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Robust and Artificial Neural Network Controller for Piezoelectric Bonded Beam

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ABSTRACT

The control of smart structures is a challenging task. This paper deals with model identification and control of vibration for a smart structure built using a cantilever beam embedded with piezoelectric patches. Model identification of this non linear process was done using ARMAX technique. Robust observer based state feedback controller and neural network predictive controller were designed for the identified model to suppress the vibration. The performance of the controllers is evaluated using MATLAB simulation.

Keywords: Model identification, Cantilever, Neural, Observer, ARMAX, Nonlinear

1.INTRODUCTION

In recent years, with the aid of advanced technologies in computer and material sciences, advanced lightweight structural systems have been designed for application in various research fields such as robotics, space structures, and manufacturing. The emergence of the smart materials has accelerated successful development of the advanced structural systems structures with integrated sensors and actuators have been developed for high performance applications such as active vibration and noise control. A number of materials and technologies have been proposed and investigated. By different researchers Chopra et al [1] have used piezoelectric materials for sensing and actuation. Modeling of smart structure using piezoelectric material as sensor/actuator can be seen in [2-5].

Various control methods such as Variable Structure Control (VSC), Genetic algorithm and Fuzzy control, have been designed and implemented for piezoelectric bonded structures [6-7]. The optimal state and output feedback controllers designed for tracking and disturbance rejection for piezoelectric bonded structures can be seen in [8-9]. The present work aims at experimentally implementing state and output feedback control to suppress the fundamental vibration mode of a smart cantilever beam using MATLAB RTW and dSPACE 1104.

2.EXPERIMENTAL SYSTEM

This consists of a cantilever beam made of aluminum, bonded with one pair of collocated piezoelectric patches as sensor/actuator at the fixed end. To apply disturbance a piezoelectric patch is bonded at the free end of the beam. The conditioned piezosensor output was given as analog input to dSPACE controller board. The control algorithm was developed using SIMULINK and implemented in real time on dSPACE system using RTW and dSPACE Real Time Interface tools..

The controller output was directed to piezoelectric actuator through driving amplifier. The experimental set-up is shown in Figure 1. The dimensions and properties of the beam and piezoelectric patches are given in table 1 and 2.

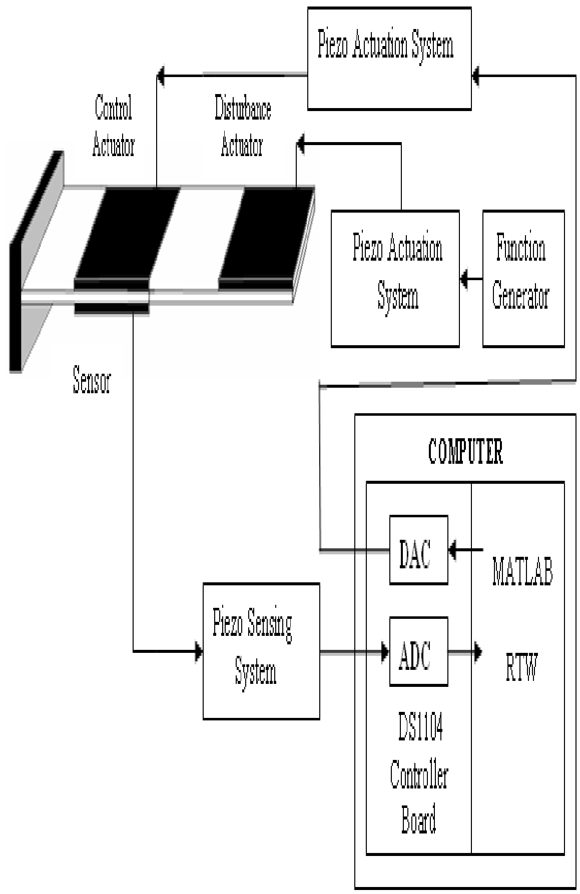

Figure 1 Experimental setup for smart structure control.

Table 1: Properties and dimensions of the Aluminum beam

Length (m)	l	0.3
Width (m)	b	0.0127
Thickness (m)	t_b	0.0023
Young's modulus (Gpa)	E_b	71
Density (kg/m^3)	ρ_b	2700
Natural frequencies (Hz)	f	31.7, 200
Damping ratio	ξ	0.0524
Damping constants	α , β	2.8676 , 4.5231x10^{-4}

Table 2: Properties and dimensions of piezoelectric sensor/actuator

Length (m)	l_p	0.0765
Width (m)	b	0.0127
Thickness (m)	t_a	0.005
Young's modulus (Gpa)	E_p	47.62
Density (kg/m^3)	ρ_p	7500
Piezoelectric strain constant (m V^{-1})	d_{31}	-247x10^{-12}
Piezoelectric stress constant (V m N^{-1})	g_{31}	-9x10^{-3}

2.2. Modeling

The mathematical model of a piezoelectric bonded beam shown in Figure 1 was developed using Finite Element Method as given in [10]. The damping ratio of the Piezoelectric bonded beam was determined experimentally as 0.0524. The direct piezoelectric equation is used to calculate the output charge created by the strain in the structure. Since the sensor electrodes are short-circuited to measure the voltage output the electric displacement developed on the sensor surface is directly proportional to the strain acing on the sensor. The sensor output voltage is:

$$V^s(t) = G_c e_{31} z b \int_0^{l_p} \mathbf{n}_1^T \ \dot{\mathbf{q}} \ dx$$

or as scalar vector product:

$$V^s(t) = \mathbf{p}^T \ \dot{\mathbf{q}} \qquad (1)$$

Where e_{31} is the piezoelectric stress/charge constant, b is the width of the sensor which is equal to the width of the beam, $z = \frac{t_b}{2} + t_a$, t_b is the thickness of the beam, t_a is the thickness of the piezoelectric actuator , $\mathbf{n}_1^T$ is the second spatial derivative of shape function of the flexible beam, $\dot{\mathbf{q}}$ is the time derivative of the nodal coordinate vector and $\mathbf{p}^T$ is a constant vector. In a piezoelectric bonded structural vibration control system, the piezoelectric sensor output is given as input to the sensor signal conditioning system (charge amplifier), which is operated in short circuit mode. The signal conditioning circuit in general has a circuit to amplify the sensor output with a gain of $\mathrm{G_c}$. The input voltage $V^a(t)$ applied to an actuator is:

$$V^a(t) = KV^s(t)$$

where, K is the controller gain.

The piezoelectric actuator experiences both the input electric field and the reaction stress field from the host structure. The actuator strain can be derived from the converse piezoelectric equation. The resultant moment M_A acting on the beam is determined by integrating the stress through the structure thickness. The resultant moment is:

$$M_A \simeq E_p d_{31} \bar{z} V^a(t) \qquad (2)$$

Where, $\bar{z} = \frac{(t_a + t_b)}{2}$ is the distance between neutral axis of the beam and the piezoelectric layer, d_{31} is the piezoelectric constant, E_p is the modulus of elasticity of piezoelectric material and the control force applied by the actuator is:

$$\mathbf{f}_{ctrl} = E_p d_{31} b \ \bar{z} \int_{l_p} \mathbf{n}_2 \ dx \ V^a(t) \qquad (3)$$

or as scalar vector product:

$$\mathbf{f}_{ctrl} = \mathbf{h} \ V^a \ (t) \qquad (4)$$

Where $\mathbf{n}_2^T$ the first spatial derivative of shape is function of the flexible beam and $\mathbf{h}^T$ is a constant vector. If any external forces described by the vector $\mathbf{f}_{ext}$ are acting, then the total force vector becomes:

$$\mathbf{f}^t = \mathbf{f}_{ext} + \mathbf{f}_{ctrl} \,. \qquad (5)$$

The dynamic equation of the smart structure is given by:

$$\mathbf{M} \ \ddot{\mathbf{q}} + \mathbf{K} \ \mathbf{q} = \mathbf{f}_{ext} + \mathbf{f}_{ctrl} \qquad (6)$$

The generalized coordinates are introduced to reduce the equation (6) such that the resultant equation represents the dynamics of the first vibration mode. Let $\mathbf{q} = \mathbf{T}\,\mathbf{g}$, where, $\mathbf{T}$ is the modal matrix containing the eigenvectors representing the first vibration mode, then equation (6) can be transformed into:

$$\mathbf{M}^* \ \ddot{\mathbf{g}} + \mathbf{C}^* \ \dot{\mathbf{g}} + \mathbf{K}^* \ \mathbf{g} = \mathbf{f}_{ext}^* + \mathbf{f}_{ctrl}^* \qquad (7)$$

$\mathbf{M}^*$, $\mathbf{K}^*$, $\mathbf{C}^*$, $\mathbf{f}_{ext}^*$ and $\mathbf{f}_{ctrl}^*$ are the generalized mass, stiffness, damping matrices, external force and control force vectors respectively. In line with standard practice Rayleigh damping is assumed, which is of the form $\mathbf{C}^* = \alpha \mathbf{M}^* + \beta \mathbf{K}^*$, where α

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and β are determined from the experiment. Their values are given in Table -1. The governing equation in (7) is often written in the state space form as

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{*-1}\mathbf{K}^* & -\mathbf{M}^{*-1}\mathbf{C}^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{*-1}\mathbf{T}^T \end{bmatrix} \left[\mathbf{h}u(t) + \mathbf{f}r(t)\right]$$

Where $u(t)$ is the control input, $r(t)$ is the external input to the system, $\mathbf{f}$ is the external force coefficient vector. The sensor equation in the modal state space form is given by:

$$y(t) = \begin{bmatrix} \mathbf{0} & \mathbf{P}^{\mathbf{T}}\mathbf{T} \end{bmatrix} \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T .$$

The above system is represented as:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{b}u + \mathbf{e}r, \ y = \mathbf{c}^T\mathbf{x} \qquad (8)$$

3.CONTROLLER DESIGN AND IMPLEMENTATION

An observer based state feedback and an output feedback controller was designed to suppress the first vibration mode of the cantilever beam. Initially, performance of the controllers was evaluated through simulation and then it was experimentally implemented in real time using DS1104 controller board [11-12].

3.1. Design of state feedback control

The Piezoelectric sensor bonded on the structure measures only the strain rate in the structure. Hence, a full order state observer was designed to estimate the strain in the structure. The observer and controller gains were;

$$\text{Observer gain: } K_e = \begin{bmatrix} 138.6 \\ 62.03 \end{bmatrix}$$

$$\text{Controller gain: } K_c = \begin{bmatrix} -7.09 & -20.3 \end{bmatrix}$$

Simulation studies were carried out by exciting the beam at resonance (a sinusoidal signal of amplitude 5 Volts, frequency 31.7Hz). The open loop and closed loop responses obtained in simulation are shown in Figure 2.

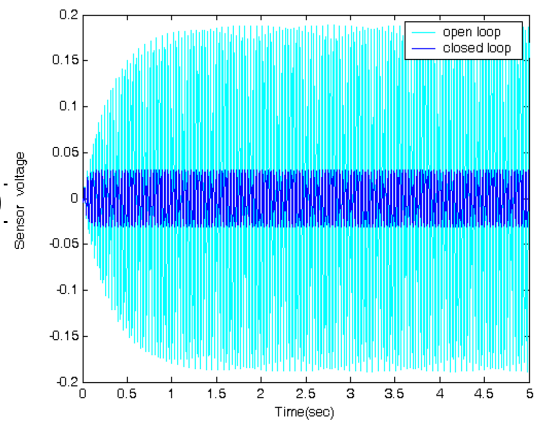

Figure 2 Open loop and closed loop responses with state feedback.

3.2.Design of output feedback control

An optimal constant output feedback controller in [12] was designed and the LQR problem was used to choose the controller gain. The controller gain **'F'** obtained for Q = 550, R = 1was 17.8 and the controller gain obtained for Q=850, R=1 was 16.2. Simulation studies were carried out by exciting the beam at resonance (a sinusoidal signal of amplitude 5 Volts, frequency 31.7Hz). The open loop and closed loop responses obtained in simulation are shown in Figure 3.

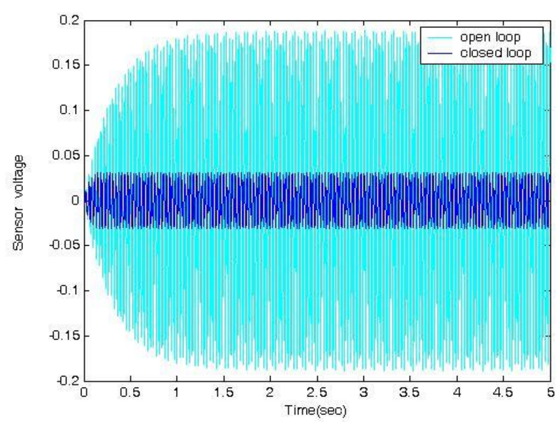

Figure 3 Open loop and closed loop responses with optimal output feedback (F=17.8).

3.3.IMPLEMENTATION

To test these controllers, we built a digital control system that consisted of SIMULINK modeling software and a dSPACE DS1104 controller in a Pentium computer. The simulink software was used to build the control block diagrams, and the Real Time Workshop was used to generate C code from the simulink model. The C code was then converted to Target Specific Code by the Real Time Interface and Target Language compiler supported by dSPACE. This code was deployed on to the Rapid Prototype Hardware system to run hardware-in-the loop simulation. The controllers designed in section 3.1 and 3.2 were implemented in real time. The disturbance applied and open loop response monitored in Control Desk experimenting tool is shown in figure 4. The closed loop response and control signal obtained with state feedback are shown in figure 5 and 6. The closed loop response and control signal obtained with output feedback is shown in figure 7.

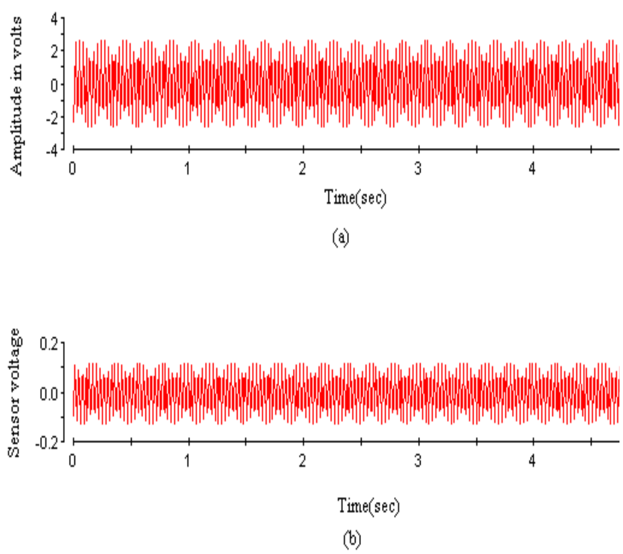

Figure 4 Experimental results (a) Disturbance signal (b) open loop response

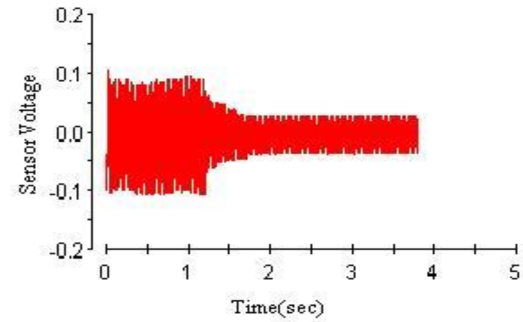

Figure 5 Response with state feedback control (experimental)

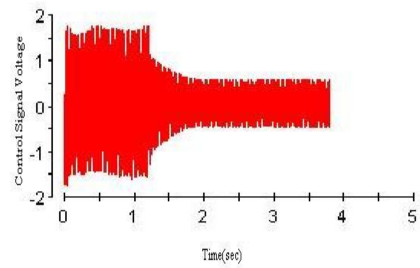

Figure 6 control signal with state feedback control (experimental)

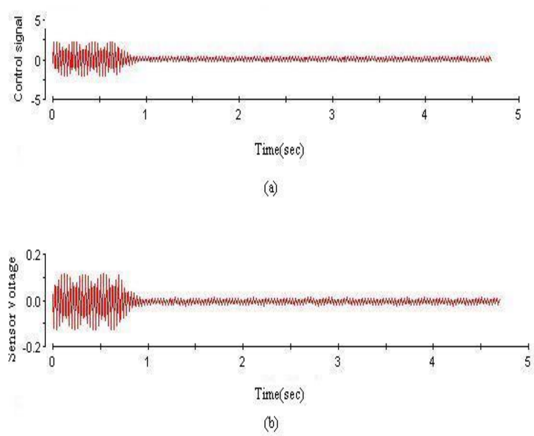

Figure 7 (a) Control signal (b) Response with output feedback control (experimental)

4.RESULTS AND DISCUSSION

The model for piezoelectric bonded beam was developed by Finite Element Method (FEM) and simulations were carried out using MATLAB. Experiments were conducted which showed that the open loop response obtained in experiment and simulation was matching the open loop response obtained from FEM model. It was also observed that the experimental results obtained with state and output feedback control were close to the simulation results.

In experiment sinusoidal disturbance with frequency of first vibration mode and amplitude of 5 volts from the function generator was applied to a Piezo patch bonded at free end of the beam, the amplitude of open loop response obtained experimentally was 0.3 volts. The amplitude of vibration was reduced to approximately 0.05 volts with state and output feedback control. It was also observed in simulation that for higher output feedback gain the amplitude of vibration reduces to 0 volts.

5.CONCLUSIONS

Active vibration control of a beam using piezoelectric patches as sensor and actuator was demonstrated. State feedback and output feedback controllers have been designed using FEM model and implemented using MATLAB RTW and dSPACE 1104. The controllers were designed to suppress the first vibration mode. The amplitude reduction observed was 75% with state feedback controller and 87% with output feedback controller.

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