EXPERIMENTAL STUDY ON VIBRATION CONTROL OF SHAPE MEMORY ALLOY ACTUATED FLEXIBLE BEAM

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Abstract- This paper describes the development of an experimental platform which analyzes and controls the vibration of a Shape Memory Alloy (SMA) actuated and piezo sensed flexible beam. The vibration is controlled using the interactive force of a pair of almost identical SMA wires connected in an antagonistic manner, arranged in parallel to and on both sides of the cantilever beam structure. Data acquisition and control are implemented using a PCI data acquisition card and LabVIEW. Standard P, PI, ON-OFF controllers have been used to control the first mode of vibration of the flexible beam. Experimental results are used to demonstrate the effectiveness of the controllers designed and usefulness of the proposed test platform by exciting the structure at resonance.

Index terms*:* Smart structure, Shape Memory Alloy, Vibration Control, LabVIEW, P, PI and ON-OFF controller.

I. INTRODUCTION

Flexible structures usually have low flexible rigidity and small material damping ratio. A little excitation may lead to destructive large amplitude vibration and long vibration decay time. These can result in fatigue, instability and poor operation of the structures. Vibration control of flexible structures is an important issue in many engineering applications, especially for the precise operation performances in aerospace systems, satellites, flexible manipulators, etc [1, 2]. Advances in smart materials have produced smaller and effective actuators and sensors with high integrity in structures.

Smart material systems offer great possibilities in terms of providing novel and economical solutions to engineering problems since they offer potential technological advantages over traditional ones. Smart materials such as piezoelectric materials, shape memory alloys (SMA) and magneto- and electro- rheological fluids have been used in diverse areas. Varieties of actuators are developed from smart materials but the more promising are the ones based on piezoelectric effect of some ceramic materials and secondly the shape memory effect of metallic alloys. Nitinol is the most widely used shape memory alloy due to its superior properties that are suitable for actuation. The significant advantages of SMA wires in comparison to that of laminated piezoelectric actuator are the relatively low voltage to generate a displacement, larger recovery force generated per unit volume by phase transformation, small size, high output excitation actuation for vibration control, its large displacement, the complete recovery deformation, high stiffness and electrical heating. SMA wires have the property of shortening when heated and thus are able to apply forces. This phenomenon called the Shape Memory Effect (SME) occurs when the material is heated above a certain transition temperature changing its crystalline phase from martensite to austenite. A typical method to trigger the transformations in SMA includes Joule heating for martensite to austenite transition and air convection cooling for the reverse transition. One of its characteristic being small bandwidth makes it suitable for low frequency vibration control application [3 - 6].

The efficiency of a shape memory actuator depends on the accuracy of its controls, which in turn depends on the mathematical model of the SMA. In structural control applications the SMA wire linear actuators can be incorporated internal or externally to the structure. However, external actuators have better control authority since the actuator can be placed at different offset distances from the structure. The distinctive feature of smart structures is that the actuators and sensors are often distributed, and have a high degree of integration with the structure, modeling is thus challenging. The dynamics of SMA actuated structures are modeled by using the finite element method and through system identification [7, 8]. The model integrates the structural dynamics with the dynamic characteristics of the SMA and the controller. Standard P, PI, ON-OFF controllers have been used to control the first mode of vibration of the flexible beam.

LabVIEW is highly suitable for virtual instrumentation as very useful user interface can be designed. Using LabVIEW one can create test and measurement, data acquisition, instrument control, data logging, measurement analysis and report generation applications and can also

create stand-alone executables and shared libraries like DLLs, because LabVIEW is a true 32-bit compiler. LabVIEW programs are called virtual instruments (VIs). VIs contain three main components - the front panel, the block diagram and the icon and connector pane. LabVIEW provides a good platform for controller design and implementation as it has exclusive toolkits for control applications and provides an efficient way to design user interfaces for such applications. LabVIEW 8.6 and its toolkits for control applications like PID control toolkit and control design and simulation toolkit have been used for computer simulation and for implementation of the designed controller in real time [9]. Data acquisition (DAQ) card PCI 6024E and corresponding device driver are used to interface the given cantilever beam structure with LabVIEW. Standard P, PI, ON-OFF controllers have been used to control the first mode of vibration of the flexible beam. P and PI controllers have been implemented using LabVIEW PID control tool kit. All the PID control VIs are reentrant. Multiple calls from high-level VIs use separate and distinct data.

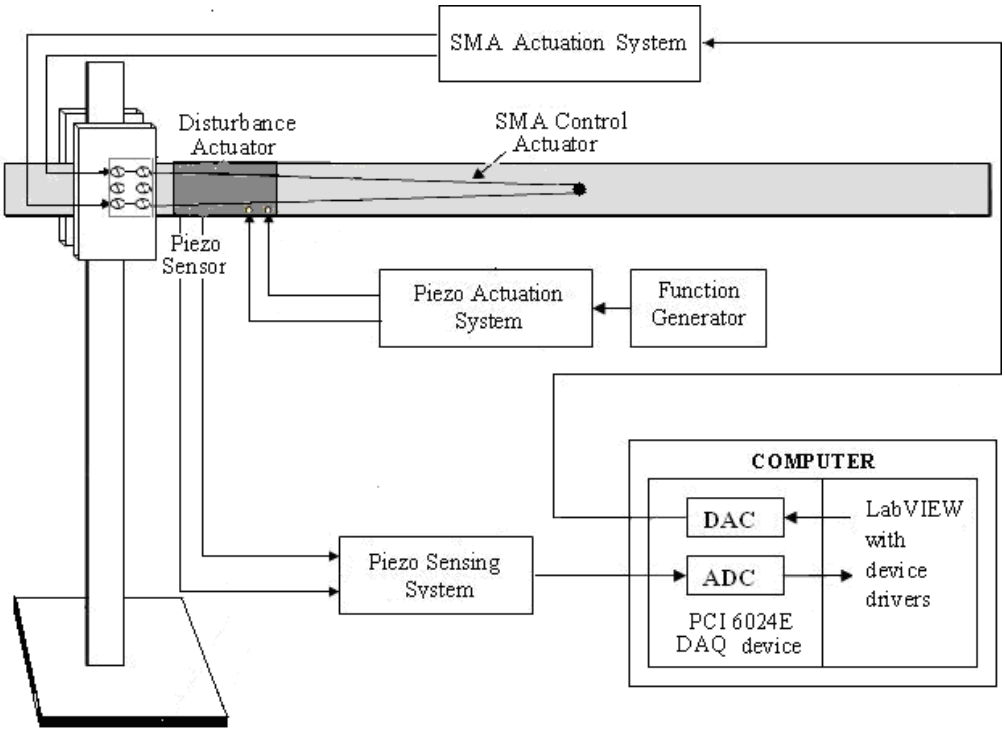
The organization of this paper is as follows: in section 2, the experimental set up of the smart structure employed for identification and control is described. The system models are given in Section 3. Controller designs and simulation results are reported in Section 4. The experimental implementation and results are presented in Section 5, followed by the conclusions in Section 6.

II. THE EXPERIMENTAL SYSTEM

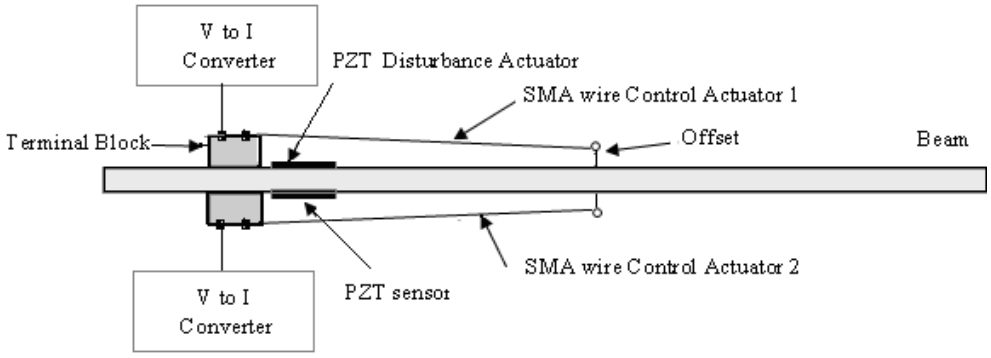
In order to verify the effectiveness of vibration control strategies, the experimental setup shown in Figure 1 (a) is designed and built. The setup consists of the following three main parts: i) the beam under test with the PZT elements bonded to its surface and externally connected SMA wire actuators and, the fixture ii) the instrumentation setup – a charge amplifier and a voltage amplifier for the PZT sensor and disturbance actuator, current amplifiers for the SMA wire actuators and the data acquisition board iii) the software interface – the visuals and the control algorithm to process the measured signal and issue the appropriate control signal.

A clamped-free aluminum beam fixed vertically along its width is considered in this work. Two collocated piezoceramic patches are surface bonded at a distance of 8 mm from the fixed end; the beam is excited using one piezoceramic patch and the response is sensed using another. Symmetrically mounted antagonistic pair of SMA (NiTiNOL) wires is attached externally to the beam on both sides to function as control actuators. The dimensions and material properties of

the beam, piezoceramic patches and NiTiNOL wires are listed in Table 1, Table 2 and Table 3 respectively. PZT (Lead Zirconate Titanate) of type SP-5H which is equivalent to NAVY TYPE VI, the product from Sparkler Ceramics Pvt. Ltd. India are used as the sensor and disturbance actuator. Nitinol wires under the trade name Flexinol® procured from Dynalloy Inc., USA are designed and used as control actuators. Flexinol is a binary alloy (Ni-Ti: 50.5–49.5%) with a one-way shape memory effect. The arrangement of Nitinol wire actuators is shown in Figure 1 (b). On each side of the beam a NiTi SMA wire (90C Flexinol) is strung between two terminal points at the fixed end of the beam and a stub with an offset, anchored at the midpoint of the beam creating two 56.5 cm parallel lengths of wire. In effect each SMA wire is electrically single while it forms two mechanically parallel wires in equivalent. This provides ease of electrical connection to the SMA wires. Such mechanically parallel but electrically serial wires provide the benefit of producing high output force. The usage of two actuator wires allows their alternate heating and cooling thereby permitting continuous actuation through joule heating. Current through them is routed by software switching, so that RMS value of the positive current heats one wire and the RMS value of negative current commands the other. The locations of the sensor and the actuators have been selected for the best performance.



(a)



(b)

Figure 1. Experimental setup (a) Schematic diagram (b) Actuator/sensor location

Table 1: Dimensions and properties of the aluminum beam

Length (m)	l_b	1.1
Width (m)	b_b	0.0254
Thickness (m)	t_b	0.00316
Young's Modulus (GPa)	E_b	76
Density (kg/m^3)	ρ_b	2962.3
First Natural Frequency (Hz)	f_1	2.13

Table 2: Dimensions and properties of the piezoceramic sensor/actuator

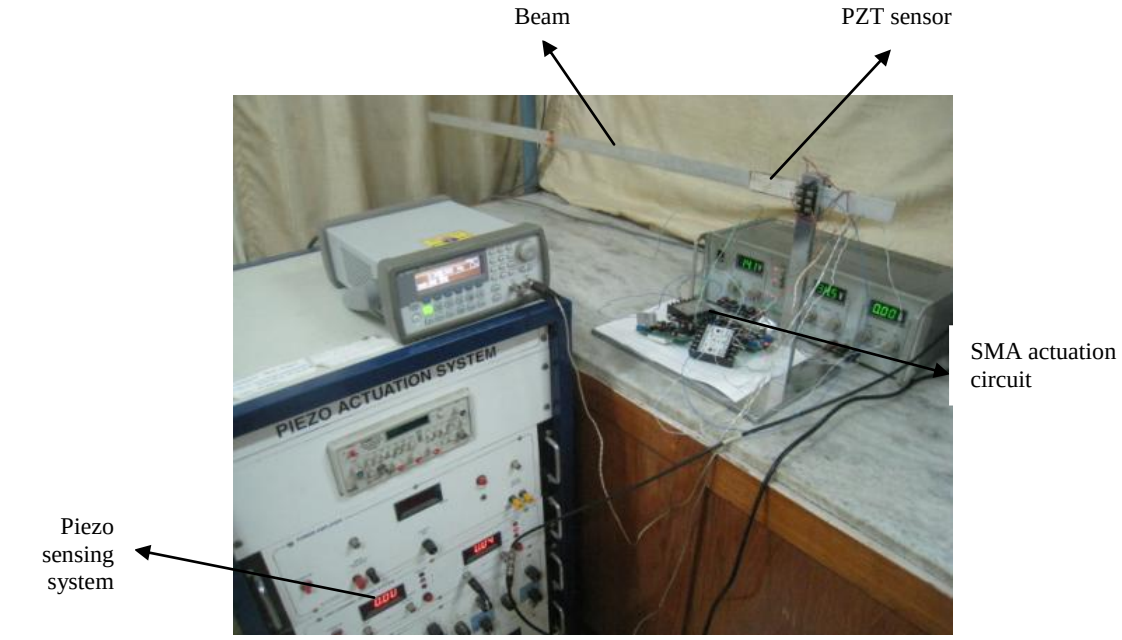
Length (m)	l_p	0.0762
Width (m)	b_p	0.0254
Thickness (m)	t_p	0.001
Young's Modulus (GPa)	E_p	47.62
Density (kg/m^3)	ρ_p	7500
Piezoelectric Strain Constant (m V^{-1})	d_{31}	-247x10^{-12}

The excitation signal to the disturbance actuator is applied using an arbitrary waveform generator (Agilent 33220A). The sensor output signal is conditioned using a piezo sensing system and is given to the analog input channel of the PCI 6024E DAQ card through SCB 68 connector. The inputs and outputs from the cantilever system are connected to the DAQ card using the SCB 68 connector. The input signal is received by the DAQ card and it is sent to the running LabVIEW program with the help of NI device driver. The LabVIEW program receives the sensor output in appropriate form and it takes the control action based on the input value and control algorithm

implemented in the program. Controller outputs available at the DAQ card through its two analog output channels are in terms of voltage. The voltage outputs are given to two voltage to current convertors. These V to I convertors supply electrical power to the SMA wires for the control action. The SMA wires used in the experiment should not be heated continuously for more than 1 second. So the LabVIEW programs have been designed such that the controllers act alternatively hence, each output channel of DAQ card can send the output for one second and then it remains inactive for the next one second. Photographs of the experimental setup are shown in Figure 2 (a) and (b). The SMA wires are too thin (0.1 mm diameter) to be visible in the photograph in Figure 2 (a).

Table 3: Dimensions and properties of the NiTiNOL wire actuator

Length (m)	l_S	1.13
Diameter (m)	d_s	0.000127
Transition Temperature (^{o}C)	T_t	90
Martensite Start Temperature (^{o}C)	M_s	72
Martensite Finish Temperature (^{o}C)	M_f	62
Austenite Start Temperature (^{o}C)	A_s	88
Austenite Finish Temperature (^{o}C)	A_f	98
Young's modulus (GPa)		
Martensite	E_M	28
Austenite	E_A	75
Resistance (ohm/m)	R_s	70.866
Approximate Current at room temperature (A)	I_s	0.25
Contraction Time (s)	t_{cont}	1
Off Time (s)	t_{off}	0.9
Maximum Pull Force (kg)	F_{max}	0.230



(a)



(b)

Figure 2. Photographs of the experimental setup
(a) Structure with electronics (b) PC with LabVIEW and interfacing device

III. MODEL OF SYSTEM DYNAMICS

The linear dynamic model of SMA actuated cantilever beam is obtained using online Recursive Least Square (RLS) parameter estimation as in [10, 11]. The unknown parameters of the smart

structure dynamics are estimated using online identification method, since it is proven to be more universal and feasible than analytical and numerical models for the present system. In addition, the RLS method based on Auto-Regressive (ARX) model is used for linear system identification, which is easy to implement and has fast parameter convergence.

The ARX model for the system shown in figure 1 is given as,

$$\begin{aligned}\hat{y}(k) + a_1 y(k-1) + \ldots + a_{n_a} y(k-n_a) = {} & b1_1 u_1(k-1) + \ldots + b1_{n_{b1}} u_1(k-n_{b1}) + \\ & b2_1 u_2(k-1) + \ldots + b2_{n_{b2}} u_2(k-n_{b2}) \\ & + e_1 d(k-1) + \ldots + e_{n_e} d(k-n_e) + d(k)\end{aligned} \quad (1)$$

where $u_1(k)$ and $u_2(k)$ are the input signals, y(k) is the piezo sensor output, e(k) is the disturbance input and n_a, n_{b1}, n_{b2} and n_e determine the model order.

The natural frequency of the structure is measured experimentally as 2.355 Hz. The first mode frequency of the structure is measured by sweeping the excitation signal frequency applied to disturbance actuator from zero until the resonance is observed. To identify the parameters online, the structure is excited by a sinusoidal signal through the disturbance actuator and a square wave signal as input to the control actuators. The disturbance signal is in the frequency range of 0 to 20 Hz which includes first two natural frequencies. Control actuator (SMA) 1 is excited for a period of 1 second and for the next 1 second control actuator 2 is actuated by the same square wave signal. The input-output data is then collected. The sampling time is set to provide approximately five measurements per cycle. The excitation signal, Root Mean Square (RMS) values of the input signals and sensor output are given to MATLAB/Simulink™ through Analog to Digital Converter (ADC) port of dSPACE DS1104 system. The RLS algorithm is implemented by writing a C-file S-function be used with Real Time Workshop of MATLAB/Simulink™. The algorithm is run dynamically until all the parameter values settle down to a final steady value.

The model is identified to represent the first vibration mode (second order model). The continuous time transfer function models derived from the identified second order ARX model are as follows:

Transfer function between output (Y) and control input from SMA actuator 1 (U_1) is

$$\frac{-0.0830\,s - 5.6121}{s^2 + 0.5587\,s + 219.9986} \quad (2)$$

Transfer function between output (Y) and control input from SMA actuator 2 (U_2) is

$$\frac{-0.0650\,s - 5.9204}{s^2 + 0.5587\,s + 219.9986} \quad (3)$$

The model has been validated and it is found that the mode frequency obtained from the identified model is 2.3379 Hz and is close to the experimentally measured mode frequency 2.36 Hz.

IV. DESIGN OF CONTROLLERS

To suppress the amplitude of the vibration at resonance of an SMA actuated cantilever beam, the basic control schemes like the On-Off control, proportional control and proportional plus integral control are designed and simulated. The design involves control of the first mode of vibration using the second order model.

a. On/Off Controller

In the On-Off controller, the controller input is given to the system only when the sensor output exceeds the given offset. The offset value is set on the basis of tolerance value and the system response to the controller. In this controller, one SMA wire suppresses the vibrations when the sensor output is greater than 0.05 volt while the other SMA wire suppresses the vibrations when the sensor output is less than – 0.05 volt. The two controllers act alternatively with a switching time of one second. The simulation Block Diagram of On-Off controller is shown in Figure 3. (a). The open loop response, response with On-Off control and its control signal obtained through simulation are shown in Figure 3. (b).

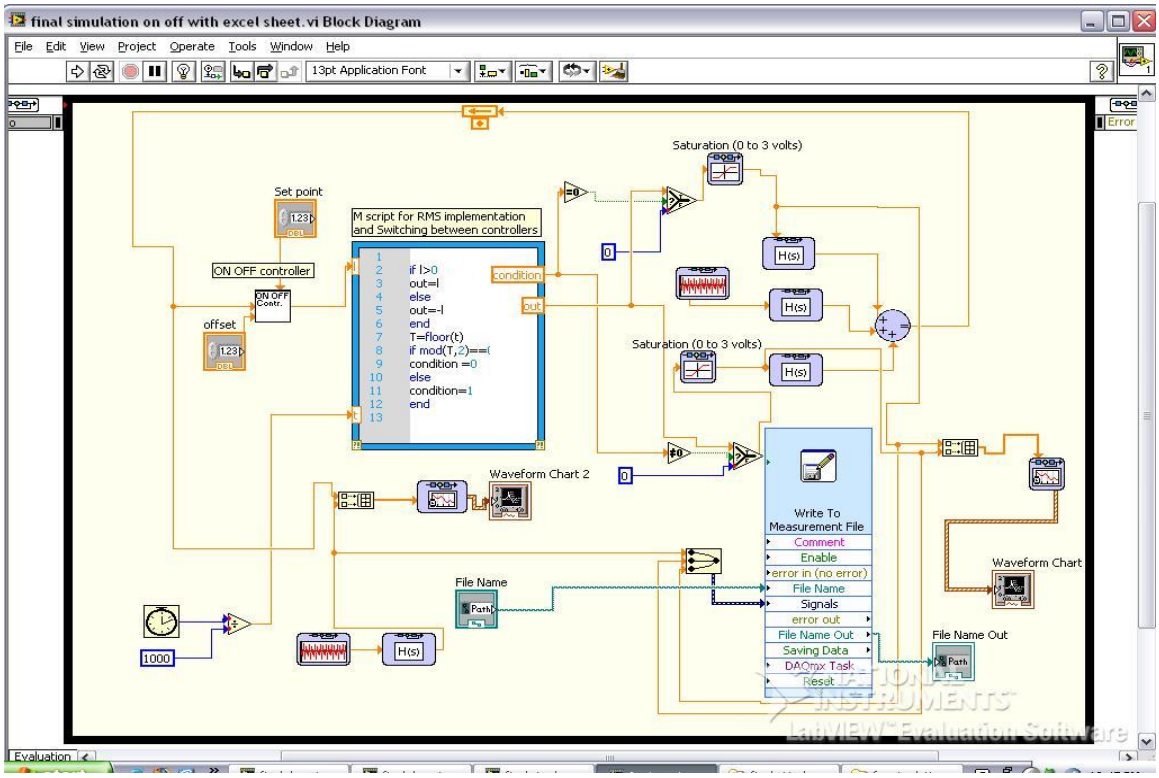


Figure 3. (a) Block Diagram of On-Off controller (simulation)

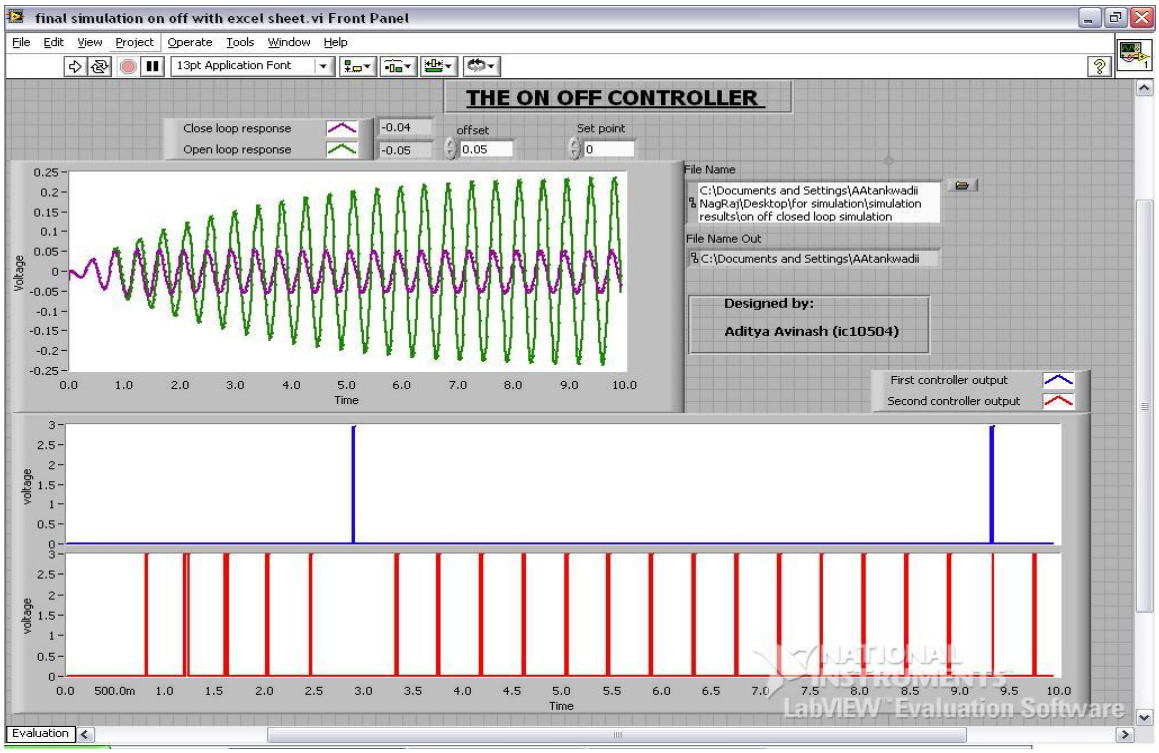


Figure 3. (b) Front Panel of On-Off control showing responses and control signals (simulation)

b) Proportional plus Integral (PI) Controller and Proportional (P) Controller

A PI controller is designed to control the actuating force of the SMA wires. Figure 7. (a) shows a conceptual diagram of the closed loop control system including the controller. The gain value of the designed controller was obtained by the pole placement method [10]. The damping factor of the original system is 0.01884 which is too small. Hence the closed loop poles are placed such that the damping factor is improved to be 0.6. The designed values are K = 17.1, K_i = 0.0161 and K_d = 0.000029. Since K_d is very small the control action is selected to be a PI controller with K = 17.1 and K_i = 0.0161. Also the effect of the P controller alone is obtained for only P control action with the proportional gain K = 17.1.

For simulation of P and PI controller, the PID VI is used which is available in the PID control toolkit. The PID gains are set on the front panel. The two inputs to the PID VI are PID gains and the output of the transfer function model. The controller output of the PID VI is sent to the M script code. The code inside the M script is responsible for the alternate action of the two controllers. Controller outputs pass through saturation blocks to limit the outputs between 0 to 3 volts. The outputs of the simulation blocks are then given to the transfer function model. The controller outputs as well as output of the transfer function model are stored in the excel sheets during program runtime. The front panel displays the open loop response, response with proportional control and its control signals obtained through simulation are shown in Figure 4.

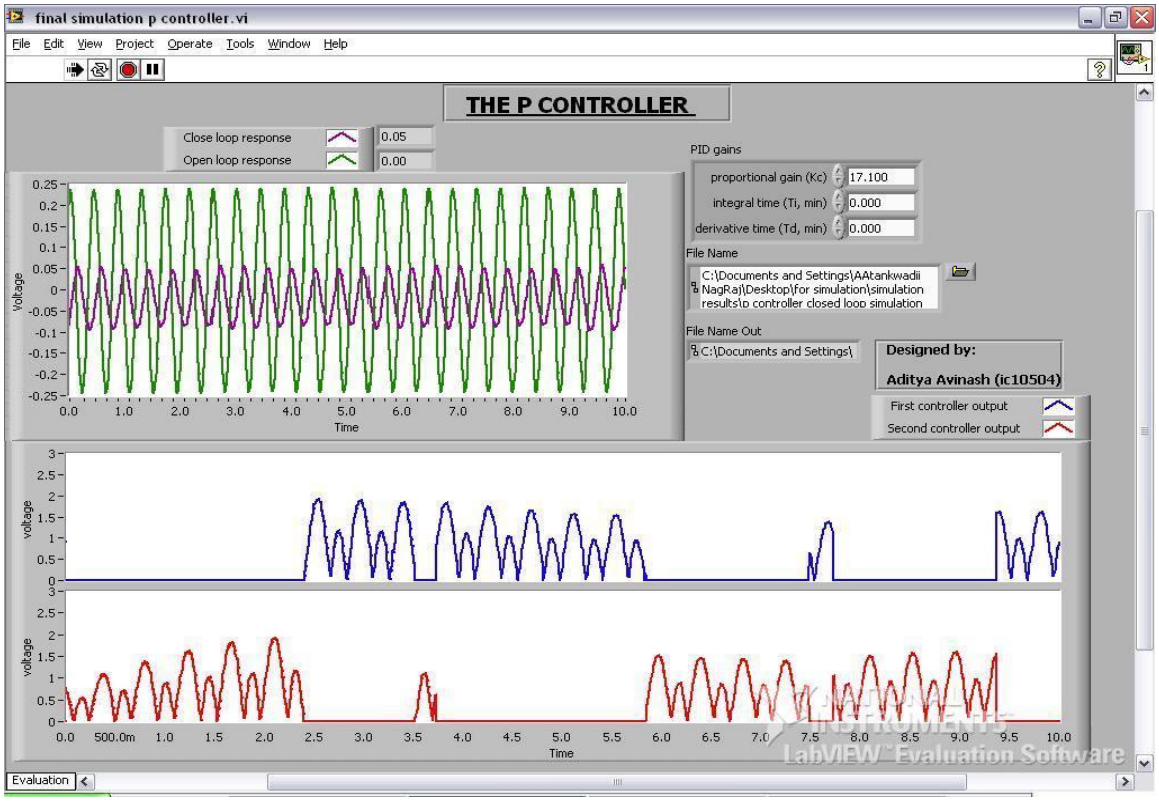


Figure 4. Front Panel of proportional control showing responses and control signals (simulation)

The open loop response, response with PI control and its control signal obtained through simulation are displayed in the front panel as in Figure 5.

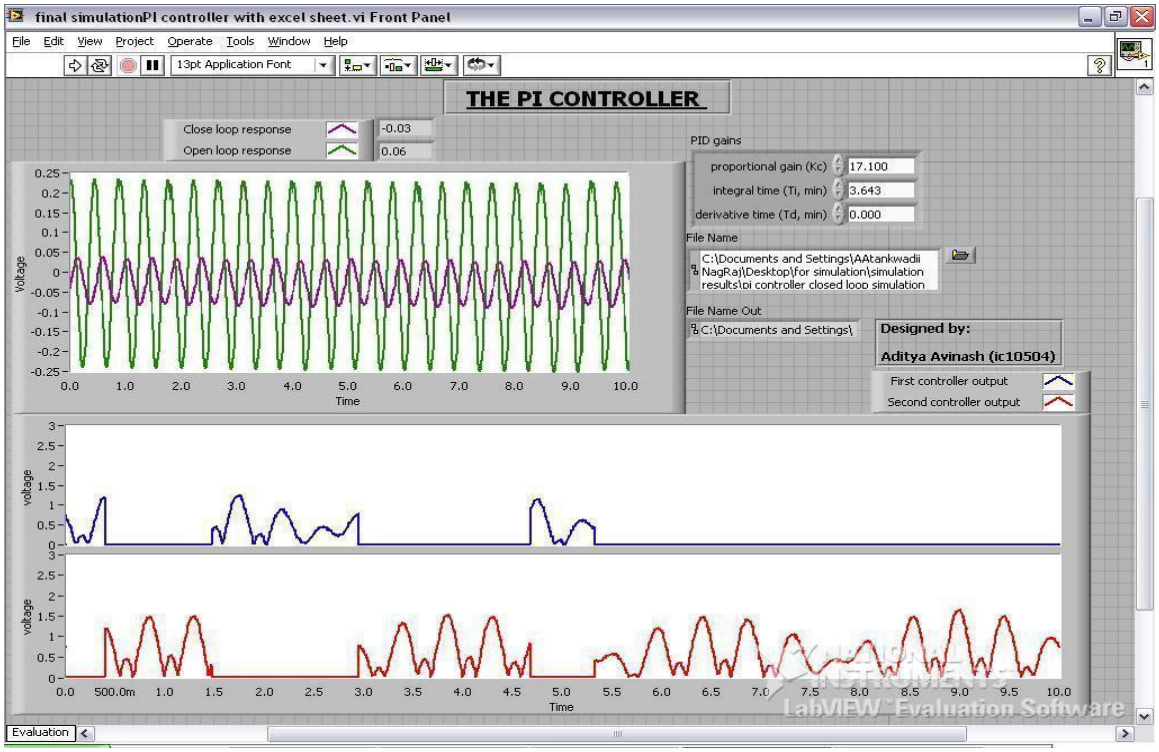
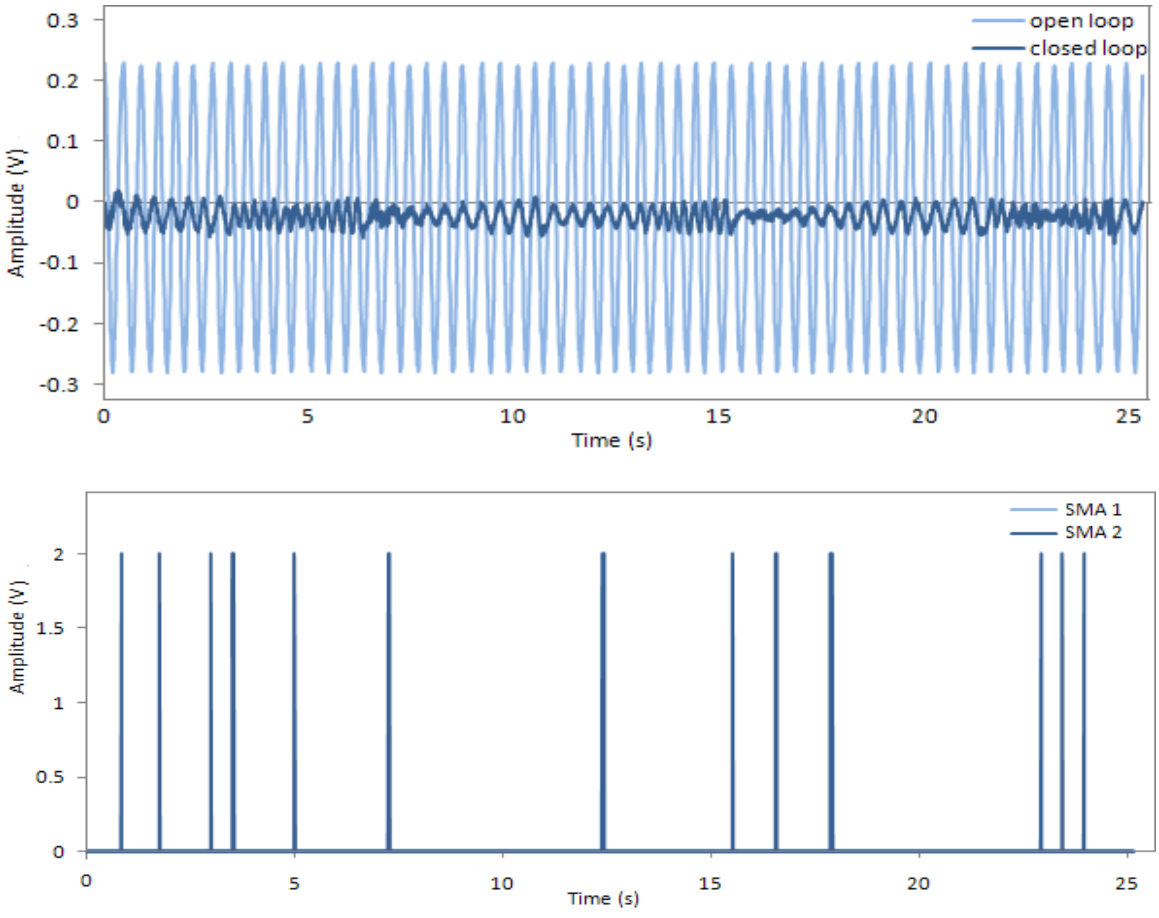


Figure 5. Front Panel of PI controller showing responses and control signals (simulation)

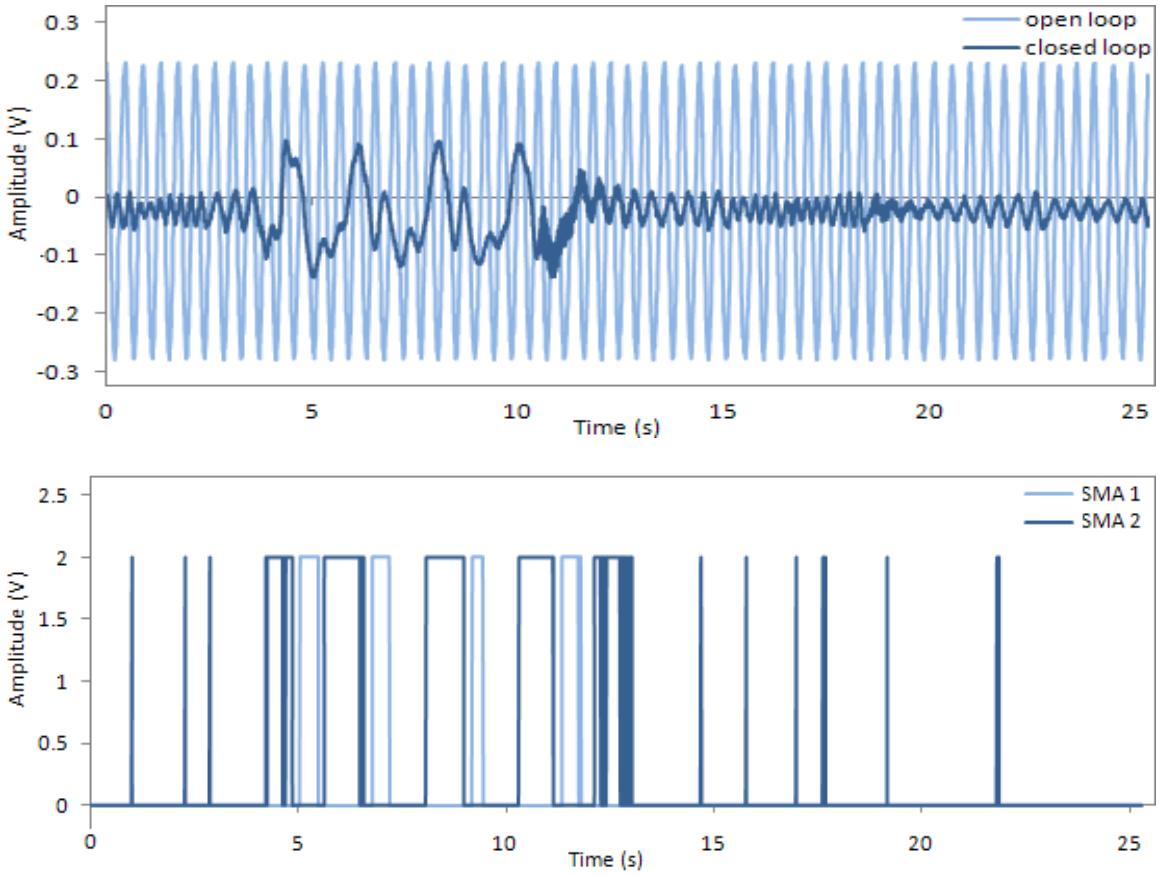
V. EXPERIMENTAL IMPLEMENTATION

Evaluation of the performance of the controller through experiment is an essential part of the design. To substantiate the design and simulation results the controller designed for the second order system is implemented using the experimental facility shown in Figure 1. The structure is made to vibrate at its first mode frequency (2.36 Hz) by applying a sinusoidal excitation signal of 1 volt peak to peak to the disturbance actuator from an arbitrary waveform generator (Agilent 33220A). This vibration is sensed by the piezo sensor which gives a corresponding voltage output. This output is connected to the analog input channel of the DAQ card through SCB 68 connector. The DAQ assistance VI in the LabVIEW program receives the output of the piezo-sensing system and it sends the signal to the On-Off/PID VI. The offset of the On-Off VI and gains of the PID VI are set on the front panel. The controller output is sent to the M script which implements the alternation action of the two controllers. The controller outputs are sent to the saturation blocks to limit the controller output to the desired range. The output of the saturation blocks are sent to the two DAQ assistance VIs. The controller outputs are available from the

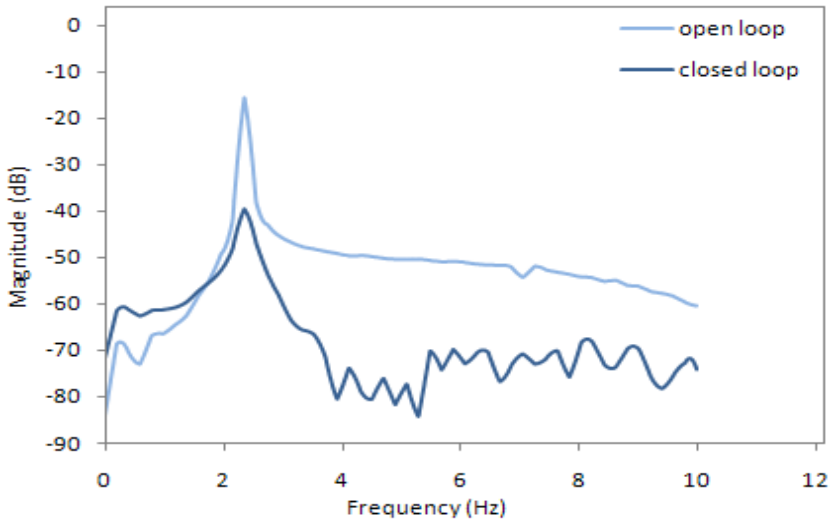
DAQ card through its two analog output channels and are sent to the V to I convertors through SCB 68 connector. The control signal generated by the controller 1 is applied to actuator 1 at alternate 1 s while the control signal generated by controller 2 is applied to actuator 2 at the other alternate 1 second. Switching between the controllers is cycled at every consecutive period of 1 second, while continuous actuation is provided to the system by the alternate actuators. The controller outputs and the piezo-sensor output are also stored in the excel sheet. The plots on the front panel show the sensor output and the controller outputs. The controller is thus implemented by developing a real time LabVIEW program. The open loop response, closed loop response with On-Off control and the corresponding control signals are shown in Figure 6. (a) and (b). The frequency responses of the system acquired using Digital Storage Oscilloscope (DSO) (Agilent 54621A) are shown in Figure 6. (c).



(a)



(b)



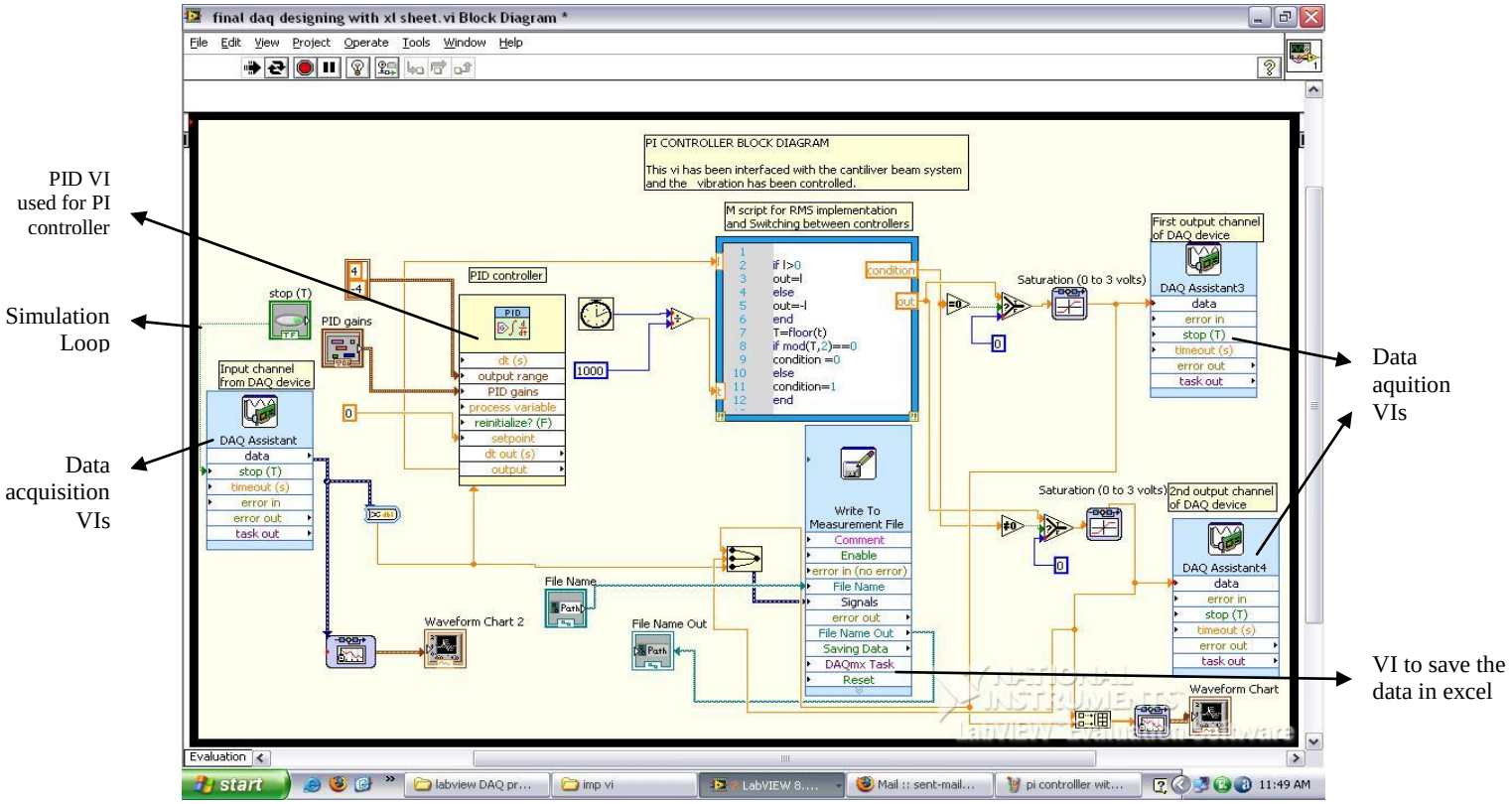
(c)

Figure 6. Experimental implementation and results with On-Off controller

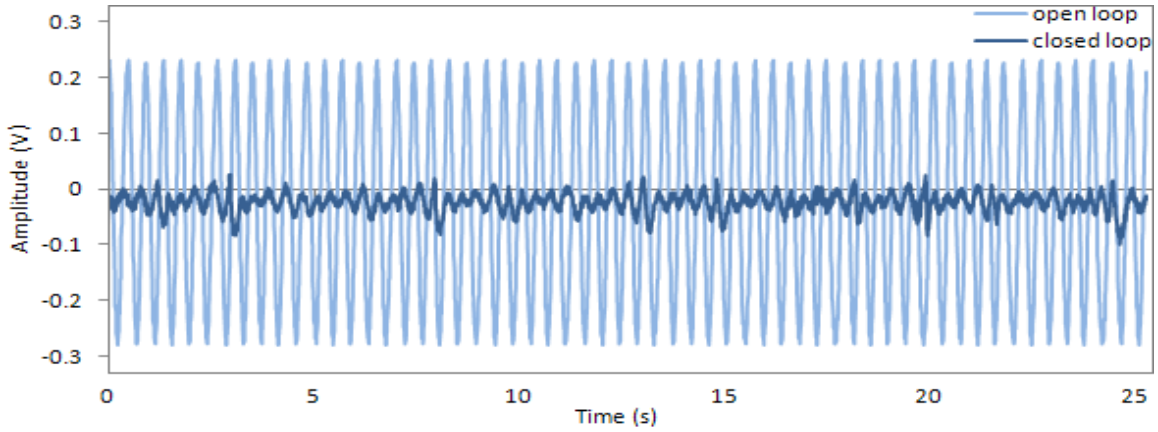
(a) & (b) Uncontrolled and controlled responses with On-Off controller and control signals

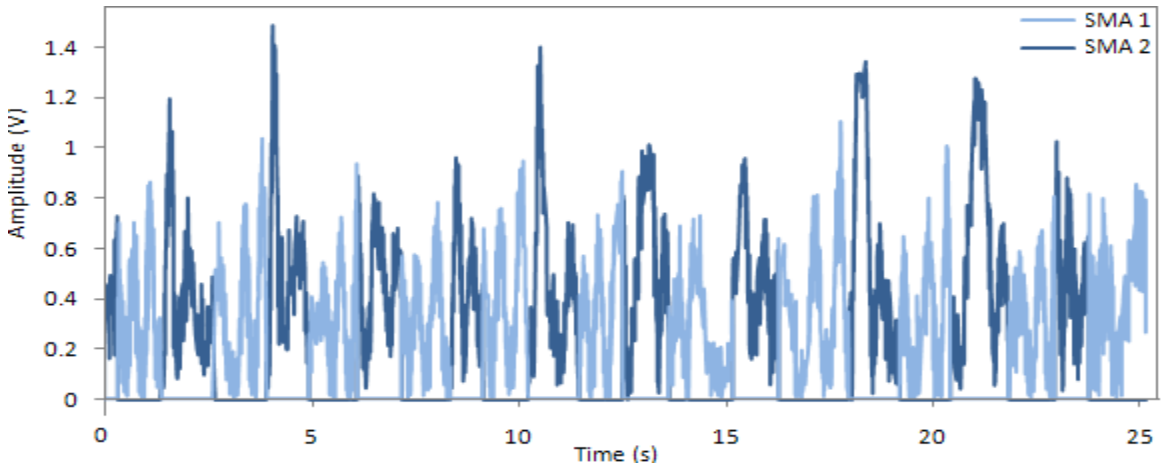
(c) Frequency responses with and without On-Off controller

The block diagram model shown in Figure 7. (a) is developed using LabVIEW for implementing the PI controller in real time. The open loop response, closed loop response with proportional control and the control signals are shown in Figure 7. (b) and the frequency responses of the system acquired using DSO are shown in Figure 7. (c).

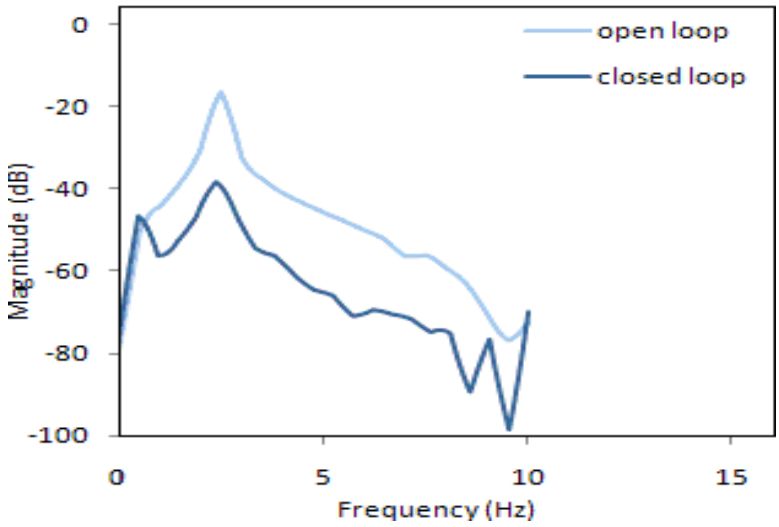


(a)





(b)



(c)

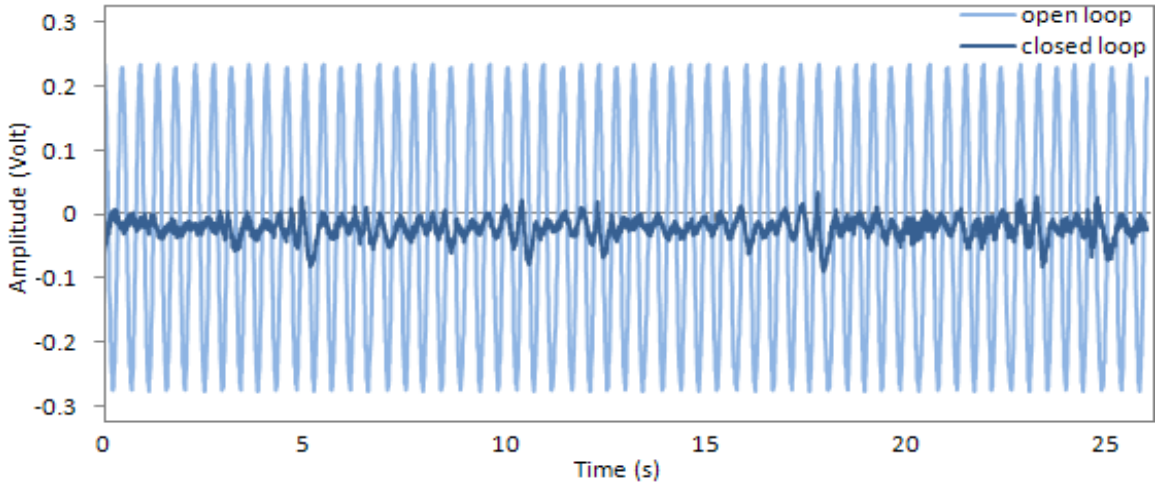
Figure 7. Experimental implementation and results with P controller

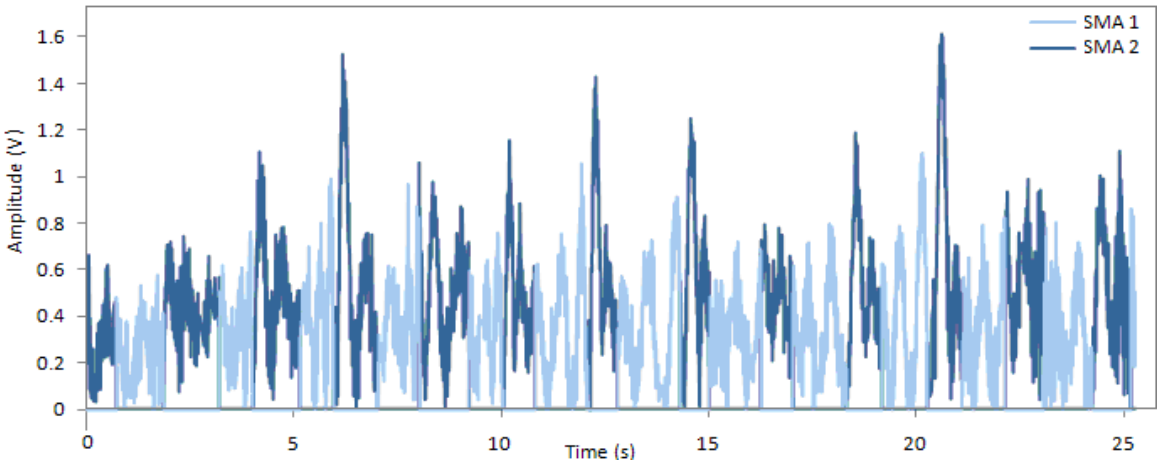
(a) Real-time block diagram for PI controller in LabVIEW

(b) Uncontrolled and controlled responses with proportional controller and control signals

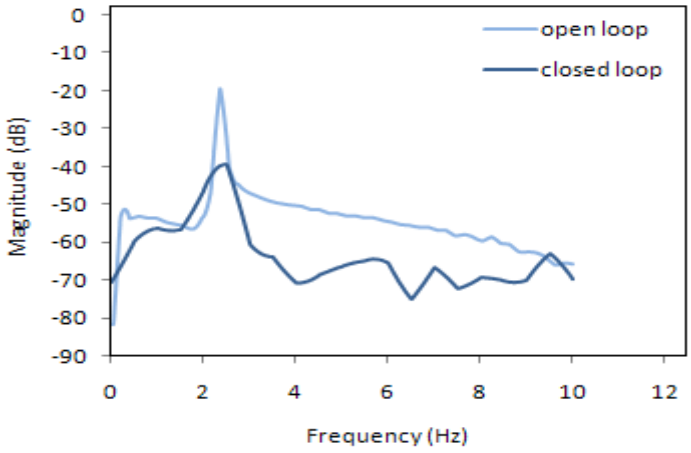
(c) Frequency responses with and without proportional controller

Similarly the open loop response, closed loop response with proportional plus integral control and the control signals are shown in Figure 8. (a) and its frequency response is shown in Figure 8. (b).





(a)



(b)

Figure 8. (a) Experimental results with proportional plus integral controller

(b) Frequency responses with and without PI controller

VI. CONCLUSIONS

The second order model of SMA actuated and piezoelectric sensed cantilever beam structure excited at its first mode of resonant frequency has been identified using online ARX RLS system identification approach. The On-Off, P and PI controllers have been designed and implemented experimentally using LabVIEW 8.6 for the system model. Controllers like the On-off which is the simplest form of control, proportional controller which attempts to perform better than the On-Off type and the PI form of PID controller are designed, simulated and implemented on the system developed to demonstrate the vibration control strategies. The closed loop responses obtained through simulation with these control actions closely matches with that of the experimental results for the system. The closeness depends on suitable design and the selection of control parameters. For a sinusoidal excitation of 1 volt peak to peak an uncontrolled response of 0.225 V peak to peak is obtained. In the problem of first mode vibration control, the following reduction in amplitude of vibration is through simulation and experimentally.

Control	Vibration reduction %	
	Simulation	Experiment
On-Off	80	78
Proportional	79	77
PI	82	80

The simulation and experimental results demonstrate the performance and practical simplicity of the controller design and implementation using LabVIEW. Experimental results show that the closed loop response obtained with these control schemes exhibits substantial reduction in the amplitude of flexural vibration at its first mode resonance. The application programs made here in LabVIEW use the software timing for timing related requirements. But software timing is affected by various factors like other processes run by operating system, system hardware specifications, user interference etc. Hence better vibration control can be achieved by implementing hardware timing and by the use of real time systems like Compact RIO controller [9]. In this paper only basic controllers have been implemented which have various inherent limitations hence advanced controllers can be implemented. During the experimental study it has been found that LabVIEW provides a very good platform to develop controllers and to implement the designed controllers in real time very easily and efficiently.

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