



# Vibration Control of a Smart Cantilever Beam Using dSPACE

**Dr. M. Shanmugavalli<sup>1</sup>, Dr. M. Banu sundareswari<sup>2</sup>, K. Hariharan<sup>3</sup>,  
G. P. Jayakanthan<sup>4</sup>, R. Dhinesh<sup>5</sup>, D. Bharath Samvel<sup>\*6</sup>**

*<sup>1,2</sup> Professor, Department of Instrumentation and Control Engineering, Saranathan College of Engineering, India.*

*<sup>3,4,5,6</sup> Student, Department of Instrumentation and Control Engineering, Saranathan College of Engineering, India.*

\*Corresponding author

DoI: <https://doi.org/10.5281/zenodo.7876987>

---

## Abstract

Vibration of a smart beam is being controlled. This smart beam setup is comprised of actuators and sensors placed at the root of a cantilever beam. Numerous factors, including human action and nearby motorized equipment, can result in vibrations. In this instance, the actuator signal is used to create the disturbance. The piezoelectric sensors are used to detect the vibration. The PID(s) controller simultaneously transmits a control signal through dSPACE to the actuator through which the vibration can be reduced. Using Ziegler-Nichols, a PID controller is designed for flexible beam structure vibration suppression in order to maximize outcomes. The model of the system which includes the dynamics of the structure together with the sensor/actuator dynamics is obtained through on line system identification technique. The performance of the PID(s) controller is evaluated experimentally using dSPACE controller board.

**Keywords:** Vibration Control, dSPACE, Cantilever Beam, Piezoelectric, PID(s) Controller (simulink).

---

## 1. Introduction

More than three decades of research in the area of smart structures has shown the viability and potential of this technology. Numerous applications have been suggested, and many of them

---

have been experimentally imagined. Examples include the control of plate and beam vibrations, control of shape and buckling, and smart skis have been commercially realized. A smart structure has actuators and sensors built into the primary structure and will be controlled by a computer. [1].

Piezoelectric materials, which are used in many uses, are one type of adaptive material that can be incorporated with smart structures. Piezo ceramics are an efficient and high-quality actuation and sensing mechanism, and their use as actuators and sensors has significantly grown over the past 20 years. Piezo ceramics has several benefits, including affordability, the lack of moving parts, quick reaction, compactness, and simplicity of use. Compared to other smart materials, problems with signal conditioning, placement, and bonding are simple to solve with piezo ceramics.

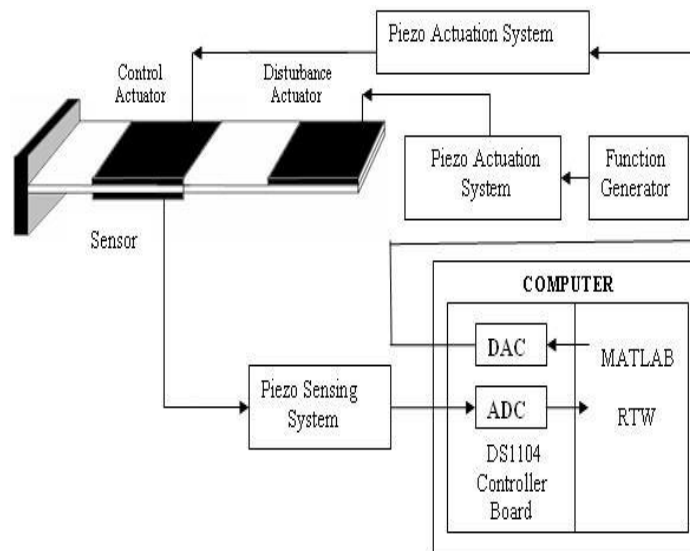
Vibration control of flexible structures by distributed sensors and actuators has been widely studied in the past decade and more dimensions are introduced to improve the control of structural behavior [2] [3]. The main design approach for systems form is the use of PID(s) controller. One tunes the controller to achieve a satisfactory dynamic response and develops the control signal for the closed-loop system that corresponds to satisfactory dynamic response. One has to design a controller for the states, because these are generally not measurable. This controller delivers the information about the states so that they can be used for control. The PID controller has been one of the most widely used tools for controlling.

However, early after its introduction, there are some drawbacks related to practical implementation issues. The tuned values , in the PID(s) computes the control signal, that actuates the beam.

Although previous works have clearly shown the tremendous potential of PID, its applications to vibration control of piezoelectric bonded structures have been limited. Therefore the objective of the present experimental work is to control with PID controller for smart structures.

The authors believe that the implementation of PID for vibration control of smart structures in real time using dSPACE is the first of its kind. (1)

## 2. Experimental Setup



**Figure.1.** Schematic diagram of the experimental set up

## 3. Hardware Description

### 3.1. dSPACE

The MATLAB Simulink tools depend on the dSPACE controller board in real-time implementation, which is a popular platform in academic research. dSPACE is a famous controller board, offering many advantages in terms of monitoring, controlling, and automating experiments and making the improvement of controllers more efficient.

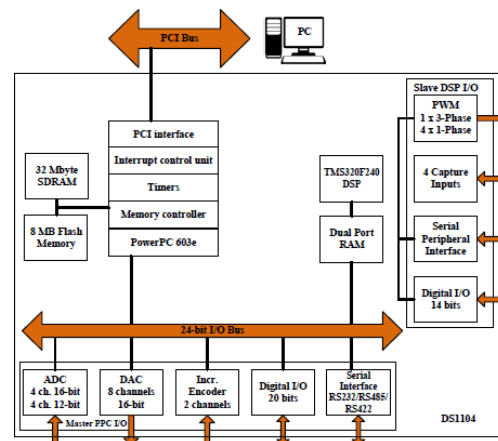
The DS1104 controller board with the best response in terms of a high memory space and faster implementation process was considered in this study. The properties of the DS1104 controller board are explained in Fig. 2.

This figure shows the general connection of the controller board with the personal computer and the converter (hardware). A photo of the DS1104 controller board is shown in Fig. 3, and the implementation flow of the dSPACE-based converter system is presented in Fig. 4.

Real-time interface (RTI) is the real-time adoption software for the dSPACE scheme that enhances the real-time C-code automation, faultlessly effects the dSPACE system and input/output hardware structure, and automatically creates, accumulates, connects, and performs the real-time C-code from the Simulink structure. Moreover, RTI produces a variable file corresponding to signals and parameters, and ControlDesk will contact this file and update the parameters.

With RTI, one may simply run the function models on the DS1104 controller board. It configures each I/O graphically by pulling RTI blocks and decreases the implementation time to a minimum. The DS1104 enhances personal computers (PCs) with a strong improvement scheme for faster control implementation.

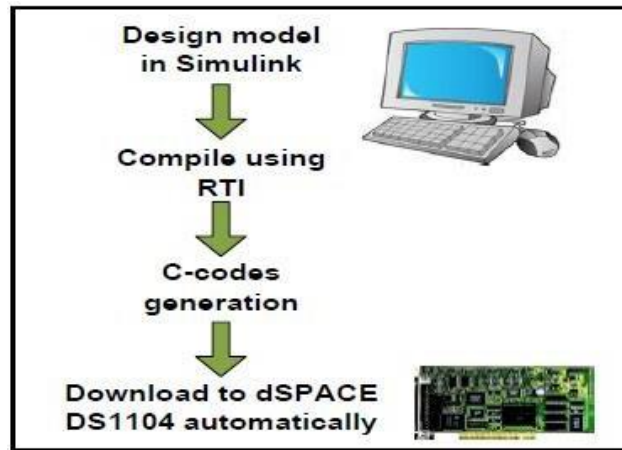
RTI produces Simulink blocks for the graphical structure of an analog-to-digital converter (ADC), a digital-to-analog converter (DAC), I/O lines, and PWM. Generally, the board may be installed in each PC with a free 5-V peripheral component interconnect (PCI) slot.



**Figure. 2.** Block diagram of the DS1104 controller board.



**Figure.3.** Photo of the DS1104 controller board.



**Figure. 4.** Flow of the implementation of the dSPACE-based converter system

There is a requirement for the signal conditioning circuits to be processed via the dSPACE controller board before feeding the signal. This requirement ensures that the voltage and current signals are specified in such a way that the levels match the ADC input range of the controller. Depending on the level condition of the input, the signal undergoes the process of reduction, amplification or current-to-voltage conversion. The signal conditioning consists of AC voltage and current conditioning circuits, and DC voltage conditioning, as depicted in Fig. 5.

The computer must be prepared with the dSPACE-associated software and hardware, namely, the ControlDesk (dSPACE 2008) software and the DS1104 controller board. Some of the parameters must be measured or tested properly to be set as inputs to the controller. For this purpose, the measurement and dissipation circuits are required.

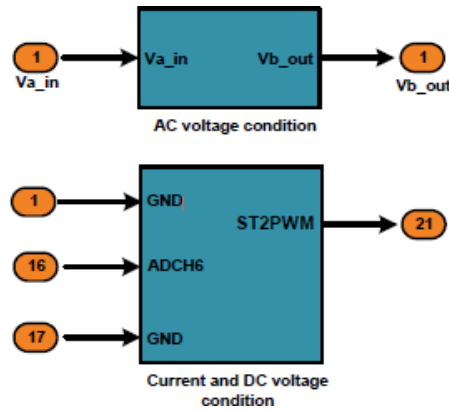


Figure. 5. Signal conditioning.

The implementation of the MATLAB/Simulink converter control technique simulated in real time is proficient with the use of the dSPACE DS1104 RTI. In doing so, the required dSPACE input-output library blocks are involved in the control technique. Fig. 6 shows the dSPACE 1104 card.

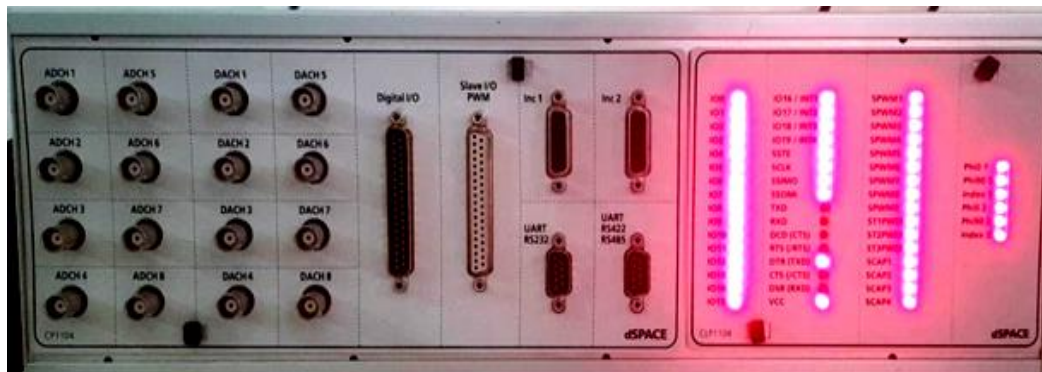


Figure.6. dSPACE 1104.

### 3.2. Design of Cantilever Beam

An aluminum cantilever beam with a piezoelectric sensor attached is used in this project. The cantilever beam has one end that is attached to a support setup and one end that is free. The cantilever beam used in this vibration control experiment is described in the following table in terms of its dimensions and material composition.

**Table.1.** Dimensions And Material Properties of Cantilever Beam

S. No	SYMBOL	PARAMETERS (with unit)	VALUES
1	L	Length (m)	0.35
2	B	Width (m)	0.025
3	H	Thickness (m)	0.003
4	P	Density (kg/m <sup>3</sup> )	2700
5	E	Young's Modulus (N/m <sup>2</sup> )	7.1*10 <sup>10</sup>
6	V	Poisson's Ratio (unit less)	0.34

### 3.3. Piezo-Electric Sensor

A piezoelectric sensor is a device which is used to measure the changes in the physical quantity such as (acceleration, temperature, force, etc.) into an electrical quantity (charge). In this project the piezoelectric sensor is fixed to the beam to sense the vibration occurred in the beam when it undergoes forced vibration. This signal is passed to the dSPACE to store the data in it and then it is monitored by using MATLAB programming. The dimension and material properties of the piezoelectric sensor is given below in the table.

**Table.2.** Dimensions and material properties of piezoelectric sensor

S. No	SYMBOL	PARAMETERS (with unit)	VALUES
1.	$L_p$	Length (m)	0.0765
2.	$B$	Width (m)	0.0127
3.	$T_a$	Thickness (m)	0.0005
4.	$E_p$	Young's Modulus (Gpa)	47.62
5.	$d_{31}$	Piezoelectric strain constant (mV <sup>-1</sup> )	-247x10 <sup>-12</sup>
6.	$g_{31}$	Piezoelectric stress constant (Vm <sub>N</sub> <sup>-1</sup> )	-9x10 <sup>-3</sup>
7.	$P\rho$	Density (kg/m <sup>3</sup> )	7500



## **4. Software Description**

### **4.1. Simulink**

Simulink is a graphical extension to MATLAB for modeling and simulation of systems. One of the main advantages of Simulink is the ability to model a nonlinear system, which a transfer function is unable to do. Another advantage of Simulink is the ability to take on initial conditions. When a transfer function is built, the initial conditions are assumed to be zero.

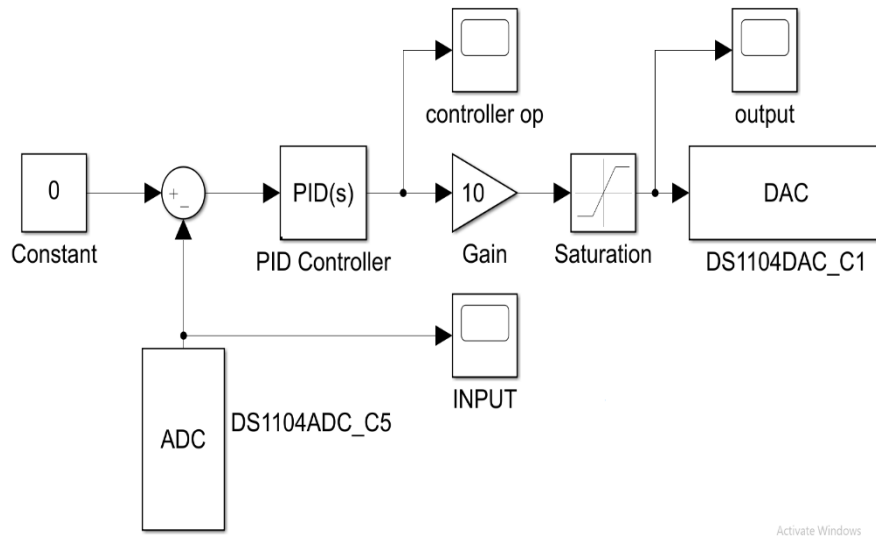
In Simulink, systems are drawn on screen as block diagrams. Many elements of block diagrams are available, such as transfer functions, summing junctions, etc., as well as virtual input and output devices such as function generators and oscilloscopes.

Simulink is integrated with MATLAB and data can be easily transferred between the programs. In these tutorials, we will apply Simulink to the examples from the MATLAB tutorials to model the systems, build controllers, and simulate the systems. Simulink is supported on Unix, Macintosh, and Windows environments; and is included in the student version of MATLAB for personal computers.

The idea behind these tutorials is that you can view them in one window while running Simulink in another window. System model files can be downloaded from the tutorials and opened in Simulink.

You will modify and extend these systems while learning to use Simulink for system modeling, control, and simulation. Do not confuse the windows, icons, and menus in the tutorials for your actual Simulink windows.

Most images in these tutorials are not live - they simply display what you should see in your own Simulink windows. All Simulink operations should be done in your Simulink windows.



**Figure.7.** Simulink of Vibration Control

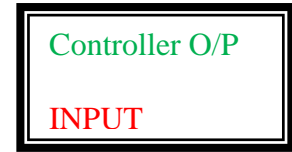
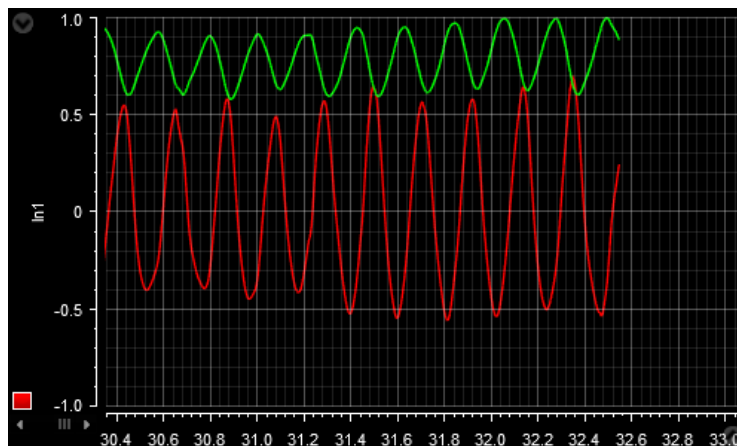
Control Desk is the dSPACE experiment software for seamless ECU development. It performs all the necessary tasks and gives you a single working environment

- Integrated ECU calibration, measurement and diagnostics access (CCP, XCP, ODX)
- Synchronized data capture across ECUs, RCP and HIL platforms, and bus systems
- Powerful layouting, instrumentation, measurement and post-processing (ASAM MDF)

Control Desk unites functionalities that often require several specialized tools.

It provides access to simulation platforms as well as to connected bus systems and can perform measurement, calibration and diagnostics on ECUs, e.g., via standardized ASAM interfaces.

Its flexible modular structure provides high scalability to meet the requirements of specific application cases. This gives you clear advantages in terms of handling, the amount of training needed, the required computing power, and costs.



**Figure.8.** Control Desk 7.2 Vibration Control

## 5. Modeling Structure

Control design of flexible structures relies on accurate modeling of the system dynamics. The analytical- model-based approaches have been highly doubtful under high precision requirements because of the difficulty in simulating the properties of these complicated systems.

The finite-element model- based methods are usually time consuming and their applications for accurate control are sometimes hindered by factors such as the assumption of perfect bonding at the interface between the structure and transducers. In most cases, these traditional modeling approaches are intractable and even impossible for highly complex structures. Hence, the unknown parameters of the smart structure dynamics are estimated using an online system identification method, which is proven to be more universal and feasible than analytical and numerical models for the present system [3].

The recursive least squares (RLS) method based on the Auto Regression with extra inputs (ARX) model is used here for linear system identification, which is easy to implement and has fast parameter convergence. In this paper, the state space model of the system based on

the work in [4] is considered for the design of controller.

$$\mathbf{X} = \mathbf{A}\mathbf{x} + \mathbf{b}u + \mathbf{e}r ; \mathbf{y} = \mathbf{cT}\mathbf{x}$$

where  $x$  is the state vector,  $u$  is the control signal,  $y$  is the sensor output,  $A$ ,  $B$ ,  $C$  are respectively the state, the input, the output matrices.

The controller design to suppress the vibration at resonance involves five steps. First is the design of state estimator, the state feedback gain calculation[6], transfer function obtaining, root locus plot and PID tuning using Ziegler-Nichols method.

### 5.1. Design of information filter

The information filter is designed to estimate the unknown states of the structure. For the design of estimator the continuous system model given in equation is discretized at a sampling interval of 0.01 sec. The initial values are chosen to be  $R=1, Q=1 \times I_4$  and zero initial states.

### 5.2. State feedback gain calculation

The state feedback controller is designed using pole placement to reduce the amplitude of vibration of a cantilever beam at resonance. Let  $(\Phi, F)$  be the discrete time system obtained by sampling the system in equation at a sampling interval of 0.01 seconds.

A stabilizing state feedback gain is obtained such that the eigen values of  $(\Phi + \Gamma F)$  are not at origin [10]. The state feedback gain obtained is

$$F = [16.2346 \quad -7.7462 \quad 11.0017 \quad 61.2536]$$

The corresponding closed loop poles of the system  $(\Phi + FF)$  are  $-0.38 \pm j0.88, 0.887 \pm j0.29$ .

### 5.3. Obtaining transfer function

The transfer function was obtained by matlab coding using the formula “ $tf=C*[SI - A]^{-1} *B$ ” giving the matrices as input.

transferFunction =

$$\frac{0.2046 s^3 + 48.02 s^2 + 9124 s - 1.322e05}{s^4 + 0.9625 s^3 + 4.271e04 s^2 + 2.038e04 s + 4.242e07}$$

Continuous-time transfer function.

Simplified transferFunction =

$$\frac{0.2046 s^3 + 48.02 s^2 + 9124 s - 132200}{s^4 + 0.9625 s^3 + 42710 s^2 + 20380 s + 424200000}$$

#### 5.4. Root locus plot

Root locus of the obtained transfer function was plotted using matlab coding and the gain and frequency

value was obtained.

Gain(Ku)= 1.03e+03 or 1030

Frequency( $\omega$ )= 125 rad/secs

#### 5.5. Tuning of PID

Tuning of the PID has done using the Ziegler-Nichols method.

#### Calculations:

$$Pu = 2\pi/\omega = 2\pi/125 = 0.05024$$

$$Ku = 1030 \quad Pu = 0.05024$$

**Table.3.** PID tuned values by Ziegler-Nichols method

Type of Control	K <sub>P</sub>		T <sub>I</sub>		K <sub>I</sub>		T <sub>D</sub>		K <sub>D</sub>	
<b>PID</b>	0.6*Ku	618	Pu/2	0.02512	KP/TI	24601.911	Pu/8	0.00628	KP*KD	3.88104

**6. Natural Frequency of a Beam**

1) Natural Frequency (fn) =  $\frac{1}{2\pi} \sqrt{\left(\frac{K}{m}\right)}$  Hz

(i)m->model mass of the beam(kg)

2) Moment Of Inertia (I) =  $\frac{bh^3}{12} m^4$

Where,

(i) b->Breadth(m)

(ii) h->Height(m)

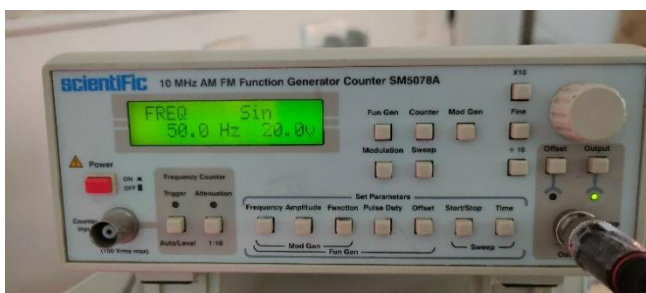
(iii)l->Length(m)

3) Beam Stiffness (K) =  $\frac{3EI}{l^3}$  (N/m<sup>2</sup>)

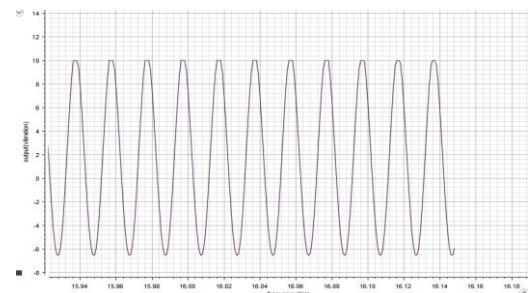
(i) E->Young’s modulus

**Calculations:**

- Moment of Inertia (I) =  $\frac{bh^3}{12}$
- Moment of Inertia (I) =  $5.625 \times 10^{-10} m^4$
- Beam Stiffness (K) =  $\frac{3EI}{l^3}$
- Beam Stiffness (K) =  $279.446041 (N/m^2)$
- Natural Frequency(fn) =  $\frac{1}{2\pi} \sqrt{\left(\frac{K}{m}\right)}$
- Natural Frequency(fn) =  $51.228008 Hz$



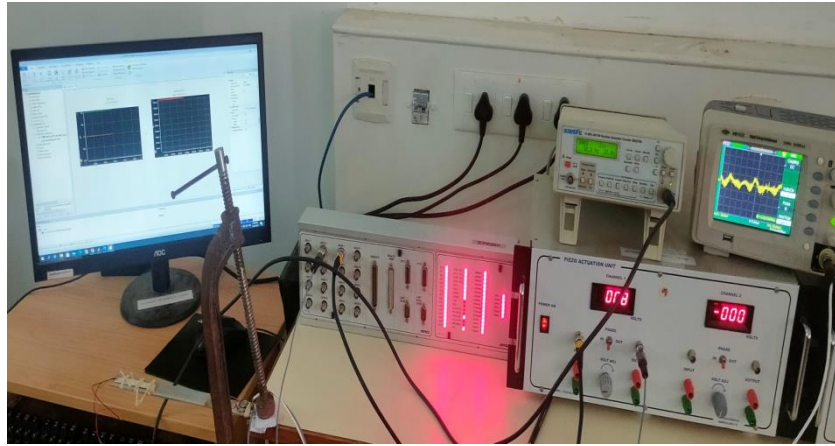
**Figure.9.** AFO Input



**Figure.10.** O/P in dSPACE

## 7. Experimental Setup/Hardware Prototype

The below figure depicts the hardware prototype that has been developed to realize the proposed methodology. The tests were conducted using the below experimental setup.



**Figure.11.** Experimental Setup

## 8. Operation

A flexible aluminum beam with fixed clamped end as shown in figure 2.1 is considered in this paper. Two piezo ceramic patches are surface bonded at a distance of 5mm from the fixed end of the beam. The patch bonded on the bottom surface acts as a sensor and the one on the top surface acts as an actuator. To apply an excitation to the structure another piezo ceramic patch is bonded on the tip of the beam. The piezo ceramics are electrode with fixed-on adherent silver of solderable quality.

Electrical contacts to the electrodes are made by soldering. This makes fragile piezo ceramics much easier to work with and easier to integrate into the structure. The sensor output is given to the piezo sensing system which consists of high quality charge to voltage converting signal conditioning amplifier with variable gain.

The conditioned piezo sensor signal is given as analog input to dSPACE1104 controller board. The control algorithm is developed using simulink software and implemented in real time on dSPACE 1104 system using RTW and dSPACE real control block diagrams and real time workshop is used to generate C code from the simulink model. The C code is then converted to target specific code by real time interface and target language compiler supported by dSPACE1104. This code is then deployed on to the rapid prototype hardware system to run hardware in-the-loop simulation. The control signal generated from simulink is interfaced to piezo actuation system through configurable analog input/output unit of dSPACE 1104 system. The piezo actuation system drives the actuator and the excitation signal is applied from simulink environment through a DAC port of dSPACE system.

## 9. Result

The PID(s) controller designed using zigler-Nichols in section IV to suppress the vibration. The sensor output is sampled at 0.01 sec through ADC port of dSPACE and MATLAB/simulink to generate a control signal. The output of the controller is compared with the plant constant.

The control signal, comparison between the plant ADC signal and constant. One can see that the output almost matches with the plant output and showing the better performance and ease of implementation with PID(s) using dSPACE. The control signal is generated by multiplying with gain and is applied to the control actuator through DAC port of dSPACE controller board.

The controller is implemented by developing a real time simulink model using MATLAB RTW in simulink. To show the performance of the controller, the beam is continuously vibrating using AFO with natural frequency of 50Hz. Constant (0) given as setpoint. ADC converts the analog input into digital which will be given by function generator to piezo which is paste on the beam. Analog signal 20V,50Hz given through ADC channel 5 in dSPACE. Constant and ADC signals are compared by comparator. PID(s) continuous controller, which was tuned by Ziegler-Nichols method. PID(s) controller generates a control signal which was multiplied by a gain(10) to amplify a signal. Saturation point is given as  $\pm 5$ . Digital signals are converted



into analog using D/A converter. Analog signal are taken from the DAC channel 1 to suppress a beam.

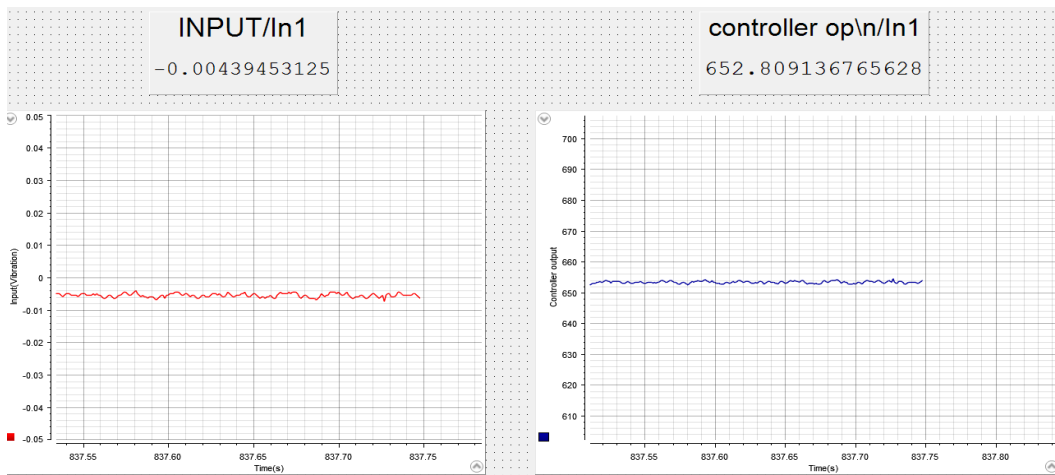


Figure.12. Before Input to the beam

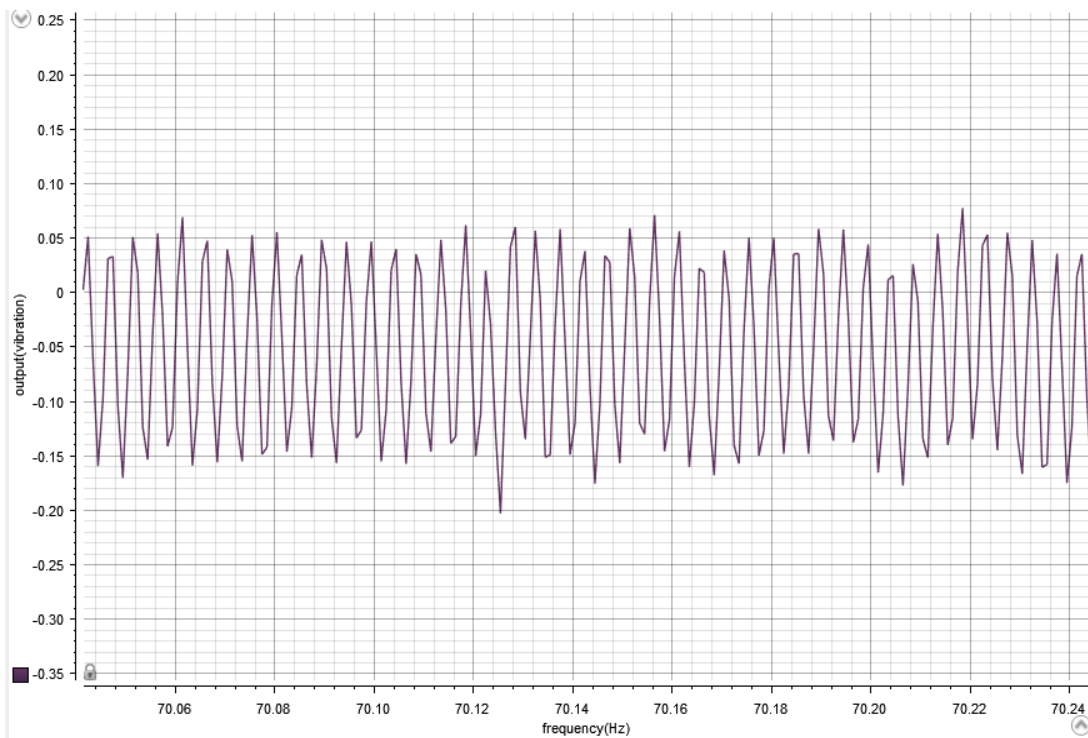
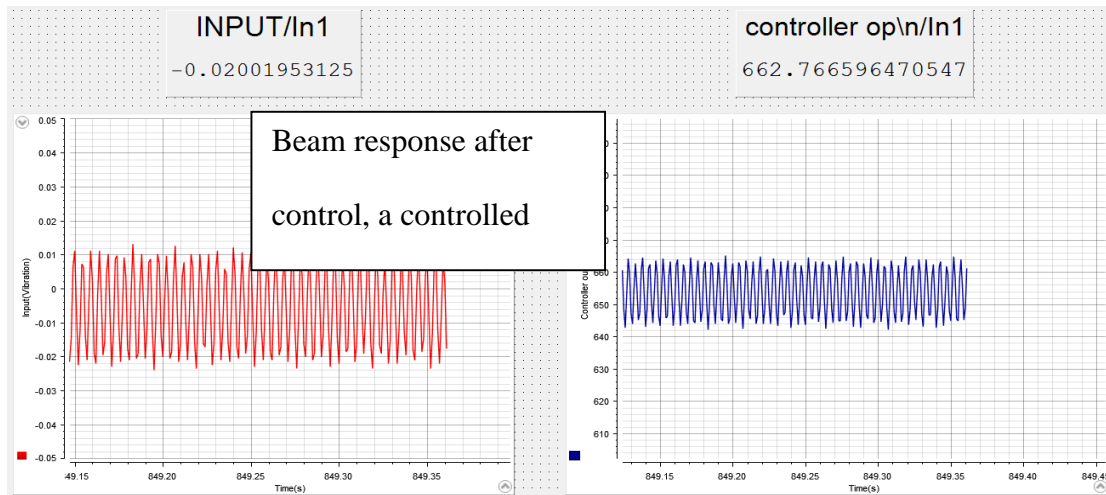


Figure.13. Beam response before control



**Figure.14.** Experimental results with PID controller

## 10. Conclusion

This paper presents an experimental evaluation of PID controller for vibration suppression of smart cantilever beam using the tuned values obtained from Ziegler-Nichols method. From the experimental results it is observed that vibration reduction is 66.7% (approx.). The experimental results demonstrate very good closed loop performance and simplicity of the PID(s)

## REFERENCES

- [1]. Mark A. Kamel, Khalil Ibrahim, Abo El-Makarem Ahmed, "Vibration control of smart cantilever beam using finite element method", Alexandria Engineering Journal (2019) 58, 591–601.
- [2]. D.Ezhilarasi, M.Umapathy, B.Bandyopadhyay, "Design and experimental evaluation of simultaneous fast output sampling Haigen Yang," Vibration Control for a Cantilever Beam with an Eccentric Tip Mass Using a Piezoelectric Actuator and Sensor", International Journal of Acoustics and Vibration, Vol. 22, No. 1, 2017.
- [3]. Huang, Z.; Huang, F.; Wang, X.; Chu, F. Active, "Vibration Control of Composite Cantilever Beams". Materials 2023, 16, 95.
- [4]. Shanmugavalli M, Pranav Kumar S, Suriya Prakaash D, Kabileshwaran R and Sathish Kumar M, "Vibration Monitoring and analysis using dSPACE Card", International Journal of Multidisciplinary Research Transactions (A Peer Reviewed Journal) Issue 6, 2022 ISSN (Print) : 2663-2381 ISSN(Online) : 2663-4007.
- [5]. Khalil Ibrahim, Abdel Badie Sharkawy, "A hybrid PID control scheme for flexible joint manipulators and a comparison with sliding mode control", Ain Shams Eng. J. 9 (2018) 3451–3457.
- [6]. S. Khot, N.P. Yelve, R. Tomar, S. Desai and S. Vittal, "Active vibration control of cantilever beam by using PID based output feedback controller", J. Vib. Control 18 (2012) 366–372.
- [7]. A. Ebrahimi-Tirtashi, S. Mohajerin, M. R. Zakerzadeh & M. A. Nojoomian, "Vibration control of a piezoelectric cantilever smart beam by L1 adaptive control system", systems science & control engineering: an open access journal, 2021, vol. 9, no. 1, 542–555.
- [8]. Junqiang Lou, Jiangjiang Liao, Yanding Wei, Yiling Yang and Guoping Li, "Experimental identification and vibration control of a piezoelectric flexible manipulator using optimal multi-poles placement control", Appl. Sci. 7–309 (March 2017)

- [9]. K. B. Waghulde et al. /International Journal of Engineering and Technology, “Vibration Control of Cantilever Smart Beam by using Piezoelectric Actuators and Sensors “, Vol.2(4), 2010, 259-262.
- [10]. Fevzi Cakmak Bolat and Selim Sivrioğlu,”Control of Elastic Beam Vibrations Using Piezoelectric Actuator”,International Journal of Applied Mathematics, Electronics and Computers Advanced Technology and Science ISSN:2147-82282147-6.
- [11]. Xu, S., Sun, G., & Li, Z. (2018),”Finite frequency vibration suppression for space flexible structures in tip position control”,International Journal of Control, Automation and Systems, 16(3),1021–1029.
- [12]. Aleksandar M. Simonovic, Miroslav M. Jovanovic, Nebojsa S Lukic, Nemanja D Zoric, Slobodan N Stupar and Slobodan S. Ilic’,”Experimental studies on active vibration control of smart plate using a modified PID controller with optimal orientation of piezoelectric actuator”, J. Vib.Control (2014)