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ACTIVE VIBRATION SUPPRESSION OF A SMART BEAM VIA SELF-SENSING PIEZOELECTRIC ACTUATOR

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ABSTRACT

In this paper, an active vibration suppression of a smart beam using self-sensing piezoelectric actuator is presented. The smart beam is composed of a cantilever aluminium beam with four surface-bonded piezoelectric patches symmetrically located both side of the beam. Piezoelectric materials can transform mechanical deformation to electric signal and vice versa. This property of piezoelectric materials enables them to be used as an actuator and a sensor. In self-sensing actuator configuration, the piezoelectric material can be used as an actuator and a sensor simultaneously. A special bridge circuit is used to decompose actuator and sensor signal. This bridge circuit includes the electrical model of the piezoelectric material and in general piezoelectric material is modelled as a voltage source with a series capacitor or a charge source with a parallel capacitor. In our study, this bridge circuit is designed and built for voltage source model of piezoelectric material. Following this, frequency response of the system is obtained by using piezoelectric patches as a self-sensing actuator. Then, analytical system model is obtained from the measured frequency response and robust controller is designed for the active vibration control of smart beam. Finally, both free and the first resonance frequency forced vibration results of open and closed loop are presented.

INTRODUCTION

Severe structural vibrations can damage components of aerospace vehicles because of their aeroelastic properties. In order to suppress structural vibrations of aerospace structures, active vibration control methods are investigated and applied by scientists and engineers. The technological advances in piezoelectric materials motivated scientists and engineers to use these materials in the area of active vibration control. The atomic lattice structure of piezoelectric materials provides the transformation of mechanical deformation to electric signal and vice versa. This property of piezoelectric materials enables them to be used an actuator and a sensor in active vibration control. In the former research studies in the Department of Aerospace Engineering of METU, piezoelectric materials are used as sensors and actuators for active vibration suppression of cantilever beam-like and plate-like structures. In the studies where piezoelectric materials are used as actuators, strain gauges and laser displacement sensor are chosen as sensing devices. [3,4]. Following these research activities, piezoelectric materials are also employed as sensor to investigate vibration characteristics of smart beam [2] as an initiative study for an active vibration suppression of smart beam via piezoelectric sensors and actuators [1].

In this study, on the other hand, self-sensing piezoelectric actuator is considered for the active vibration control of smart beam. For this purpose, at first, a special bridge circuit is designed and built to decompose actuator and sensor signal of self-sensing piezoelectric actuation. After this, frequency response of the system is obtained by using this self-sensing piezoelectric actuator. Having acquired the analytical model from the measured frequency response, robust controller is designed for the active vibration control of smart beam. Finally, free and the first resonance frequency forced vibration results of open and closed loops are presented.

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SMART BEAM

The smart beam (Figure 1) consists cantilever aluminium beam (490 × 51× 2 mm) with eight surface bonded SensorTech - BM500 (25 × 20 × 0.5 mm) PZT (Lead - Zirconate -Titanate) patches (Figure 2). A thin isolation layer is placed between the aluminium beam and piezoelectric patches so that each piezoelectric patch may be employed as a sensor and an actuator independently.

In our study, piezoelectric patches are labelled according to their positions on each surface of the aluminium beam (Figure 3). In order to have more actuation ability, piezoelectric patches (1A-1B and 4A-4B) are configured as bimorph and used as self-sensing actuator.

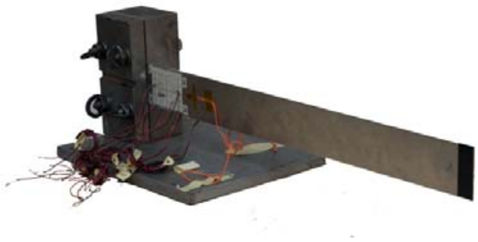

Figure 1: *Smart Beam*

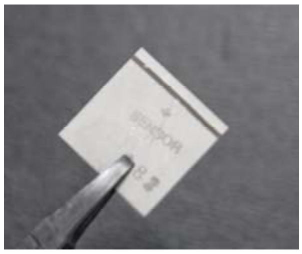

Figure 2: *SensorTech - BM500 PZT Patch*

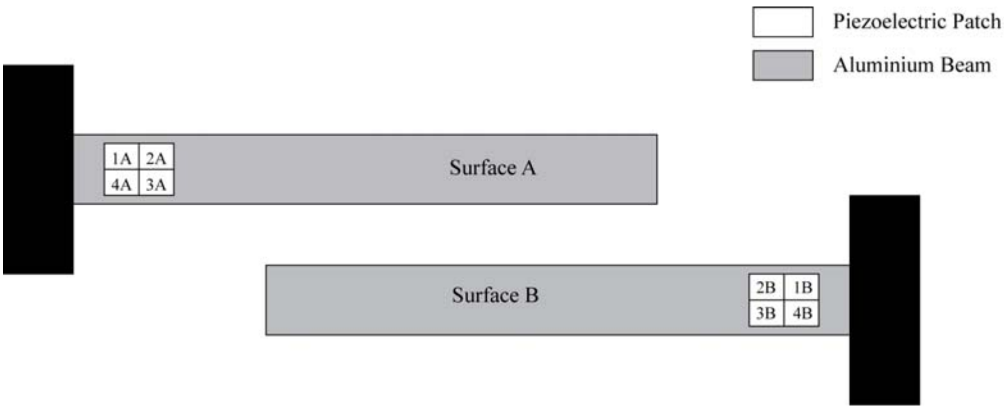

Figure 3: *Piezoelectric Patches on Smart Beam*

SELF–SENSING PIEZOELECTRIC ACTUATOR CONFIGURATION

Our aim is to use four of the piezoelectric patches simultaneously as a sensor and an actuator for the active vibration control. Piezoelectric materials generate electrical signal when they are under mechanical stress. This property of piezoelectric material enables them to be used as a sensor. On the other hand, piezoelectric materials are mechanically deformed when electric field is applied to them. In consequence of this property, piezoelectric materials can be also used as actuators [6]. Beside these, a piezoelectric material can be simultaneously used as a sensor and an actuator when actuation and sensing signals are decomposed. For this purpose, a special bridge circuit can be used [5,7]. The bridge circuit shown in Figure 4 includes the electrical model of the piezoelectric material with additional circuit elements. The piezoelectric material is modelled as a voltage source (V_P) with a series capacitor (C_P). When the values of capacitors (C_1 and C_2) and resistors (R_1 and R_2) are selected as identical, and the amount of capacitance (C_A) is set to capacitance of piezoelectric material, the subtraction of the voltage V_1 and V_2 indicates the sensing signal (V_S) independent from actuation signal (V_A).

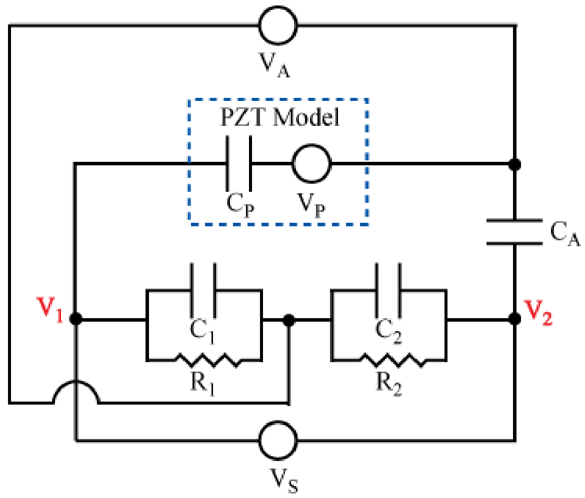

Figure 4: *Bridge Circuit for Self-Sensing Actuator*

The relationship between the piezoelectric voltage (V_P) and the sensing signal ($V_2 - V_1$) is determined by applying Kirchhoff's current and voltage laws. Equation 1 shows the Laplace transform of the subtraction of voltages V_2 and V_1.

$$V_s = V_2 - V_1 = \frac{sC_A R_2}{1 + s(C_2 R_2 + C_A R_2)} V_a - \frac{sC_p R_1}{1 + s(C_1 R_1 + C_p R_1)} V_a + \frac{sC_p R_1}{1 + s(C_1 R_1 + C_p R_1)} V_p \qquad (1)$$

In Equation 1, the sensing signal becomes independent from actuation signal when the following equilibriums are satisfied.

$$C_A = C_p \,, \quad C_1 = C_2 \quad and \quad R_1 = R_2 \qquad (2)$$

The sensing voltage is obtained by assuring the conditions in Equation 2.

$$V_s = V_2 - V_1 = \frac{sC_p R_1}{1 + s(C_1 R_1 + C_p R_1)} V_p \qquad (3)$$

The sensing signal in Equation 3 is the high-pass filtered form of the piezoelectric material's voltage. The cut-off frequency of this high-pass filter is determined by selection of resistance and capacitance values. In order to capture low frequency dynamic of the system, the cut-off frequency of the high pass filter should be kept very low.

In our study, the total capacitance of the piezoelectric patches (1A-1B-4A-4B) is measured as 75 nF. The value of resistances and capacitances are selected as 3.3 MΩ and 72 nF. In addition to these, the amount of capacitance (C_A) is adjusted in order to satisfy the Equation 2.

VIBRATION CHARACTERISTICS OF SMART BEAM

Using the self-sensing piezoelectric actuator, the smart beam is excited with the sinusoidal signal within in the bandwidth of 2 Hz -115 Hz while the response of smart beam is measured using sensor voltage acquired by the bridge circuit. The frequency response of the system is then obtained using Brüel & Kjaer 3560-5 PULSE platform from the decomposed actuation and sensing signals. A linear model of the system is fitted to the measured frequency response by using least square algorithm in MATLAB R2007b® [8] and presented in Figure 5. The corresponding eight order transfer function including the first three resonance modes of the system and the coefficients of this function are given in Equation 4 and Table 1 respectively.

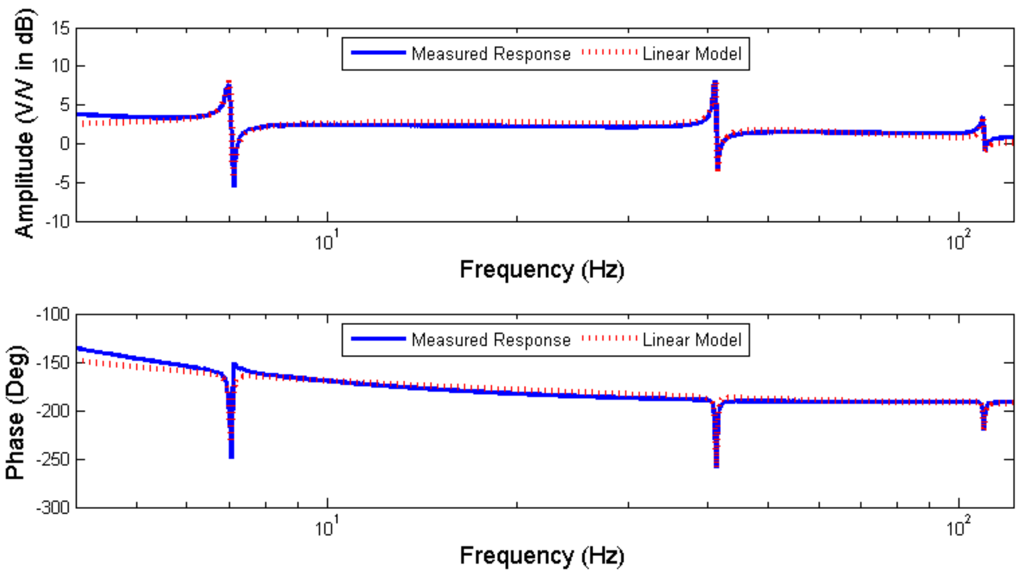

Figure 5: *Experimental Frequency Response and Linear Model for Smart Beam using Self-Sensing Piezoelectric Actuator*

$$G(s)=\frac{a_0s^8+a_1s^7+a_2s^6+a_3s^5+a_4s^4+a_5s^3+a_6s^2+a_7s+a_8}{b_0s^8+b_1s^7+b_2s^6+b_3s^5+b_4s^4+b_5s^3+b_6s^2+b_7s+b_8} \quad (4)$$

Table 1: *Coefficients of Transfer Function G(s)*

Coefficient	Value	Coefficient	Value
a_0	-8.677×10^{-1}	b_0	1.000
a_1	-6.617×10^{2}	b_1	4.979×10^{2}
a_2	-4.778×10^{5}	b_2	5.512×10^{5}
a_3	-3.569×10^{8}	b_3	2.667×10^{8}
a_4	-3.013×10^{10}	b_4	3.704×10^{10}
a_5	-2.172×10^{13}	b_5	1.605×10^{13}
a_6	-8.363×10^{13}	b_6	2.877×10^{14}
a_7	-4.157×10^{16}	b_7	3.027×10^{16}
a_8	-3.308×10^{16}	b_8	4.091×10^{17}

DESIGN OF ROBUST CONTROLLER

In this section, the design of robust controller for suppression of free and the first resonance frequency forced vibration is explained. The objective of robust controller is to minimize H-infinity norm of transfer function between the system inputs and system outputs. The block diagram used for design of robust controller is given in Figure 6. In this diagram, system and controller blocks are shown with the weighted performances and uncertainty blocks. The high frequency dynamics of the system are comprised in the multiplicative uncertainty block (W_m). The disturbance weight (W_d) and noise weight (W_n) are also included. In addition to these, expected system performance is also considered within the performance block (W_P).

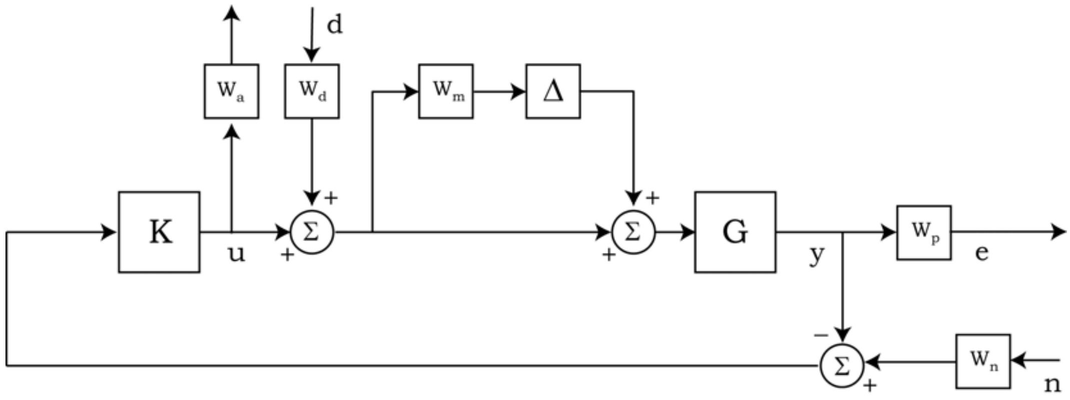

Figure 6: *Block Diagram of Robust Controller*

The disturbance, performance and uncertainty blocks are designed in order to have a stable and effective suppression of free and the first resonance frequency forced vibration. The frequency responses of open and closed loops are shown in Figure 7. Applying robust controller, a considerable reduction (4 dB) in the first mode is achieved for the self-sensing piezoelectric actuator.

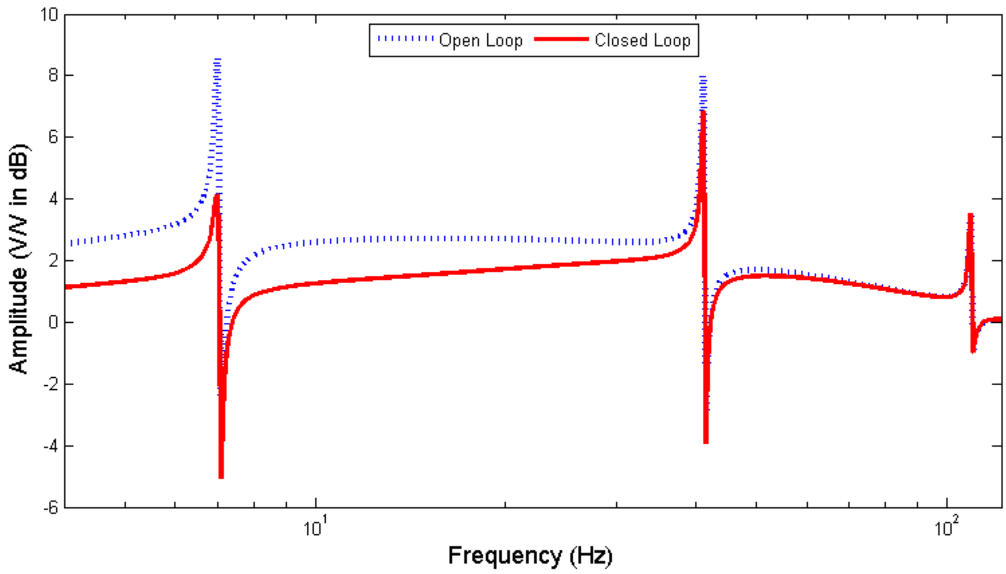

Figure 7: *Frequency Responses of the Open Loop and Closed Loop*

EXPERIMENTAL SETUP

Robust controller is applied to suppress vibration of the smart with the experimental setup shown in Figure 8. In this setup, four-channel programmable controller is included with actuator and sensor voltage. The output of programmable controller (actuator voltage) is amplified 30 times with the SensorTech SA10 high voltage amplifier. This high voltage amplifier is powered by SensorTech SA21 high voltage power supply. Besides these, the experimental setup contains the self-sensing circuit used for decomposition of actuator and sensor signal. As mentioned above, piezoelectric patches (1A-1B and 4A-4B) are used as self-sensing actuator. Meanwhile, the vibration of the smart beam is also monitored by piezoelectric patch 2A. Brüel & Kjaer 3560-5 PULSE platform is used to record the voltage measurements from this piezoelectric patch 2A.

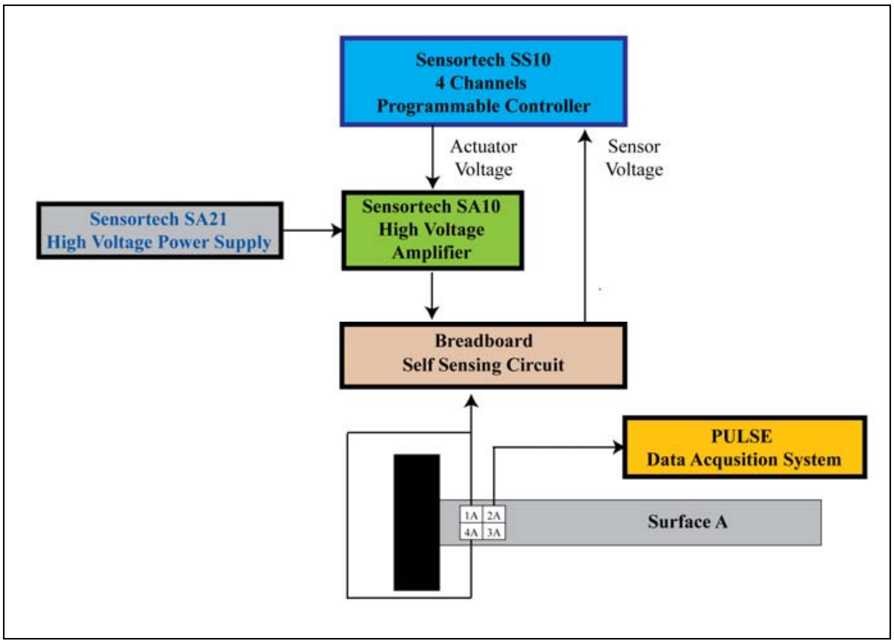

Figure 8: *Experimental Setup*

EXPERIMENTAL RESULTS OF ACTIVE VIBRATION CONTROL

The piezoelectric patches on surface of cantilever-beam like structure are used as self-sensing actuators to suppress free and forced vibration. Active vibration control is archived by using four piezoelectric patches as self-sensing actuators. During the experiments, another piezoelectric patch, 2A, is also used to monitor the vibration of the smart beam. For cantilever-beam structures, maximum curvature at the clamped-end corresponds with the maximum tip displacement in the first bending mode. Therefore, monitoring of voltage of piezoelectric patch 2A reflects the tip displacement of smart beam for the free and first resonance forced vibrations.

Suppression of Free Vibration

At the first part of active vibration control, analyses of open-loop and closed-loop time responses are performed by applying a 6 mm initial tip displacement with zero initial tip velocity which corresponds approximately to 600 mV monitored voltage of patch 2A. The open-loop time responses are obtained when robust controller via self-sensing actuator is inactive while the closed-loop time responses are acquired when robust controller via self-sensing actuator is active. Corresponding time responses are given in Figure 9.

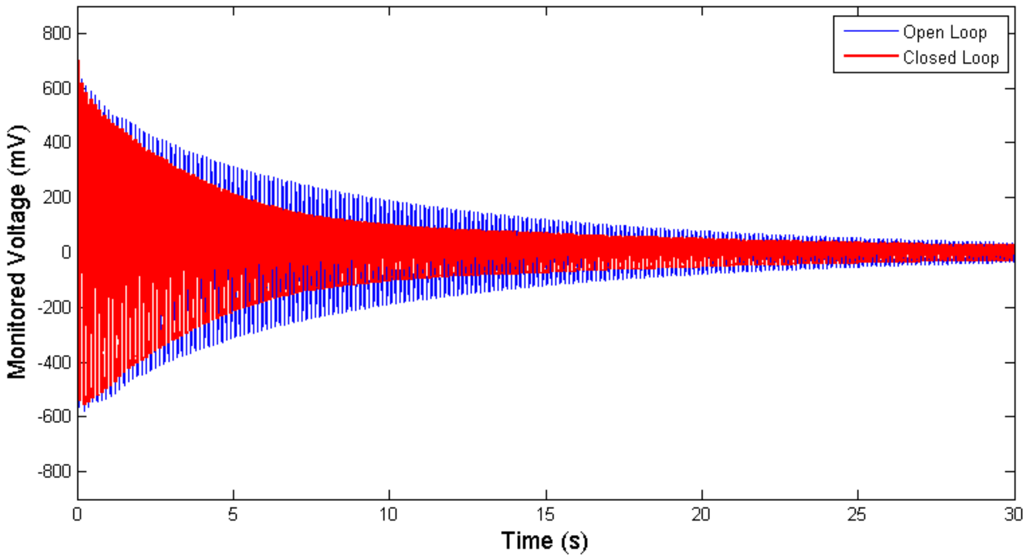

Figure 9: *Open and Closed Loop Time Responses of Free Vibration (Monitored by Piezoelectric Patch 2A)*

Suppression of Forced Vibration

At the second part of active vibration control, analyses of open-loop and closed-loop time responses are performed by applying a 150 V(p-p) sinusoidal signal to bimorph configured piezoelectric patches (3A and 3B) at the first resonance frequency (7 Hz). Similar to the suppression of free vibration results, the open-loop time response corresponds to the situation where the robust controller via self-sensing actuator is inactive whereas the closed-loop time response corresponds to the active robust controller via self-sensing actuator. Corresponding forced-vibration time responses are given in Figure 10.

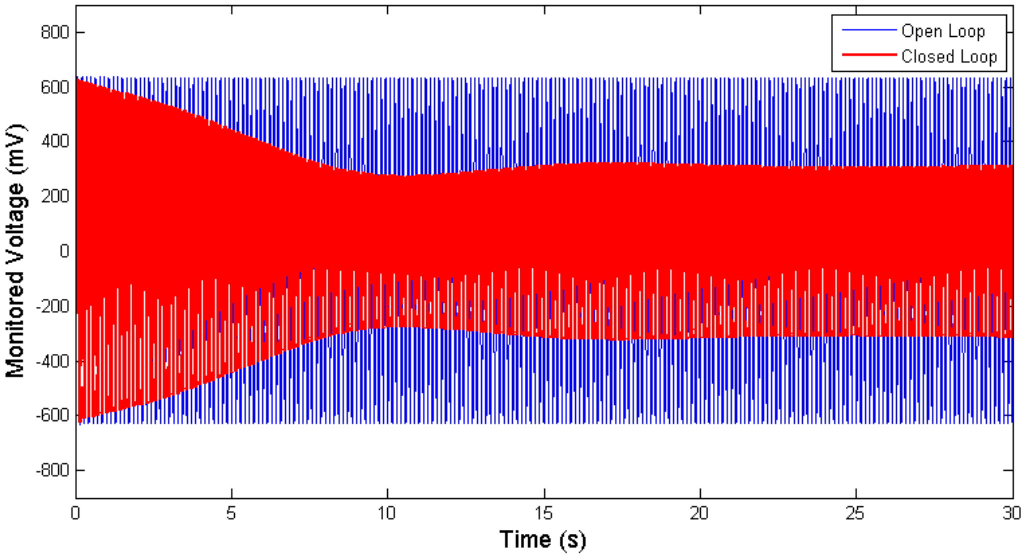

Figure 10: *Open and Closed Loop Time Responses of First Mode Forced Vibration (Monitored by Piezoelectric Patch 2A)*

CONCLUSION

In this study, self-sensing piezoelectric actuator is used for an active vibration suppression of the smart beam with robust controller which is designed for the stable and the effective suppression of free and the first resonance forced vibration.

For the free vibration suppression, reduction of one-quarter of the maximum voltage takes more than 13 seconds at the open-loop, however at the closed-loop, suppression of free vibration to the one-quarter of the maximum voltage takes only 7 seconds. In the case of forced vibration suppression, the monitored voltage at closed-loop is half of the monitored voltage at open-loop. This means that the robust controller via self-sensing actuator can suppress half of the amplitude of vibration in the forced vibration.

As a conclusion, with this study, active vibration control of a smart beam is achieved with employment of piezoelectric patches as self-sensing actuators via designed robust controller. The experimental work performed on the suppression of free and forced vibrations shows the effectiveness of these self-sensing actuators with the robust controller.

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