full (ANSYS) Finite Element model. T. C. Manjunath et al. [5], presented a robust decentralized controller for a multimode smart flexible system using a periodic output feedback control technique when there is a failure of one of the piezoelectric actuator. Manning et. [6], presented vibration control scheme of a smart structure using system identification and pole placement technique. Halim et al. The mathematical model of the system is very crucial for controller design as any control system design procedure. However, due to incomplete knowledge of the system dynamics especially the behavior of the piezoelectric material bonded on the structure at any instant of time, it has been difficult to develop an accurate model of the system that describes the entire dynamics of the system. Therefore, the system model uncertainty resulted from the modeling process using Finite Element Method can be minimized by modeling it using System Identification techniques. Xiongzhu Bu et al. [7] implemented System Identification ARMAX model and pole placement method to achieve the desired closed loop control for vibration suppression of flexible beam. Xing-Jian Dong et al. [1] presented a System Identification technique based on measured input and output data of the smart plate using observer/ Kalman filter identification technique in numerical simulation and experimental study for active vibration control of smart plate using the Linear Quadratic Gaussian (LQG) control algorithm. Fei J. [2] investigated both strain feedback and optimized PID compensator methods for active vibration control of cantilever beam bonded piezoelectric actuators. Peng et al. Vasques et al. [9] presented comparison of the classical control strategies and optimal control strategies for active vibration control of piezoelectric smart beams. Shan J. et al. [10] analyzed and experimentally demonstrated PPF controller for suppressing multi-mode vibrations while slewing the single-link flexible manipulator. Moreover, the experimental robustness of PPF is studied for active vibration suppression of flexible smart structure by Song et al.[11].

The research work in the area of active vibration control are focusing on designing state feedback and output feedback control algorithms. The difficulty with state feedback controllers is that they need state observers to estimate the entire system states for feedback. However, unlike system states, the output of any system is always available for measurement. Hence, it is preferred to focus on output feedback for the above reason besides it is easy to realize practically. Therefore, the purpose of the present study is to develop and evaluate the performance of strain and displacement feedback control laws as applied to a smart beam in SISO configuration towards suppression of vibration amplitude.

## 2. Mathematical Modeling

Mathematical modeling of the system can be approached in two ways. One way to achieve the mathematical model in the form presented above is the utilization of Finite Element modeling technique. However, due to incomplete knowledge of the system dynamics especially the behavior of the piezoelectric material bonded to the structure at any instant of time, it is difficult to develop an accurate model of the system that describes the entire dynamics of the system. Controller design of smart structures relies on the accuracy of the system dynamic model for non robust controllers. Hence, this technique is considered to be less effective compared to the System Identification technique. Therefore, the system model uncertainties resulted from the other approach using FEM can be minimized by System Identification techniques. System Identification is a well known modeling tool used in building an accurate model of complex systems from time-series input and output data for numerous engineering applications. In this work, the system identification algorithm used to identify the system is based upon MATLAB System Identification Toolbox ARX method. In this method, a model is obtained by using the fitting a model state space to the experimental frequency response function data. The system model eventually can be represented in the state space form as:

$$\dot{x}(t) = A(t)x(t) + Bu(t)$$
$$y(t) = Cx(t) + Du(t) \qquad (1)$$

where $x(t)$ is the state vector, $y(t)$ is output.

Using this System Identification toolbox state space model of $4^{th}$ order is obtained. Similar to the estimation, the validation results of the identified model with a fit of 82.49%. Frequency response of the identified model clearly shows that it has resonance frequencies at 28 Hz (178 rad/s), and 170 Hz (1070 rad/s) for the first and second mode of vibration respectively. The indentified system corresponding state matrix A, input matrix B, output matrix C, and the direct transmission matrix D are found to be:

$$A = \begin{bmatrix} -9.007 & -1171000 & -3360000 & -3.615e10 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$
$$C = \begin{bmatrix} -0.1743 & -392.7 & -96100 & -8.419e7 \end{bmatrix} \quad and \quad D = \begin{bmatrix} 0 \end{bmatrix} \qquad (2)$$

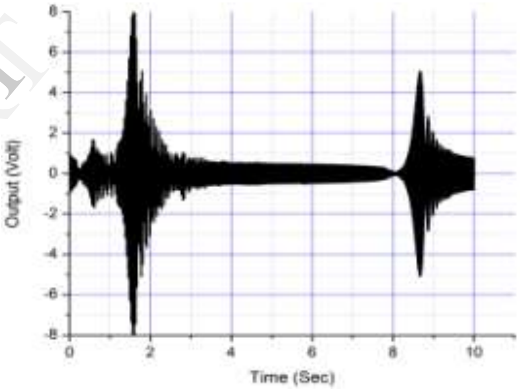

Fig.1 Beam sweep input response

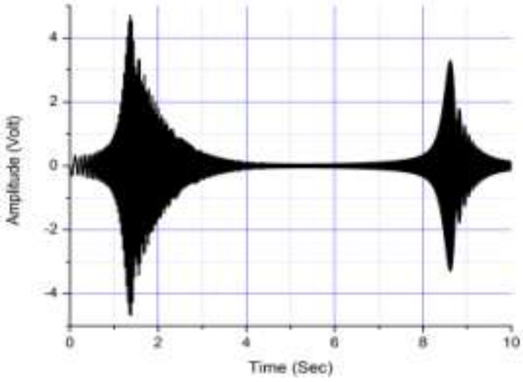

Fig.2 Identified model response to sweep input

The mathematical model obtained is checked for sweep signal of same band of frequencies from 5 Hz to 200 Hz for 200 s simulation time. As shown in

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Figure 5, the model responses to the first dominant frequencies only but for the rest frequencies there is relatively no response as expected, hence the model is a good estimation of the smart beam if the beam external excitation is within this frequency band. The model estimate to a best fit value of 82.49% the accuracy of modeling to a highest level as compared with the other models.

## 3. Experimental Setup

The experimental setup consists of a $(0.3\times0.024\times0.005m)$ beam in free-fixed configuration with a pair of piezoelectric patches as sensor and actuator mounted on both faces of the beam. The optimal location of the piezoelectric pairs used as sensor and actuator is in the regions of higher nodal strain energies of the beam [8]. Hence, the two piezoelectric patches are mounted at a distance of 10 mm from the fixed end to be used as a sensor and actuator pair as shown in Fig.3.

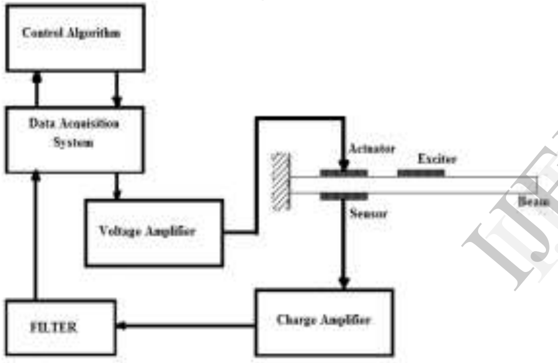

Fig.3 Experimental setup block diagram

Moreover, a third PZT is mounted at 44mm distance from the fixed end to excite the beam. The sinusoidal and sweep signals are generated by signal generator. This signal is applied as an excitation signal to set the beam into continuous vibration after being amplified to the level of 120V. The real-time control algorithm is coded on National Instruments cRIO9022 processor using LabVIEW.

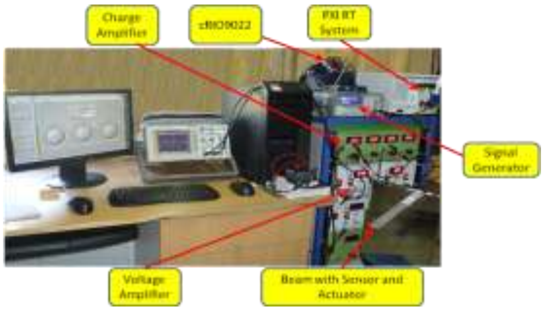

Fig. 4 Photographic view of experimental set-up

NI 9234 DAQ is used to acquire the sensor data from the charge amplifier. The acquired signal is filtered for high frequency noise using 3rd order Butterworth low pass digital filter. This conditioned strain signal is then used for feedback as well as to calculate the equivalent tip displacement of the beam. The actuating signal generated by the controller is sent to the voltage amplifier using NI 9264 analog output module and supplied to PZT after amplification to actuate the beam.

## 4. Control and Simulation

To prove the effectiveness of Strain feedback and Displacement feedback vibration suppression strategies numerical simulation is carried out prior to experimentation. These control laws are implemented in this study because the output of a system is always available for measurement unlike state feedback techniques in which all the states usually may not be available for measurement. Besides, these control laws are among the computationally simple and effective feedback techniques which can be easily implemented in a real time. In the present analysis, direct strain feedback and displacement feedback control laws are considered. The control law in case of direct strain feedback is:

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$$V_a(t) = K_s v_s(t) \tag{3}$$

where $K_s$ denotes the feedback control gain, $V_a(t)$ the actuating signal, and $v_s(t)$ the sensed signal proportional to the stain induced due to beam vibration (output of the charge amplifier).

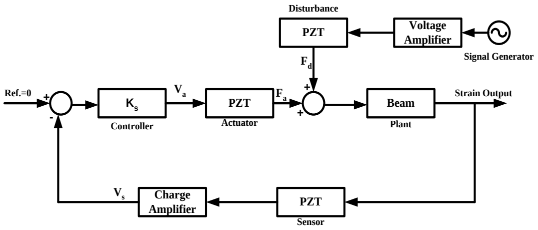

Fig. 5 Closed loop schematic diagram

The effectiveness of the controllers for resonance frequency is more important than the remaining frequencies because the amplitude levels of non resonance frequencies does not cause any malfunctioning of systems or catastrophic failures of structures in reality. To demonstrate the proposed approach, a closed loop control simulation was performed on the system model for the first two dominant modes of vibration in Matlab/ SIMULINK environment.

Figure 6, and 7 show the simulated strain feedback response of the smart beam for the first and second modes of vibration respectively.

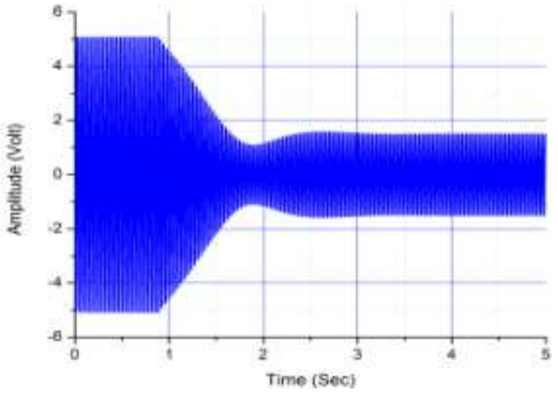

Fig. 6 First mode simulation result

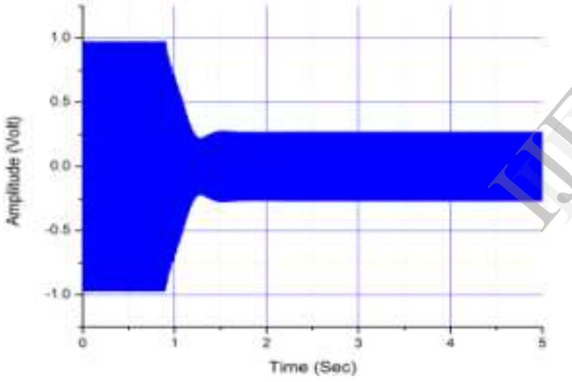

Fig. 7 Second mode simulation result

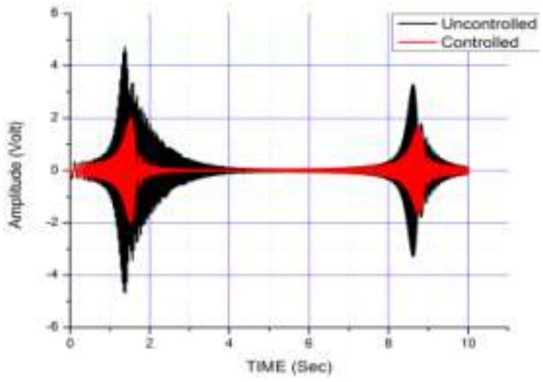

Fig. 8 Sweep input simulation result

## 6. Results and Discussion

The simulation and experimental results show that the beam responds significantly to those excitation frequencies corresponding to the resonance frequencies. Strain feedback control law is simulated first in MATLAB/SIMULINK to obtain the corresponding controller gains using the mathematical model derived initially. For the purpose of illustration, the effectiveness of the controller is analyzed by comparing the open and closed loop system dynamics in terms of system natural frequency and damping ratio. The transient and steady state dynamics of the smart beam depends on the location of system poles and zeros. However, the transient effect of the poles located relatively far towards to the left of the S plane decays faster compared to the one closer. Hence, the transient response of the smart beam mainly depend on the dominant poles. Therefore, the locations of the open and closed loop poles are identified. The system open and closed loop dominant poles are presented in Table1 are considered for the following analysis.

Table1: System open loop and closed loop poles

| System Open Loop Poles | System Closed Loop Poles |
|---|---|
| -3.1156+ 1067.35i | -4.2 +1070.87i |
| -3.1156 -1067.35i | -4.2 - 1070.87i |
| **-1.3878+ 178.13i** | **-2.3 + 182.23i** |
| **-1.3878 - 178.13i** | **-2.3 - 182.23i** |

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The dominant open loop poles are $-1.3878 \pm 178.13i$ ,which play a major and critical role in deciding the transient response of the smart beam. The open loop effective natural frequency and damping ratio is found to be 178.13 rad/s and 0.0078 respectively. In closed loop, the locations of the open loop poles are shifted towards left side of the imaginary axis using the respective feedback gains. These pair of dominant closed loop poles are -2.3 $\pm$ 182.23i and $-3.65 \pm 188.06i$ for Strain feedback.

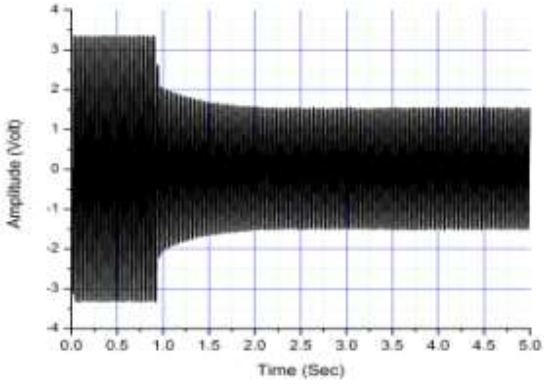

Fig. 9 First mode experimental result

The percentage increment in the effective system natural frequency and damping ratio using this pair of dominant poles is found to be 2.3% and 61.54% for Strain feedback. From the analysis, it can be inferred that Strain feedback control law makes the system to response faster and it also introduces more addition damping to the system as well.

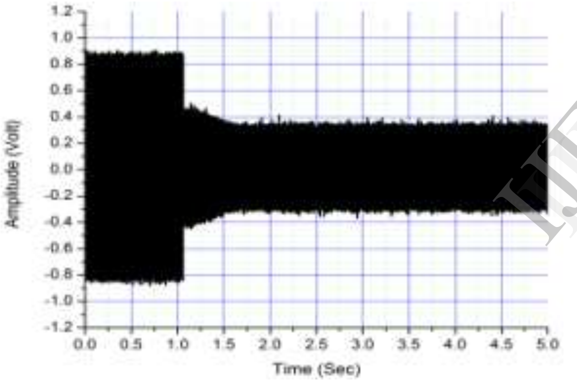

Fig. 10 Second mode experimental result

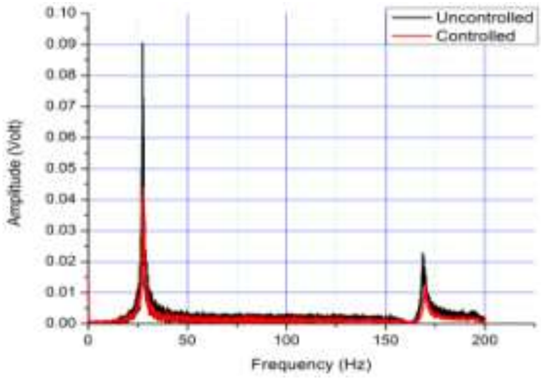

Fig. 11 Sweep input experimental result

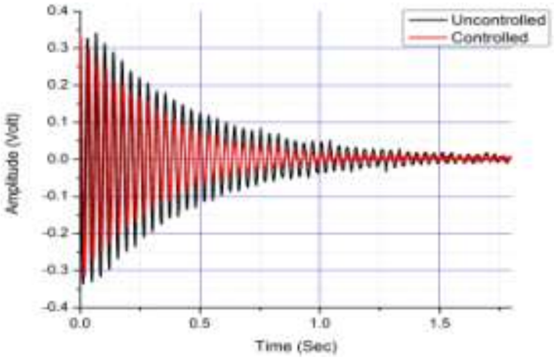

Fig. 12 Impulse input experimental result

Experimental results demonstrate that the experimental result shows that Strain feedback for the first and second modes of vibration produced 53.91% and 62.5% reduction respectively. Moreover, the controller showed its effectiveness to settle the beam faster for impulse input.

## 7. Conclusion

The mathematical model of the smart beam derived using System Identification technique was successfully simulated for controller design. The Strain feedback control logics has been implemented to actively suppress the vibration of the beam. The effectiveness of this feedback law in suppression the vibration of smart beam for the first two dominant frequencies has been demonstrated experimentally. From the results, it has been observed that this control law showed a stable system response due to minimum computational time delays. Experimentally 53.9% and 63.5% reduction is demonstrated for the first and second modes of vibration respectively using this feedback law. Moreover, the beam settled faster for impulse input in closed loop than in open loop configuration.

Acknowledgements

The authors acknowledge the financial support provided by Center for System Design (CSD) at National Institute of Technology Karnataka.

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