Active Vibration Control: An Experimental Investigation Using PD Controller and Lab VIEW

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Vibrations can be reduced by applying mass damping and stiffness on suitable locations on a structure that is known as Passive vibration reduction. These techniques include traditional vibration dampers, shock absorbers, and base isolation. But these techniques result in increased weight and low response. So, the mechanical vibrations induced in light weight aerospace and large-scale flexible structures have attracted engineers to investigate and develop materials to suppress these vibrations. Piezoelectric materials can be used as sensors and actuators for vibration control because of low mass, high actuating force and fast response. The discipline of vibration engineering is becoming increasingly more important because of higher machinery speeds, operational loads, compact and lightweight designs, and engineered materials. Experimental work is evolving very rapidly with the advent of high speed processors, signal processing and control modules, smart sensors and actuators, and digital instrumentation in general. Now this area can be viewed as truly interdisciplinary since it includes the elements of many branches of engineering and physical sciences.

Kaywords : Traditional vibration dampers, Shock absorbers and isolation.

I. INTRODUCTION

Active vibration control : It is the active application of force in an equal and opposite fashion to the forces imposed by external vibration. With this application, a precision industrial process can be maintained on a platform essentially vibration-free. Many precision industrial processes cannot take place if the machinery is being affected by vibration. For example, the production of semiconductor wafers requires that the machines used for the photolithography steps be used in an essentially vibration-free environment or the sub-micrometer features will be blurred. Active vibration control is now also commercially available for reducing vibration in helicopters, offering better comfort with less weight than traditional passive technologies.

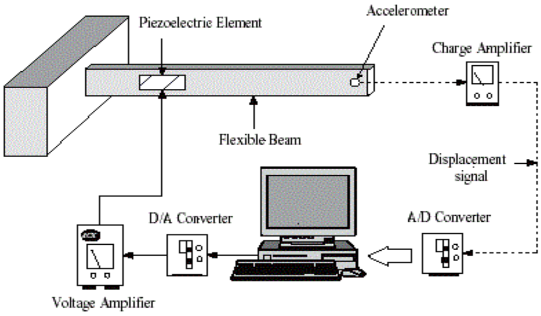

Fig.1 : Schematic diagram for Active Vibration Control

Smart structures

A Smart structure (also known as an active or adaptive structure) is a mechanical structure with the ability to alter its configuration, form or properties in response to changes in the environment. The term active structure also refers to structures that, unlike traditional engineering structures (e.g. bridges, buildings), require constant motion and hence power input to remain stable. The advantage of active structures is that they can be far more massive than a traditional static structure: an example would be a space fountain, a building that reaches into orbit.

Function

The result of the activity is a structure more suited for the type and magnitude of the load it is carrying. For example, an orientation change of a beam could reduce the maximum stress or strain level, while a shape change could render a structure less susceptible to dynamic vibrations. A good example of an adaptive structure is the human body where the skeleton carries a wide range of loads and the muscles change its configuration to do so. Consider carrying a backpack. If the upper body did not adjust the centre of mass of the whole system slightly by leaning forward, the person would fall on his or her back.

An active structure consists of three integral components besides the load carrying part. They are the *sensors*, the *processor* and the *actuators*. In the case of a human body, the sensory nerves are the sensors which gather information of the environment. The brain acts as the processor to evaluate the information and decide to act accordingly and therefore instructs the muscles, which act as actuators to respond. In heavy engineering, there is already an emerging trend to incorporate activation into bridges and domes to minimize vibrations under wind and earthquake loads.

Aviation engineering and aerospace engineering have been the main driving force in developing modern active structures. Aircraft (and spacecraft) require adaptation because they are exposed to many different environments, and therefore loadings, during their lifetime. Prior to launching they are subjected to gravity or dead loads, during takeoff they are subjected to extreme dynamic and inertial loads and in-flight they need to be in a configuration which minimizes drag but promotes lift. A lot of effort has been committed into adaptive aircraft wings to produce one that can control the separation of boundary layers and turbulence. Many space structures utilize adaptivity to survive extreme environmental challenges in space or to achieve precise accuracies. For example, space antennas and mirrors can be activated to precise orientation. As space technology advances, some sensitive equipment (namely interferometric optical and infrared astronomical instruments) are required to be accurate in position as delicate as a few nanometers, while the supporting active structure is tens of meters in dimensions.

Design

Man-made actuators existing in the market, even the most sophisticated ones, are nearly all one dimensional. This means they are only capable of extending and contracting along, or rotating about 1 axis. Actuators capable of movement in both forward and reverse directions are known as two-way actuators, as opposed to one-way actuators which can only move in one direction. The limiting capability of actuators has restricted active structures to two main types: *active truss structures*, based on linear actuators, and *manipulator arms*, based on rotary actuators.

A good active structure has a number of requirements. First, it needs to be easily actuated. The actuation should be energy-saving. A structure which is very stiff and strongly resists morphing is therefore not desirable. Second, the resulting structure must have structural integrity to carry the design loads. Therefore the process of actuation should not jeopardize the structure's strength. More precisely, we can say: We seek an active structure where actuation of some members will lead to a geometry change without substantially altering its stress state. In other words, a structure that has both static determinacy and kinematic determinacy is optimal for actuation.

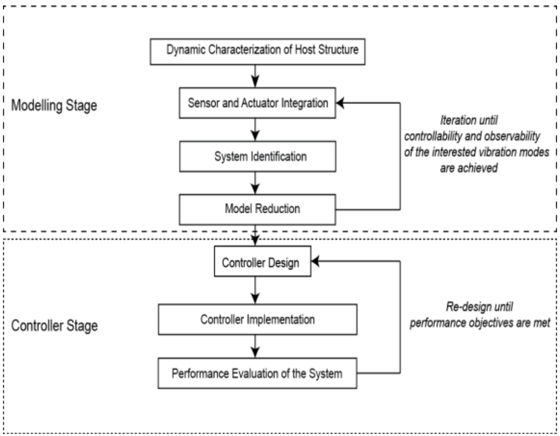

Fig.2 : Smart structure design methodology

II. PIEZOELECTRICITY

Piezoelectricity is the ability of some materials such as crystals and certain ceramics, to generate an electric potential in response to applied mechanical stress or heat. If the piezo crystals are not short-circuited, the applied charge induces a voltage across the material. The word Piezo is derived from the Greek "Piezein", which means to squeeze or press. The piezo material exhibits both "Direct piezo electric effect" as well as 'Converse piezo electric effect". Direct piezo electric effect is the production of electricity when the crystals are mechanically stressed and the converse piezo electric effect is the stress or strain in the crystals when an electric potential is applied. The most common crystals used is lead zirconatetitanate crystals.

The Piezo effect finds many applications such as the production and detection of sound, generation of high voltages, electronic frequency generation, microbalances, and ultra fine focusing of optical assemblies. It is also the basis of a number of scientific instrumental techniques with atomic resolution, the scanning probe microscopies and everyday uses such as acting as the ignition source for cigarette lighters and push-start propane barbecues.

How it works?

In a piezoelectric crystal, the positive and negative electrical charges are separated, but symmetrically distributed. This makes the crystal electrically neutral. Each of these sides forms an electric dipole and dipoles near each other tend to be aligned in regions called "Weiss domains". The domains are usually randomly oriented, but can be aligned during poling, a process by which a strong electric field is applied across the material, usually at elevated temperatures.

When a mechanical stress is applied, this symmetry is disturbed, and the charge asymmetry generates a voltage across the material. In Converse piezoelectric effect, application of an electrical field creates mechanical deformation in the crystal. The most common application of piezo crystals to generate a potential is the electric cigarette lighter. Pressing the button of the lighter causes a spring-loaded hammer to hit a piezoelectric crystal, producing a sufficiently high voltage that electric current flows across a small spark gap, thus heating and igniting the gas. Some substances like quartz can generate potential differences of thousands of volts through direct piezo electric effect.

As a sensors

The principle of operation of a piezoelectric sensor is that a physical dimension, transformed into a force, acts on two opposing faces of the sensing element. Depending on the design of a sensor, different "modes" to load the piezoelectric element can be used: longitudinal, transversal and shear. Detection of pressure variations in the form of sound is the most common sensor application, e.g. piezoelectric microphones (sound waves bend the piezoelectric material, creating a changing voltage) and piezoelectric pickups for acoustic-electric guitars. A piezo sensor attached to the body of an instrument is known as a contact microphone.

Piezoelectric sensors especially are used with high frequency sound in ultrasonic transducers for medical imaging and also industrial nondestructive testing (NDT).

For many sensing techniques, the sensor can act as both a sensor and an actuator – often the term *transducer* is preferred when the device acts in this dual capacity, but most piezo devices have this property of reversibility whether it is used or not. Ultrasonic transducers, for example, can inject ultrasound waves into the body, receive the returned wave, and convert it to an electrical signal (a voltage). Most medical ultrasound transducers are piezoelectric.

In addition to those mentioned above, various sensor applications include:

- Piezoelectric elements are also used in the detection and generation of sonar waves.
- Power monitoring in high power applications (e.g. medical treatment, sonochemistry and industrial processing).
- Piezoelectric microbalances are used as very sensitive chemical and biological sensors.
- Piezos are sometimes used in strain gauges.
- Piezoelectric transducers are used in electronic drum pads to detect the impact of the drummer's sticks, and to detect muscle movements in medical acceleromyography.
- Automotive engine management systems use piezoelectric transducers to detect Engine knock (Knock Sensor, KS), also known as detonation, at certain hertz frequencies. A piezoelectric transducer is also used in fuel injection systems to measure manifold absolute pressure (MAP sensor) to determine engine load, and ultimately the fuel injectors milliseconds of on time.
- Ultrasonic piezo sensors are used in the detection of acoustic emissions in acoustic emission testing.

As an actuator

As very high electric fields correspond to only tiny changes in the width of the crystal, this width can be changed with better-than-µm precision, making piezo crystals the most important tool for positioning objects with extreme accuracy — thus their use in actuators. Multilayer ceramics, using layers thinner than 100 µm, allow reaching high electric fields with voltage lower than 150 V. These ceramics are used within two kinds of actuators: direct piezo actuators and Amplified piezoelectric actuators. While direct actuator's stroke is generally lower than 100 µm, amplified piezo actuators can reach millimeter strokes.

- Loudspeakers: Voltage is converted to mechanical movement of a piezoelectric polymer film.
- Piezoelectric motors: Piezoelectric elements apply a directional force to an axle, causing it to rotate. Due to the extremely small distances involved, the piezo motor is viewed as a high-precision replacement for the stepper motor.
- Piezoelectric elements can be used in laser mirror alignment, where their ability to move a large mass (the mirror mount) over microscopic distances is exploited to electronically align some laser mirrors. By precisely controlling the distance between mirrors, the laser electronics can accurately maintain optical conditions inside the laser cavity to optimize the beam output.
- A related application is the acousto-optic modulator, a device that scatters light off of soundwaves in a crystal, generated by piezoelectric elements. This is useful for fine-tuning a laser's frequency.
- Atomic force microscopes and scanning tunneling microscopes employ converse piezoelectricity to keep the sensing needle close to the probe.
- Inkjet printers: On many inkjet printers, piezoelectric crystals are used to drive the ejection of ink from the inkjet print head towards the paper.
- Diesel engines: High-performance common rail diesel engines use piezoelectric fuel injectors, first developed by Robert Bosch GmbH, instead of the more common solenoid valve devices.
- Active vibration control using amplified actuators.
- X-ray shutters.
- XY stages for micro scanning used in infrared cameras.
- Moving the patient precisely inside active CT and MRI scanners where the strong radiation or magnetism precludes electric motors.
- Crystal earpieces are sometimes used in old or low power radios

III. APPLICATIONS

1. In Energy Harvesting

We can generate energy by using Piezoelectric materials by accumulating energy due to vibrations generated.

2. As sensing elements

Detection of pressure variations in the form of sound is the most common sensor application, e.g. piezoelectric microphones. Sound waves bend the piezoelectric material, creating a changing voltage.

3. Ultrasound imaging

Piezoelectric sensors are used with high frequency sound in ultrasonic transducers for medical imaging .For many sensing techniques, the sensor can act as both a sensor and an actuator. Ultrasonic transducers, for example, can inject ultrasound waves into the body, receive the returned wave, and convert it to an electrical signal (a voltage).

4. Sonar sensors

Piezoelectric elements are also used in the detection and generation of sonar waves. Applications include power monitoring in high power applications such as medical treatment, sonochemistry and industrial processing etc.

5. As chemical and biological sensors

Piezoelectric microbalances are used as very sensitive chemical and biological sensors. Piezo are also used as strain gauges.

6. In Music instruments

Piezoelectric transducers are used in electronic drum pads to detect the impact of the drummer's sticks.

7. Automotive application

Automotive engine management systems use a piezoelectric transducer to detect detonation by sampling the vibrations of the engine block. Ultrasonic piezo sensors are used in the detection of acoustic emissions in acoustic emission testing.

8. Piezoresistive silicon devices

The Piezoresistive effect of semiconductors has been used for sensor devices employing all kinds of semiconductor materials such as germanium, polycrystalline silicon, amorphous silicon, and single crystal silicon. Since silicon is today the material of choice for integrated digital and analog circuits the use of Piezoresistive silicon devices has been of great interest. It enables the easy integration of stress sensors with Bipolar and CMOS circuits.

9. Piezoresistors

Piezoresistors are resistors made from a Piezoresistive material and are usually used for measurement of mechanical stress. They are the simplest form of Piezoresistive device.

IV. DESIGN OF CONTROLLER (PD)

PD controller is a type of PID controller, which can be used in the active vibration control. Besides this PD, PI, POF, LQR, LQG controllers can also be used in this active vibration control. Each of these has some advantages as well as their limitations. We have to choose according to our application.

POF is a part of the PID control scheme which is named after its three correcting terms, whose sum constitutes the manipulated variable (MV). The proportional, integral, and derivative terms are summed to calculate the output of the PID controller. Defining $u(t)$ as the controller output, the final form of the PID algorithm is:

$$\mathrm{u}(t) = \mathrm{MV}(t) = K_p e(t) + K_i \int_0^t e(\tau)\, d\tau + K_d \frac{d}{dt} e(t)$$

But for only Proportional term it becomes,

u (t) = MV(t) = K_pe(t)

where

K_P: Proportional gain, a tuning parameter

K_i: Integral gain, a tuning parameter

K_d: Derivative gain, a tuning parameter

e: Error $= SP - PV$

t: Time or instantaneous time (the present)

τ : Variable of integration; takes on values from time 0 to the present t.

Proportional term

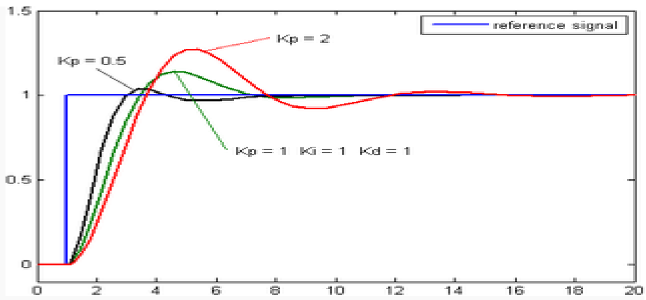

Fig.3 : Plot of PV vs time, for three values of K_p (K_i and K_d held constant)

The proportional term produces an output value that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant K_p, called the proportional gain constant.

The proportional term is given by:

$$P_{\mathrm{out}} = K_p\, e(t)$$

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable. In contrast, a small gain results in a small output response to a large input error, and a less responsive or less sensitive controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances. Tuning theory and industrial practice indicate that the proportional term should contribute the bulk of the output change.

Derivative term

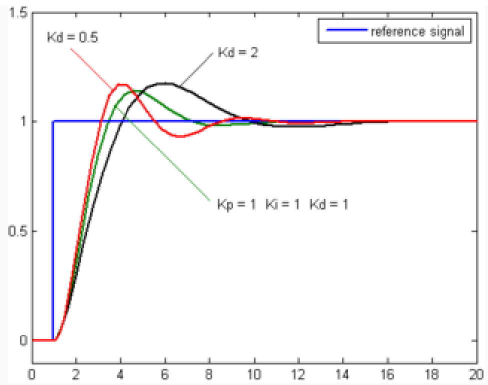

Fig.4 : Plot of PV vs time, for three values of K_d (K_p and K_i held constant)

The derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain K_d. The magnitude of the contribution of the derivative term to the overall control action is termed the derivative gain, K_d.

The derivative term is given by:

$$D_{\mathrm{out}} = K_d \frac{d}{dt} e(t)$$

Derivative action predicts system behavior and thus improves settling time and stability of the system.

Derivative action, however, is seldom used in practice because of its inherent sensitivity to measurement noise. If this noise is severe enough, the derivative action will be erratic and actually degrade control performance. Large, sudden changes in the measured error (which typically occur when the set point is changed) cause a sudden, large control action stemming from the derivative term, which goes under the name of *derivative kick*. This problem can be ameliorated to a degree if the measured error is passed through a linear low-pass filter or a nonlinear but simple median filter.

Proportional-derivative term :-

PD is a term in which the proportional and derivative terms as discussed above are taken. The Integral term is kept constant and thus a different type of PID controller known as PD controller is made up. The equation for a PD controller can be written as :

$$P_{out} = K_p e(t) + K_d \frac{d}{dt} e(t)$$

V. EXPERIMENTAL INVESTIGATION USING LABVIEW

The above table shows the material properties and dimensions of piezo-patch used in theexperiments. The block diagram is used to find out the frequency response of the cantilever plate in the labview.

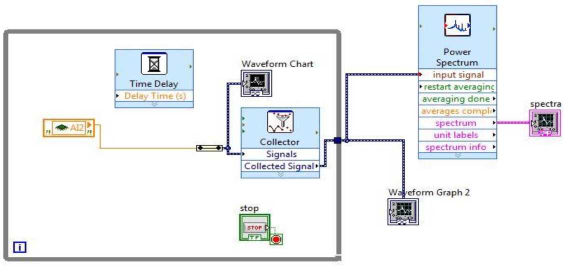

Fig.5 :LabVIEW block diagram for frequency response

AI2 is the DAQ card input which is the electrical output of piezo-patch, spectra showing the frequency response. The input graph of signal produced by piezo-patch is shown below.

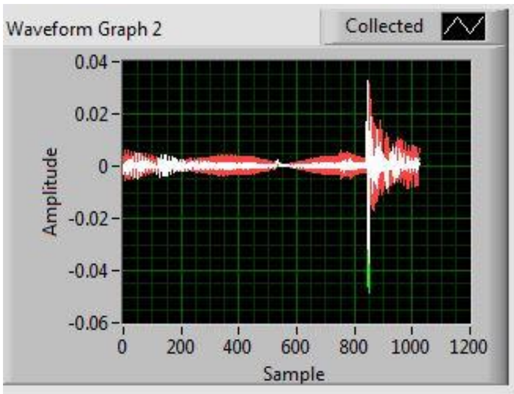

Fig.6: Input frequency response

The spectrum graph showing the natural frequency in labview is below

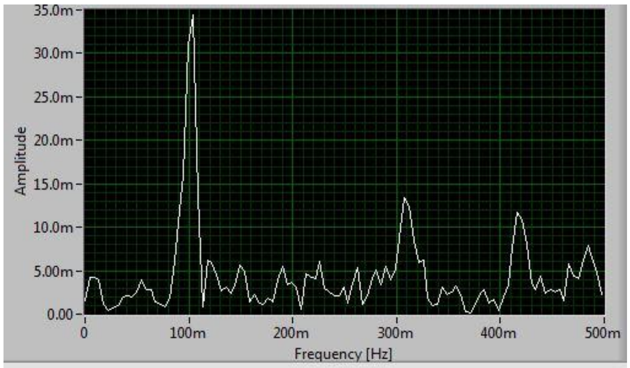

Fig.7: Spectural graph showing Natural frequency

The controller used is PD controller to give the actuator proper gain to produce the force to stop vibrations of the plate. The implementation of the pid controller in labview is shown in block diagram below

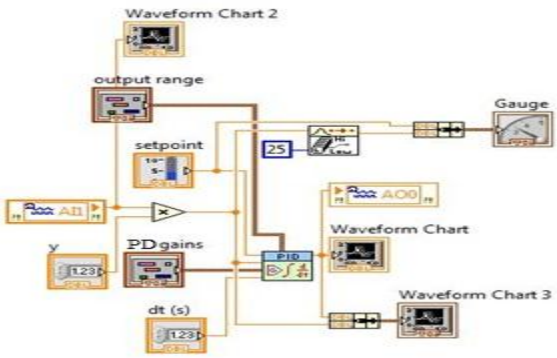

Fig.8 :LabVIEW block diagram for PD controller

In this we have taken AI1 as input and AO0 as output from controller. The corresponding control signals plate of the block diagram is shown below.

Equipments used

1. Computer system, in which Lab VIEW is installed.
2. An Aluminum plate (16x16 cm.)
3. Piezoelectric patches (PZT 5a)
4. Controller(Real time compactRio)
5. DAQ cards(NI9263,NI9234)
6. NI PS-15 power supply battery system
7. Amplifier
8. Connecting wires, Cables
9. Micrometer
10.
11. Epoxy adhesive

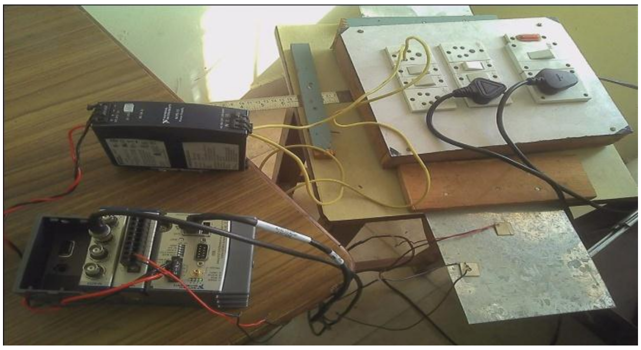

Fig.9 : Various equipments

Working

First of all, an aluminum plate of dimension (16x16 cm.) and thickness of 0.6 mm is fixed at one edge to make a cantilever plate structure. Now, piezoelectric patches are fixed up and below on the cantilever plate with the help of epoxy adhesive. The connections are made such that the upper piezo-patch worked as a sensor and lower as an actuator. The sensor piezo-patch is connected with the input DAQ card (NI9234) and the actuator piezo-patch is connected with the output DAQ card (NI9263) with the help of connecting cables. These DAQ cards are mounted on a real time compact RIO controller framed in a chassis. This controller is attached with NI PS-15 power supply battery system, which is connected with mains AC power supply. Now the compactRio controller is connected with Ethernet cable with computer system. Thus the all connections necessary for experiment can be made.

Fig. 10 :CompactRio real-time controller

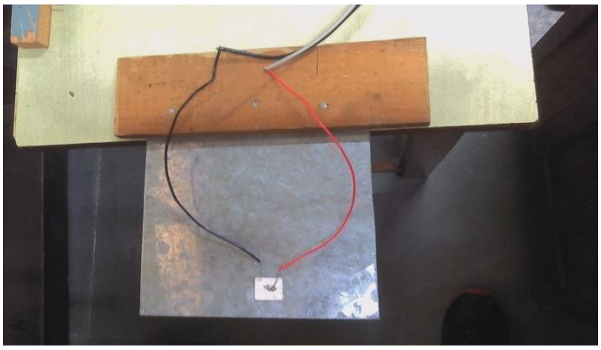

Fig.11 : Cantilever plate with piezo sensor

Now, the working in computer system can be explained as follows:

1. First, open Lab VIEW in the computer system.
2. Now, click on the create project and choose a blank project.
3. Make a sequential block diagram for PD controller used in the active vibration control.
4. The frequency responses are taken into account on the basis of given vibration pattern.
5. Now the input and output vibrations are achieved in waveform graphs on Lab VIEW by running it.
6. We see that the input and output frequencies are equal and opposite in nature.
7. Thus, the vibrations can be controlled by using PD controller.

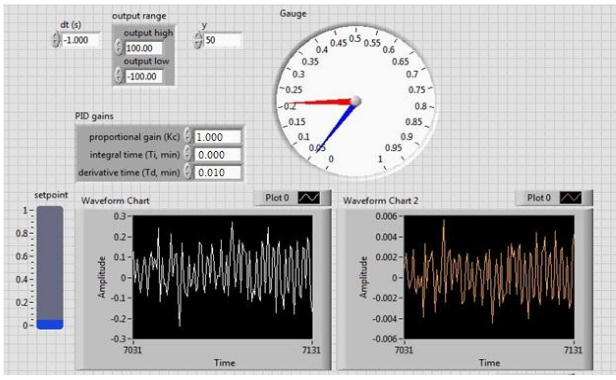

Fig. 12 :- Input and output waveforms in LabVIEW

The following graph is showing the input signal as well as corresponding control output. The white graph showing real time input and red one showing corresponding PD output.

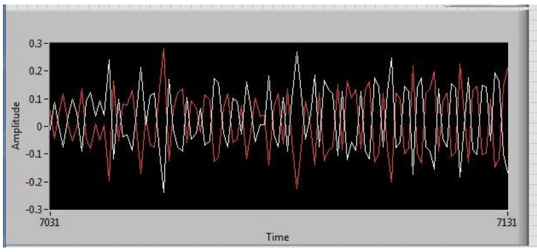

Fig.13 :- Real time input

VI. CONCLUSION

This work shows the basic technique for analysis of active vibration control using piezoelectric sensor and actuator. In this project work, the theoretical techniques to suppress the vibrations are studied, which are based on the finite element method, piezoelectric equations for sensor/actuator and PD controller. And then with the help of LabVIEW software, experimental results are obtained. The experimental work gives satisfactory and efficient results as compared to the theoretical.

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