Active Vibration Control of a Smart Cantilever Beam at Resonance: A Comparison between Conventional and Real Time Control

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***Abstract*—All mechanical systems suffer from undesirable vibrations during their operations. These vibrations are unavoidable as they depend on various factors. However, for efficient operation of the system, they 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 coupled with feedback algorithms. In this paper, direct output feedback based active vibration control has been implemented on a smart cantilever beam at its resonant frequency using PZT (Lead Zirconate Titanate) sensors and actuators. The work aims to showcase the performance abilities of the conventional PC based control and a dedicated REAL TIME CONTROL at resonance. The platform used is LABVIEW RT with FPGA hardware and the system performance is compared with the conventional time multiplexed Operating System (Windows 7) where LABVIEW is again used with the appropriate DAQ devices.**

Keywords-smart cantilever beam; active vibration control; direct output feedback; PZT-5H patches; real time control; LABVIEW FPGA; cRIO-9022

I. INTRODUCTION

Data measured from a vibrating system in time domain when converted into frequency domain gives information regarding the system's natural frequencies where, the vibrations observed would be at its maximum. In a normal engineering system investigation process, a complex physical system is first mathematically modeled so that further analysis can be easily carried out on the model instead of the actual system. This helps in attaining a clearer understanding of the system's dynamics and is also cost effective. Once the tests are confirmed with respect to the model responses, they can be carried out on the physical system. Both results are then compared and analyzed. If the responses do not match, then the assumptions made during modeling are re defined and the entire process is repeated till satisfactory matching responses are obtained.

The developments in piezoelectric materials have motivated many researchers to work in the field of smart structures. A smart structure can be defined as the structure that can sense an external disturbance and respond to it actively as per the designed control algorithm so as to maintain its dynamics within the desired levels. Here, active devices like sensors and actuators are either attached or embedded in the structure along with their integrated processor networks. Smart structures are widely used in place of traditional structures on account of their ability to adapt to the prevailing disturbances. Mechanical vibrations of these structures tend to affect their operational efficiency to a great extent and so the need to control/damp out these vibrations was felt. The simplest yet effective control strategy that can be implemented to suppress the occurring system vibrations is direct output feedback of the sensed parameter back into the system after suitable amplification and conditioning. Measurable parameters like strain, displacement, velocity, acceleration, etc. are the commonly fed signals.

In this work, a simple cantilever beam was selected. It was made smart by the usage of PZT-5H patches that were used as sensors as well as actuators. The system parameters like its stiffness, damping, natural frequency, etc. were theoretically determined. The obtained parameter values were included in the free vibration simulation of the beam. The free vibration simulation results obtained were then compared with those obtained from carrying out the same tests on the physical system and a satisfactory match was obtained. This validated the obtained values of the system parameters. The smart cantilever beam used in this work is depicted in Fig. 1 and its properties including its physical dimensions are given in Table 1. 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 their low cost makes PZT a very popular choice as a sensor and actuator. The PZT patch properties that are mentioned in Table 2.

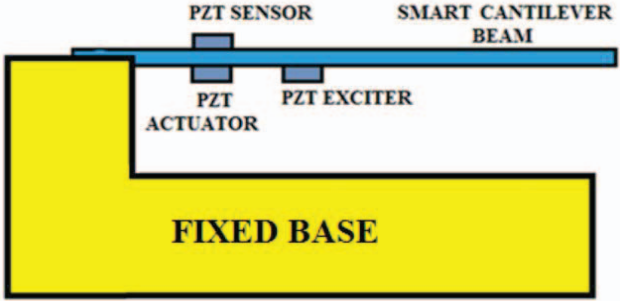

Figure1. System under Study

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TABLE 1. CANTILEVER BEAM PROPERTIES

PARAMETER	SYMBOL	UNIT	VALUE
Length	L	m	0.3
Width	b	m	0.025
Thickness	h	m	0.003
Modulus	E	N/m^2	7.1×10^{10}
Density	ρ	kg/m^3	2700
Mass Density	M	kg/m	0.06075
Modal Mass	m	kg	0.015377

TABLE 2. PZT PATCH PROPERTIES

PROPERTIES	PZT-5H
Density	7350 kg/m^3
ELASTIC STIFFNESS MATRIX	
C_{11}	12.6×10^{10} N/m^2
C_{12}	7.95×10^{10} N/m^2
C_{13}	8.41×10^{10} N/m^2
C_{33}	11.7×10^{10} N/m^2
C_{44}	2.33×10^{10} N/m^2
PIEZOELECTRIC STRAIN MATRIX	
E_{31}	6.5 C/m^2
E_{33}	23.3 C/m^2
E_{15}	17 C/m^2
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

Lastly, the system was subjected to forced vibrations through the PZT shaker (Exciter patch) and the designed control algorithm was implemented on a real time platform as well as on the traditional time multiplexed platform so as to achieve and compare the results of vibration control. The setup consisted of one PZT patch that acted as the exciter thereby making the cantilever beam undergo forced excitation at a defined frequency and amplitude. Another patch was used as a sensor to detect the occurring vibrations while a third patch was used as the actuator to damp out the sensed vibrations. The placements of the PZT patches on the beam were determined through modal analysis using ANSYS as shown in [1]. Satisfactory active vibration control was achieved using the traditional time multiplexed system (Windows 7) in LABVIEW domain by [2] with real time data and in this work the same technique was carried forward using real time operating system (RTOS) so as to further improve the control action there by improving the operational efficiency of the system. As reported in [5], presence of the PZT patches shifts the natural frequencies of the passive structure to higher frequencies. Piezoelectric material was used by [6] in their work where a normal cantilever beam was made smart. Active control of hybrid smart structures under forced vibrations was investigated by [7].

II. REAL TIME CONTROL USING LABVIEW RT

Real Time Operating System (RTOS) functions in the same way as the general purpose operating system. The only difference here is that RTOS performs the assigned tasks with a very precise timing as well as with a high degree of reliability. This is especially important in time critical fast processes where downtime is costly and random program delays are a safety hazard.The feature of deterministic timing in RTOS was noted by [16]. These service times can be mathematically formulized and they should be strictly algebraic with no random timing elements included. The importance of the deterministic behavior is highlighted when accurate control is required in fast and critical processes in aerospace, defense, bio-instrumentation, etc. however, general purpose operating systems (Windows, Linux, etc.) are non-deterministic and so while in operation, random delays are introduced in the application software thereby making the application go slow at times. Another advantage of RTOS over the general purpose operating system is their ability to ensure a constant load independent timing.

LABVIEW based RTOS along with DAQ boards was used to realize real time control by [17]. The same paper discussed in detail, real time control and monitoring of on-going operations either locally or remotely via the internet. Also the constraints while implementing real time control was discussed in detail. In this work, the same concept of LABVIEW based real time control was successfully implemented to achieve the vibration control of the smart cantilever beam through active means. Fig. 2 depicts the schematic of real time output feedback based active vibration control of a smart cantilever beam on a LABVIEW platform with its associated hardware.

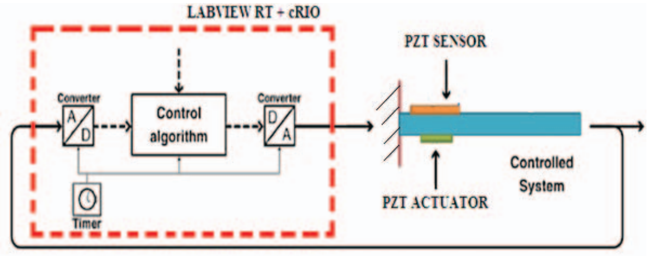

Figure 2. Real Time Output feedback Control loop of a Smart Cantilever beam

Here, the vibrating cantilever is first analyzed in terms of its modal parameters in ANSYS [1] and later, it was subjected to free as well as forced vibrations. The measured data is transferred on to the LABVIEW domain for its frequency as well as time domain analysis. However, for achieving the desired vibration control, the output feedback algorithm was implemented in the traditional multi-threaded operating system as well as in real time operating system.

The traditional multi-threaded operating system involved Windows 7 where LABVIEW was run and the sensor data was obtained through the employment of Compact Data Acquisition System (cDAQ) along with the appropriate NI C-Series modules. Here, it was found that a number of system processes were being serviced continuously by the PC processor in the back ground and this affected the efficiency of the control algorithm being implemented as the processor time was divided so as to ensure the service of each interrupt request. Also, the sampling rates played a decisive role in determining the accuracy of the control action. Next, the same control algorithm was implemented using RTOS. Here, the software platform used was LABVIEW RT in the FPGA mode coupled with the Compact Reconfigurable Input Output (cRIO) FPGA controller with appropriate NI C-Series modules. The glaring difference in the accuracy and efficiency of the control action was visible. In RTOS, a smaller controller gain yielded a much satisfactory response as compared to the control action implemented on a WINDOWS 7 OS where a higher controller gain was necessary to achieve a similar amount of reduction in the vibration amplitude of the system. Also, the duration of the successful control action which was in question in the traditional OS based control due to its multi-threaded nature was satisfied in the RTOS based control of the vibrating system.

III. LABVIEW BASED SIMULATAION OF THE VIBRATING CANTILEVER BEAM

The first step in this work was to determine the system parameters of the smart cantilever beam and it was accomplished by subjecting the beam to a free vibration test. Through the free vibration test, values critical system parameters like its natural frequency, damping coefficient, stiffness etc. were obtained. The obtained experimental response was then validated with the simulated response where the system parameters were theoretically analyzed.

From the concept of machine vibrations, the natural frequency of the vibrating cantilever beam was determined as:

$$\omega_n = \sqrt{\frac{k}{m}} \tag{1}$$

Where, ω_n = the natural frequency of the beam (rad/sec) $=2\pi f_n$

k = the beam stiffness (N/m^2)

m = the modal mass of the cantilever beam (Kg)

f_n = the natural frequency of the beam in Hz.

The dimensions of the system are as given in Table 1from which the beam cross section second area moment was determined by the following formula:

$$I = \frac{bh^3}{12} \tag{2}$$

Using Equation (2) along with the known young's modulus (E) of the Aluminum based cantilever beam, the beam stiffness was calculated through the following formula:

$$k = \frac{3EI}{L^3} \tag{3}$$

From the free vibration test, the logarithmic decay ratio (δ) was determined as:

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

Also the logarithmic decay ratio can be formulized as:

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

Further solution of (5) yielded the value for damping ratio (ζ) as:

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

Further simplification of (6) gives the relation for damping coefficient (c) as:

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

The final list of the main system parameters along with their determined values are shown below in Table 3:

TABLE 3. SYSTEM PARAMETERS

Parameter	Formula	Value	Unit
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	$\delta = \frac{1}{n}\ln(\frac{X_n}{X_{n+1}})$	0.06346	--
Damping Coefficient	$c = \frac{2\delta\sqrt{km}}{\sqrt{\delta^2+4\pi^2}}$	0.07203	Ns/m

IV. FORCED VIBRATION OF THE SMART CANTILEVER BEAM

The smart cantilever beam was subjected to harmonic excitation at its first natural frequency. The work focused on achieving satisfactory vibration control at the first natural frequency as it was at this frequency that maximum strain was developed at the fixed end. The output parameter fed back to control the vibrations is strain developed at the fixed end. This was suitably sensed through the PZT-5H sensor patch. The block diagram of the strain feedback based active vibration control of the smart cantilever beam is as shown in Fig. 3.

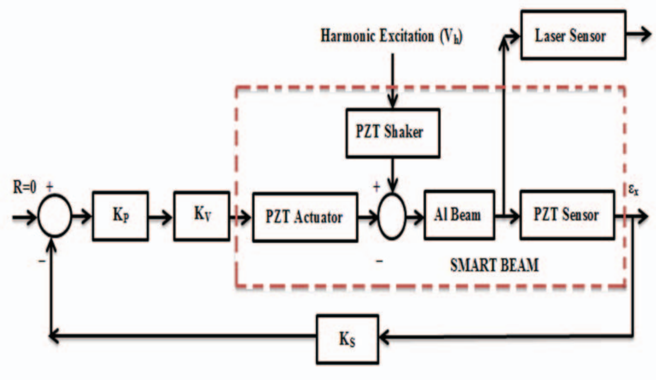

Figure 3. Block Diagram of Strain Feedback Closed Loop Control

The sensed strain is converted to a corresponding voltage by the piezo sensor which after suitable conditioning and amplification is transferred on to the LABVIEW domain. As per the mentioned objective of this work, the control algorithm was designed in LABVIEW and implemented through the Windows 7 Operating System along with the associated hardware (cDAQ + NI C series modules). The same process was repeated on a Real Time Operating System platform with LABVIEW RT configured in FPGA mode along with the associated hardware (cRIO + NI C series Modules). The obtained results were then compared and analyzed so as to bring out the difference between a generalized control and a dedicated control.

V. RESULTS AND DISCUSSION

The strain feedback based control of a vibrating smart cantilever beam was successfully implemented as is visible from the results. The logic was implemented on both – a conventional time-multiplexed operating system (LABVIEW on a Windows 7 platform) as well as through a dedicated real time operating system (LABVIEW RT in FPGA mode through cRIO stand-alone controller). Critical system parameter values were obtained from the free vibration test and these were successfully validated with those obtained from the theoretical analyses followed up by the computer simulations as shown in Fig. 4a and 4b.

While implementing the control action on Windows 7 platform, it was observed that the durability and accuracy of the control tend to get affected. This was attributed to the processor of the PC allotting it's time for servicing all the occurring interrupt requests. Thus a dedicated control could not be achieved. In this paper, while implementing output feedback based active vibration control on a LABVIEW platform in Windows 7 OS, for a controller gain of 10, the vibrations related voltage dropped by around 67% as shown in Fig. 5. However, the steady state voltage was not maintained due to PC processor dividing its time among all the occurring processes and the variations were at times out of the desired limits.

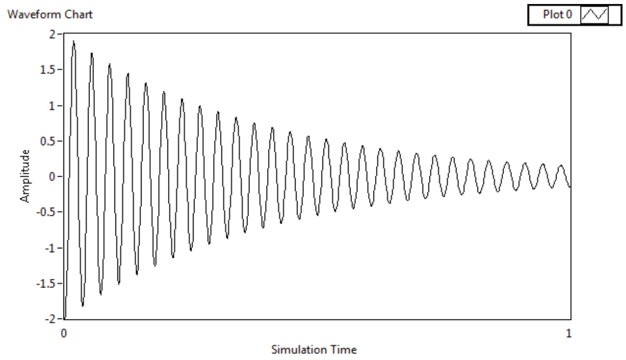

Figure 4a. Simulated Response of Free Vibration of smart beam

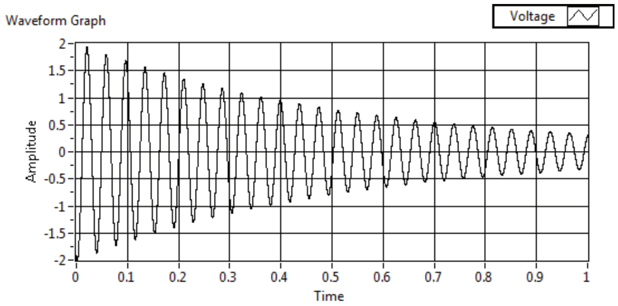

Figure 4b. Experimental response of Free Vibration of Smart Beam

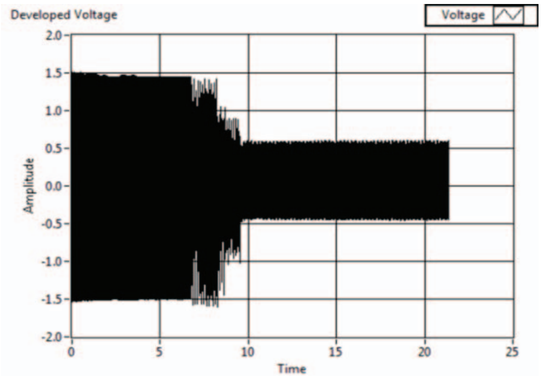

Figure 5. Output Feedback Control of Smart Cantilever Beam on Conventional Operating System (LABVIEW on Windows 7)

On the other hand, when real time control is applied through LABVIEW FPGA with cRIO-9212, for a small controller gain of 2.06, the strain related voltage at the fixed end dropped by around 58% as shown in Fig. 6. Thus from these results, it can be concluded that implementation of real time control provides a much better controlled response of the system with an excellent transient response as well as highly reliable steady state response.

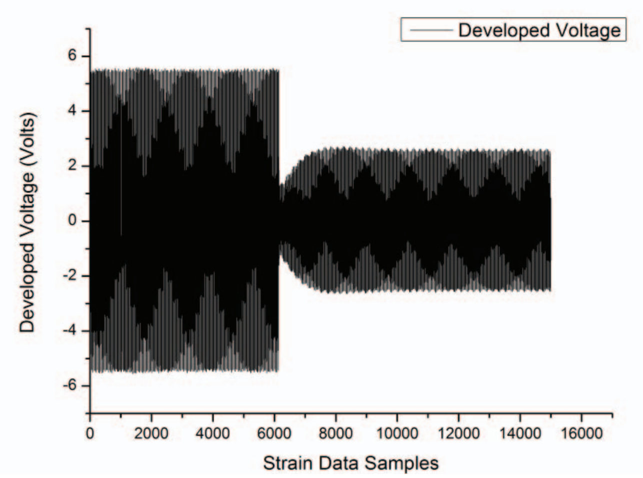

Figure 6. Real Time Output Feedback Control of Smart Cantilever Beam (LABVIEW RT + cRIO 9022)

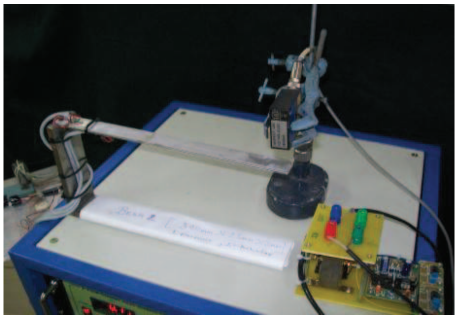

Figure 7. Experimental Setup

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