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EMBEDDED COMPUTER BASED ACTIVE VIBRATION CONTROL SYSTEM FOR VIBRATION REDUCTION OF FLEXIBLE STRUCTURES

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ABSTRACT

Research on Active Vibration Control System (AVCS) is being carried out to reduce structural vibrations caused by unwanted vibrations in many application areas such as in space, aircraft structures, satellites, automobiles and civil structures (bridges), particularly at low frequencies. The unwanted vibration may cause damage to the structure or degradation to the structure's performance. The AVCS comprises physical plant, a sensor to detect the source vibration, a DSP based electronic controller using an actuator connected to the structure generates a counter force that is appropriately out of phase but equal in amplitude to the source vibration. As a result two equal and opposite forces cancel each other by the principle of super position and structure stops vibrating. The main objective of this research work is to develop an embedded computer based real time AVCS for reducing low frequency tonal vibration response of a vibrating flexible cantilever beam by automatic modification of the vibrating beam's structural response and to verify the performance of the developed system experimentally. The developed AVCS is a generic design platform that can be applied for designing adaptive feed forward AVC and feedback AVC. This study presents the vibration control methodology adapted for reducing tonal vibration generated by a sine generator connected to the primary source actuator attached to one end of the cantilever beam. The secondary actuator is attached to the beam on the other end through the AVCS to reduce primary vibration by destructive interference with the original response of the system, caused by the primary source of vibration. Adaptive feed forward Active Vibration Control (AVC) technique is used with Filtered-X Least Mean Square (FxLMS) algorithm using FIR digital filter. A cantilever beam was considered as plant and embedded computer based AVCS was tested and evaluated using an experimental setup. The experimental results are presented for the cantilever beam excited at one of its natural frequency using active vibration control system and an appreciable reduction was achieved up to 20 dB.

Keywords: Active Vibration Control (AVC) System, Embedded Computer, Vibration Reduction, FxLMS Algorithm, Flexible Cantilever Beam

1. INTRODUCTION

Research on Active Vibration Control (AVC) is being carried out in reducing unwanted vibrations of flexible structures as the unwanted vibrations have detrimental effect in many real life applications. Vibration of mechanical structures at the low frequency is a challenging problem in lightweight and flexible structures such as automobiles and household appliances. Large space structures are especially very flexible since they are large in size and have structurally light damping. Once these lightweight and flexible structures are excited by external forces and moments, they vibrate on their natural frequencies and are subjected to large amplitudes

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due to the condition resonance. The conventional passive methods of increasing damping and adding mass or stiffness to these flexible structures may have disadvantages on the efficiency or cost. Therefore, active control methods have been investigated in the past two decades as an alternative to the conventional passive techniques for reducing low frequency vibration. Active vibration control is a promising technique to increase the performance of those lightly damped flexible structures with light-weight design, where sometimes attenuation of the vibrations by passive treatments is not sufficient or even impossible, i.e., large space structures, high precision machines. For example, the lead-impregnated sheets used to reduce aircraft cabin propeller noise impose a severe weight penalty, but active control might perform as well with a much smaller weight penalty. AVC problem of flexible beams has at2 tracted significant interest due to its generic nature and easily applied in many practical problems such as robot manipulator, aircraft fuselage and civil structures. The development of various control strategies has been widely studied where the performance of the control schemes has been analyzed via simulation and experimental studies. Active vibration control is a multi-field topic including vibration analysis, modeling and analysis of structures, selection of suitable sensors and actuators, controller design, digital implementation and so on.

Lueg (1936) is among the first who used AVC in order to cancel the vibrations. Since then, a large number of researchers (Snyder and Tanaka, 1995; Takawa and Fukuda, 2003) have concentrated on developing methodologies for the design and implementation of AVC systems. Several control methodologies have been developed in literature for AVC problems of the flexible structures. Dr. Teik Lim, Professor of Mechanical Engg., University of Cincinnati, USA investigated vibration control of beams with piezoelectric sensors and actuators using finite element analysis in both frequency and time domain. Jha and Rower (2002) and Manning *et al.* (2000) presented a smart structure vibration control scheme using system identification in 3 phases: Data collection, model characterization and parameter estimation. Negative velocity feedback is used as the controller to reduce vibration amplitudes. Karagulle *et al*. (2004) simulated the active vibration control of a cantilever beam having piezo-electric patches by ANSYS finite element package. Guglielmino *et al*. (2005) discussed conventional and non-conventional smart damping systems for ride control. Haichang and Song (2007) proposed the robust model reference controller and shown the robustness and effectiveness of the proposed method. Lavu and Gupta (2009) successfully designed and implemented a PID controller to control the vibrations of structures using MATLAB/SIMULINK. Xia and Ghasempoor (2011) introduced an AVC system which, using dynamic neural networks, automatically detects noisy sinusoidal vibration parameters of a cantilever beam and generates control signals for an actuator to minimise the beam vibration.

Active vibration control is defined as a technique in which the vibration of a structure is reduced or controlled by applying counter force to the structure that is appropriately out of phase but equal in amplitude to the original vibration (Hansen and Snyder, 1997). As a result two equal and opposite forces cancel each other and structure stops vibrating. Active Vibration Control System uses two types of control strategies and is realized using feedback and feed forward controllers, respectively (Xia and Ghasempoor, 2007; 2008; 2011). The various possible applications of active vibration control are increased material durability and fatigue life, lower operating costs due to reduced facility down-time for installation and maintenance and reduced operator fatigue and improved ergonomics. These advantages received new emphasis in the last few years. However, benefits may extend far beyond those mentioned above. The compact size and modularity of active systems can provide additional flexibility in product design, even to the point of a complete product redesign.

The aim of this study is to design and implement an embedded computer based Active Vibration Control System for reducing amplitude of one of the resonance frequency vibration of a flexible cantilever beam. The AVCS comprises sensors, actuators, pre and post conditioning amplifiers. The developed AVCS is a generic design platform that can be applied for designing adaptive feed forward AVC and feedback AVC. The study also presents the vibration control methodology adapted for reducing tonal vibration generated by an electromagnetic exciter source from a sine generator connected to the primary exciter at the fixed end of the beam. Adaptive feed forward AVC technique is used with Filtered-X Least Mean Square (FxLMS) algorithm using FIR digital filter. Experimental results are presented for active cancellation of tonal vibration at one of the natural frequency of the beam. The vibration reduction obtained at second mode was observed to be 20 dB.

2. MATERIALS AND METHODS

The important components of active vibration control system are a sensor to detect the vibration, an electronic controller to manipulate the signal from the detector and an actuator which influences the mechanical response of the system. Electromagnetic actuators are used to generate a secondary vibrational response in a linear mechanical system, which could reduce the overall response by destructive interference with the original response of the system caused by the primary source of vibration.

The principle of operation is that active control system, based on the sensor input and a mathematical model of the system, generates an anti vibration field, that is, a field that as closely as possible is identical to the uncontrolled vibration field but with opposite phase. If these two vibration fields (the uncontrolled and the actuator generated) were identical in amplitude and had exact the opposite phase and then the addition of the two fields would lead to complete elimination of the vibrations levels as shown in **Fig. 1**.

2.1. Hardware Implementation

An embedded computer based active vibration control system for flexible cantilever beam has been designed and implemented using EZ-ANC from M/s. Causal Systems Pvt. Ltd., Australia, as a general platform for control of noise as well as vibration signal using digital processing. The authors used the EZ-ANC system as a platform for AVC application as vibration controller that consists of ADSP-2181 digital signal processing system with noise/vibration control software. The vibration control methodology adapted for reducing vibration generated by a primary exciter fitted to the flexible cantilever beam is single channel adaptive feed forward active vibration control technique that uses Filtered-x Least Mean Square (FxLMS) algorithm with FIR filter. The functional block diagram of single channel adaptive feed forward AVC as applied to the flexible beam is shown in **Fig. 2**.

2.2. AVC Hardware System Description

The AVC system comprises a primary exciter as vibration source, flexible cantilever beam as physical system for vibration transmission, sensors (reference and error accelerometers), actuators (electro-magnetic exciters), Active Vibration Control Development System and associated instrumentation such as power amplifiers, charge-amplifiers and vibration measuring equipment. The reference sensor (accelerometer) at one end of the beam picks up the vibration source as reference signal input for processing. The error accelerometer sensor at the other end of the beam senses the existing vibration level, which is again input to the EZ-ANC controller to effectively reduce the vibration level, enabling ‘*adaptation*’ by the controller.

The actuator produces the anti-vibration signal that causes ‘*destructive interference*’ of the vibration propagating in the flexible beam, caused by the primary vibration exciter. The anti-vibration signal is generated by the EZ-ANC system continuously after processing the input signals (reference and error sensor signals) according to the various ANC parameters. The EZ-ANC system processes the input signals by executing noise control program invoked upon RESET with the execution of communication program through PC as terminal (using a terminal emulation program, KERMIT) that is connected to the serial port of EZ-ANC. KERMIT software has been used in this project to program into EZ ANC system’s software. The AVC parameters such as number of errors, number of controls, sample rate selection, adjusting input and output amplifier gains, control filter, adaptive algorithm, system identification, storing data, uploading and downloading data and programs to and from the host computer-PC. The generated anti-vibration control signal is fed to the actuator-secondary vibration exciter. The processing logic of input signal is based on the use of Filtered-X LMS algorithm, for adaptive feed forward control. A brief description of the principle of adaptive feed forward AVC system with Filtered-X LMS algorithm for a flexible cantilever beam is given below.

2.3. Adaptive Feed Forward AVC

The theoretical FXLMS algorithm is implemented in the practical EZ-ANC development system based on ADSP-2181, for achieving reduced vibration source transmitted through beam that is shown in the **Fig. 3**. The Filtered–X Least Mean Square (FXLMS) Algorithm is a popular Adaptive Algorithm for feed forward ANC/AVC systems. Using a digital frequency domain representation of the problem, the ideal active noise control system uses an adaptive filter W(z) to estimate the response of an unknown primary acoustic path P(z) between the reference input sensor and the error sensor.

The z-transform of e(n) can be expressed as:

$$E(z)=D(z)+Y(z)=X(z)*[P(z)+W(z)] \tag{1}$$

Where:

E(z) = The error signal, D(z)= The primary noise
X(z) = The input signal, P(z)= The Plant/Beam
Y(z) = The adaptive filter output. After the adaptive filter W(z) has converged, E(z) = 0.

Hence Equation (1) becomes Equation 2:

$$W(z) = - P(z) \tag{2}$$

Which implies that Equation 3:

$$y(n) = - d(n) \tag{3}$$

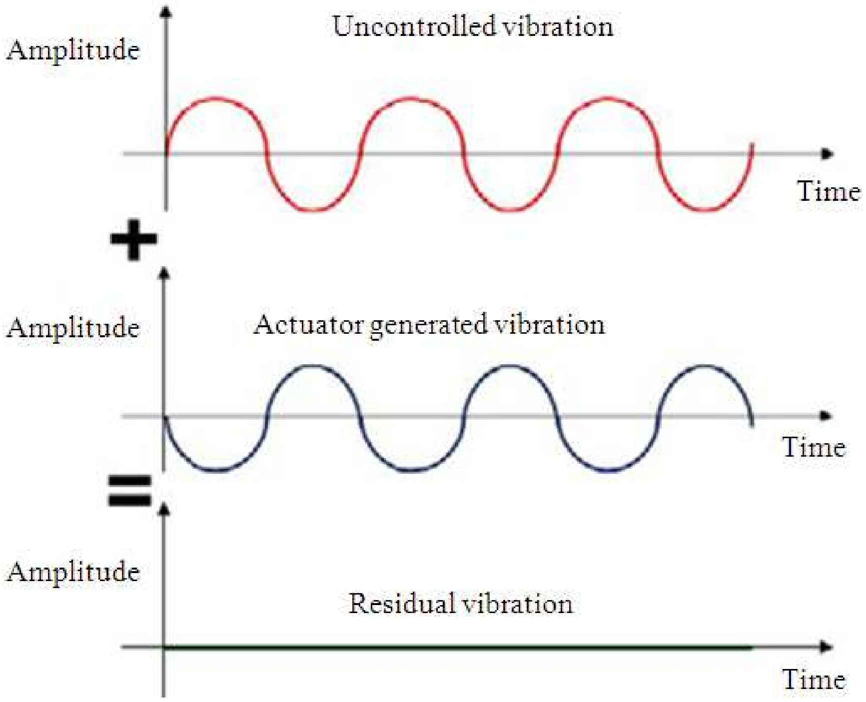

Fig. 1. Principle of active vibration control

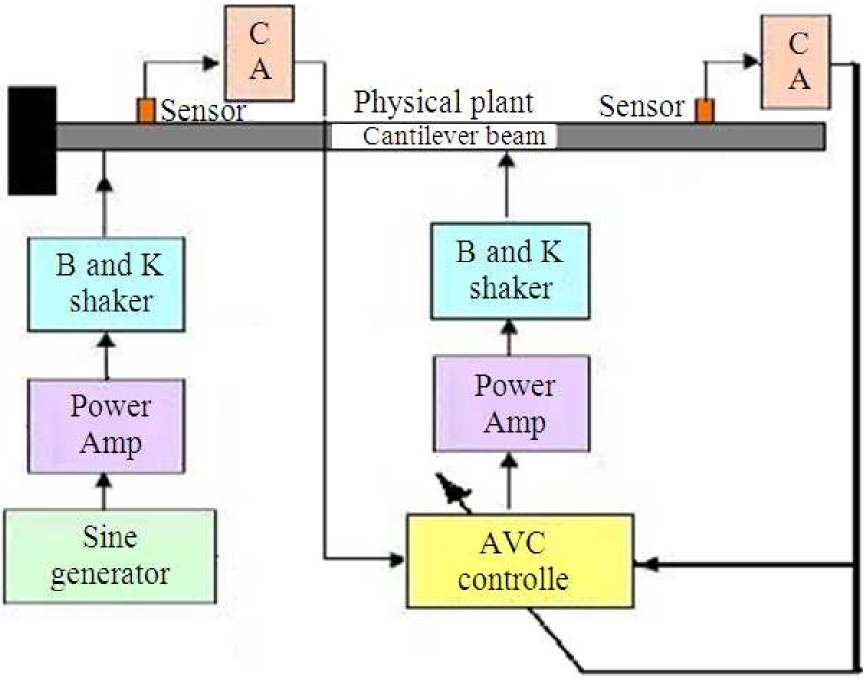

Fig. 2. Functional block diagram of AVCS for flexible cantilever beam

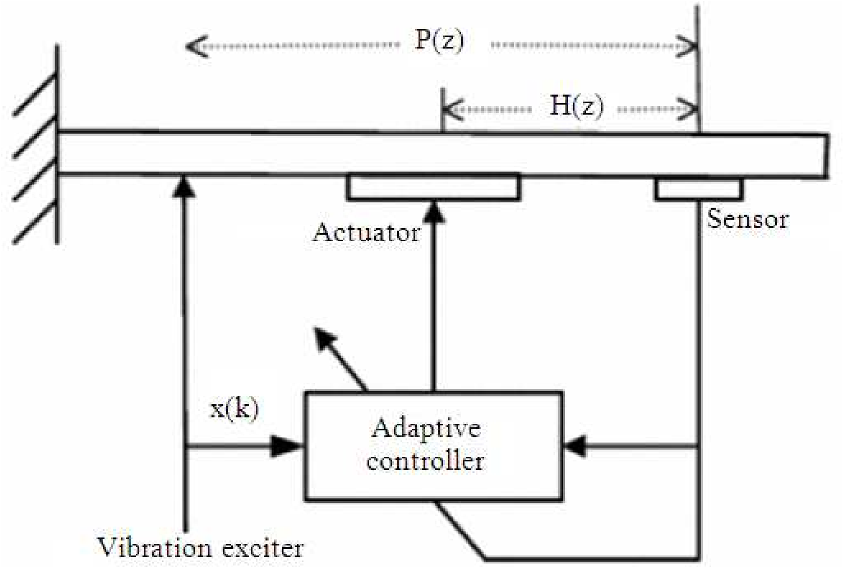

Fig. 3. Adaptive feed forward AVC using FxLMS algorithm

Therefore, the adaptive filter output y(n) has the same amplitude but is 180° out of phase with the primary noise d(n). When d(n) and y(n) are acoustically combined, the residual error becomes zero, resulting in cancellation of both sounds based on the principle of superposition.

In this study, a clamped-free aluminum flexible cantilever beam is considered with a length of 31 cm, a width of 2.6 cm and a thickness of 0.7 mm, respectively. The longitudinal modulus of elasticity of the aluminum cantilever beam was 69 GPa and the density of material was 2700 kg m^{-3}. The disturbance was applied vertically to the free end of the beam as a point force by using an impact hammer to obtain the natural frequencies experimentally.

2.4. System Modeling

There are number of natural frequencies present in any flexible structure when it is subjected to vibratory forces and moments. These vibratory forces and moments will excite the natural frequencies of the beam and whenever these forcing frequencies coincide with the natural frequencies of the beam, the resonance condition occurs and the beam is subjected to large amplitudes of vibration causes structural failure. In particular, these vibratory forces and moments will excite the natural frequencies of the beam predominantly the lowest three modes.

It is therefore required to determine the natural frequencies of the beam using experimentally and analytically by finite element analysis method. In the present study, the first three natural frequencies of the beam are computed using finite element analysis software ANSYS. The cantilever beam is modeled as one end fixed and the other end is left free as shown in **Fig. 4**.

It is also calculated the modal frequencies of the cantilever beam by using the empirical formula given below:

$$f_n = \frac{\omega_n}{2\pi} \text{Hz}$$

Where:

$$\omega_n = A\sqrt{\frac{EI}{\mu I^4}}$$

ωn = Circular frequency in rad/sec,
A = Constant = 3.52, 22, 61.5
E = Young’s modulus of the material in N/m2,
I = Moment of inertia of the beam in m4,
M = Mass/Length, in
Kg/m, = Length of the beam in meters

The other modal frequencies of the beam for different mode shapes were calculated theoretically by varying the constant A. By the above method the modal frequencies were calculated and compared with ANSYS and Experimental Results are given in **Table 1**.

2.5. Experimental Natural Frequencies

The experimental procedure consisted of finding out the natural frequencies of the cantilever beam by exciting it with an impact hammer and measuring the frequency response function at the specified position for obtaining the first three natural frequencies of the beam system. When the beam was excited with an impact hammer at the free end and the natural frequencies of the beam are found to be 25Hz, 153Hz and 416Hz, respectively as shown in **Fig. 5** and are also tabulated in **Table 1**.

2.6. Performance Evaluation of AVCS

An experiment was setup for a case study of an aluminium cantilever beam subjected to the sinusoidal vibration with the help of a sine generator was tested and evaluated using the active vibration control system developed for reducing vibration of one of the natural frequency of a flexible cantilever beam is shown in **Fig. 6**. The beam is clamped at one end and the other end is free. A shaker placed close to the root is used to excite the beam. The error signal (response) of the beam is measured by a piezoelectric accelerometer sensor. Another electromagnetic actuator (shaker) is located near the clamped end, where the maximum strain is induced. An accelerometer placed very near to the actuating point is used for picking up the reference signal. To minimise the effect of the shakers on the structure, they are attached to the beam through stingers. These serve to isolate the shakers from the structure, reduce the added mass and cause the force to be transmitted axially along the stingers. The control shaker is attached to the beam firmly; but the primary shaker simply pushes up against the beam. The resulting preload is used to maintain contact between the control shaker and the beam. The objective of the AVC system is to minimise the vibration of the beam at the error sensor location.

Vibration source signal was generated by the sine generator (B&K, Type 1023) and sent to the power amplifier (B&K, Type 2712) which feeds that signal to the vibration exciter (B&K, Type 4809) to excite the flexible cantilever beam at one of the natural frequency of the beam. The response of the cantilever beam was measured by an accelerometer (B&K, Type 4507 B003) and sent to the Active vibration controller developed using EZANC controller with DSP processor and loaded in the ADSP2181 real-time processor.

Table 1. Comparison of natural frequencies

	Natural frequency [Hz]		
Mode	ANSYS	Empirical formula	Experimental
1.	25.641	25.5	25
2.	160.610	159.5	153
3.	449.630	447.3	416

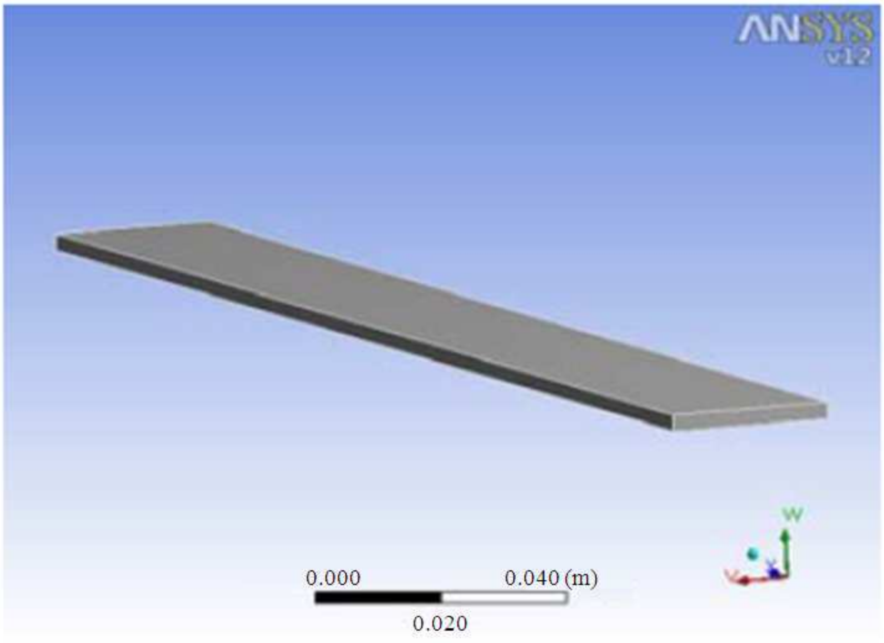

Fig. 4. Cantilever beam modal using ANSYS

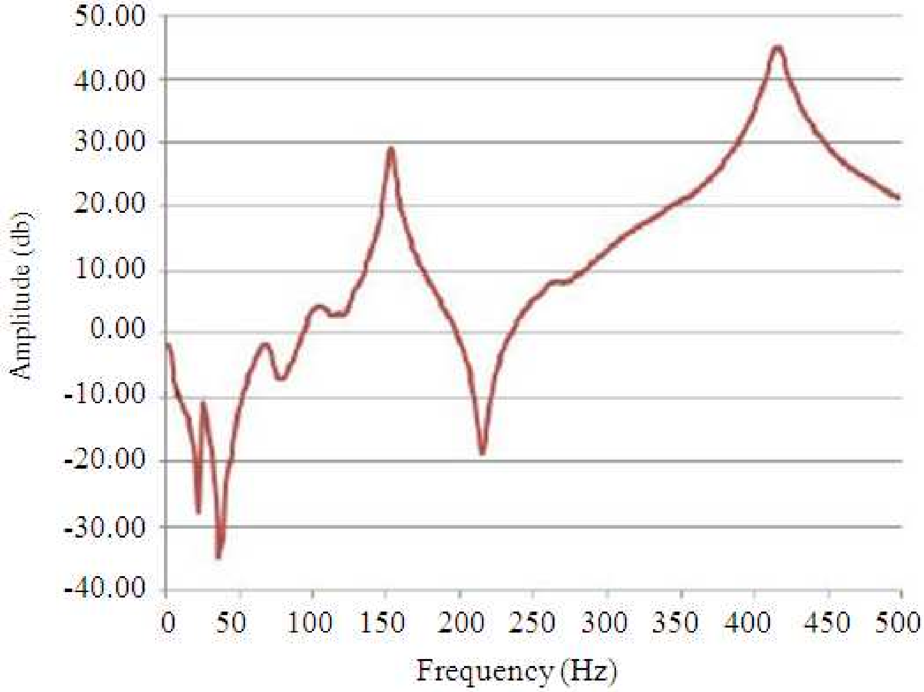

Fig. 5. Natural frequencies of cantilever beam

Controller produced the control (anti-vibration) signal to the response from the accelerometer and was sent to another power amplifier (B and K, Type 2706) which feeds that signal to the vibration exciter (B and K, Type 4809) used to control the vibrations occurred in the beam due to sinusoidal vibration signal generated by sine generator.

3. RESULTS

The authors have developed and tested an embedded computer based active vibration control system as shown in **Fig. 6**. The cantilever beam is vibrating with a sinusoidal vibration at a frequency of 153Hz is chosen as the excitation source signal since it is one of the dominant natural frequencies of the beam. The primary vibration source is picked up by the reference accelerometer and is fed to the AVCS, while the control signal is extracted from the second output channel of the signal generator and the Single Input Single Output (SISO) vibration control experiment is carried out. Control is achieved by changing the phase of the control signal generated through a secondary exciter and the control performance is monitored as shown in **Fig. 7**. The active vibration control system results indicate that more than 20dB of vibration reduction is achieved for sinusoidal vibration at one of the natural frequency of the flexible cantilever beam structure. In **Fig. 7** the blue color signal indicates the error sensor response, i.e., the response after the secondary source and the other signal indicates the reference signal (primary excitation source), which is picked up by the reference accelerometer. Since there is no control signal fed to the secondary actuator, the beam vibrates and the amplitude of vibration is shown in Peak-Peak acceleration.

4. DISCUSSION

The embedded computer based active vibration control system for reducing sinusoidal vibration of a flexible cantilever beam structure is developed. The present configuration demonstrates single input single output adaptive feed forward active vibration control system using filtered x LMS algorithm with FIR filter. The experimental results showed that control has been achieved because of the opposite phase of the secondary input to the beam. The frequency data of the error signal before and after the control when the beam was excited by at a tonal frequency of 153Hz was achieved. The red colored curve indicates when AVC system OFF and Blue colored curve indicates when AVC ON.

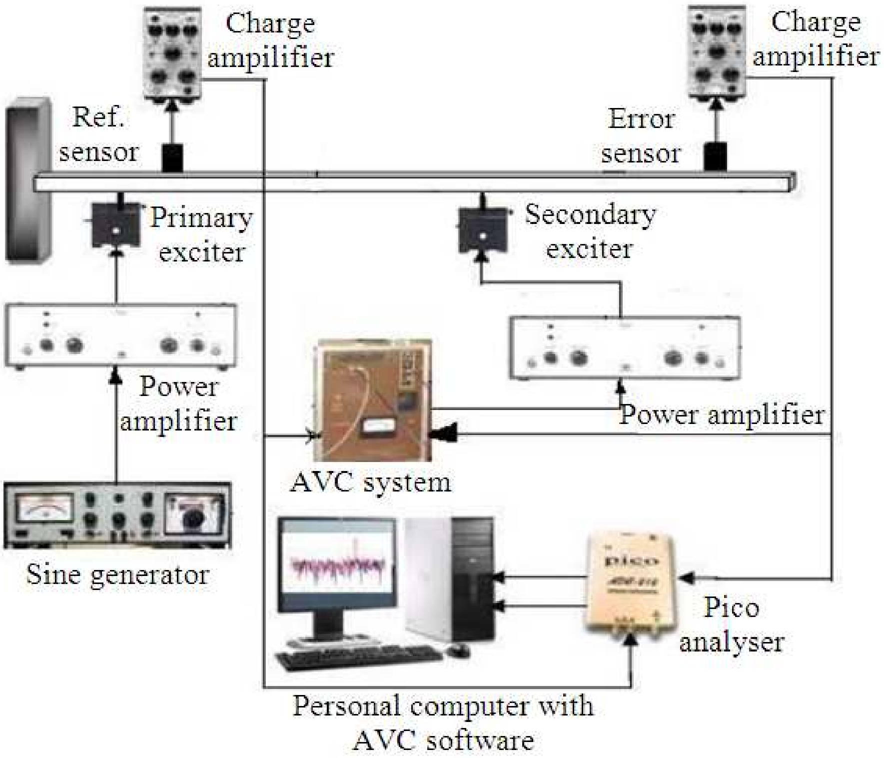

Fig. 6. Experimental setup for evaluation of AVCS

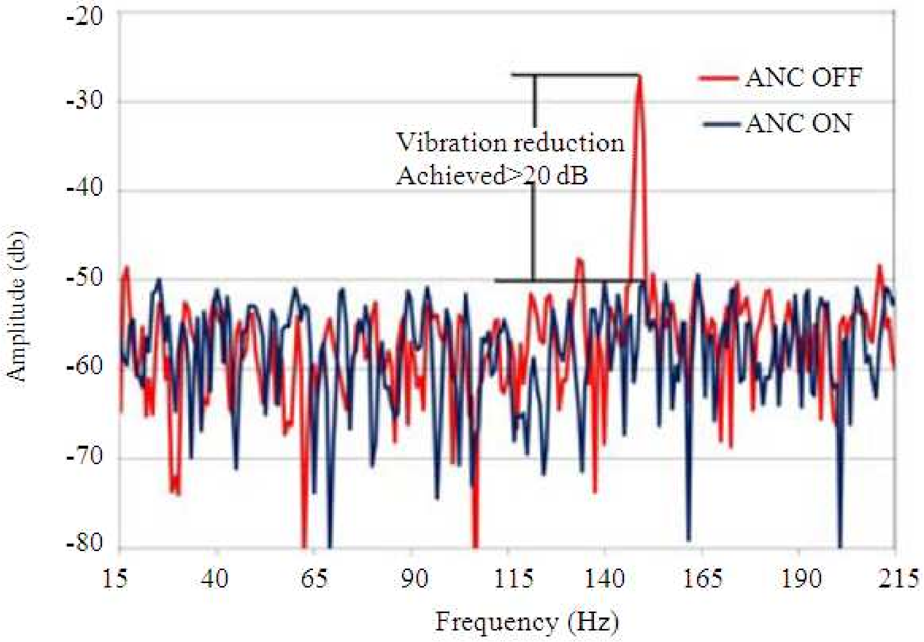

Fig. 7. Experimental results of AVCS

5. CONCLUSION

An effective, adaptable and real-time AVC system to suppress noisy sinusoidal vibrations of a cantilever beam has been achieved. The efficiency of this controller is shown through experimental verification. This AVC system could be used for real life applications like machining chatter suppression because it is widely known that chatter signals have harmonic shapes and their frequencies are around the respective natural frequencies of the machining systems. Moreover, some tools, e.g., a boring bar, can be modeled as some cantilever beams.

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