OPTIMISATION OF ACTIVE VIBRATION CONTROL OF CANTILEVER BEAM BY USING PIEZOELECTRIC (PZT) SENSORS & ACTUATORS

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Abstract: *The study focuses on improving vibration suppression performance in smart structures through optimized sensor–actuator placement. A finite element model (FEM) of the piezoelectric material was developed using ANSYS software to determine the modal frequencies and identify dominant vibration modes using a modal cost-based model reduction technique. The obtained modal data were further utilized to optimize the size and positioning of the PZT actuators for maximum control effectiveness. A cantilever beam integrated with piezoelectric sensors and actuators was then analyzed under dynamic loading, and its impulse response characteristics were studied. The simulation results demonstrated that the proposed optimization approach significantly enhances vibration attenuation, energy efficiency, and response accuracy. This work provides a robust foundation for the design and control of smart adaptive structures used in aerospace, automotive, and precision engineering applications.*

Keywords: *Active vibration control, Cantilever beam, Piezoelectric (PZT) sensors, Piezoelectric actuators, Finite Element Method (FEM)*

INTRODUCTION

Controlling mechanical and structural vibrations plays a crucial role across various industries. In manufacturing, excessive vibrations can lower production efficiency and affect the quality of finished products. In civil engineering, unwanted vibrations can impact the comfort and safety of people in buildings or structures. Similarly, in the automotive and aerospace sectors, vibrations can shorten the lifespan of components and create unwanted noise during operation.

1.1 Passive Vibration Control

In engineering applications, a number of methods have been developed to reduce undesired vibrations. Passive vibration control is the term for the traditional usage of isolators and passive dampers to reduce mechanical vibrations. However, active vibration control has also drawn interest due to developments in sensor-actuator technology and digital data processing. Preventing vibrations from moving from their source to the object is one of the fundamental ideas of vibration isolation. While the second way seeks to shield the object from undesired vibrations transmitted from the ground, the first method concentrates on isolating the dynamic forces generated by a machine before they reach the ground. Depending on the energy source, control mechanism, and technical design, vibration control systems are generally categorized into passive and active types. Passive methods typically include:

- Preventing vibration at its source,

- Modifying system parameters,
- Making structural changes, and
- Implementing vibration isolation techniques.

These passive methods work by dissipating, storing, or converting vibrational energy. However, they have some limitations, such as reduced effectiveness at low frequencies and sensitivity to changes in operating conditions.

1.2. Active Vibration Control

Active methods use external power source to make structural adjustments, can reduce vibration more effectively. These methods help in achieving a balance between several engineering requirements, including stiffness, dynamic stability, low vibration levels, and good machine efficiency. To neutralize vibrations in active systems, a controlled external power source either supplies or absorbs energy from particular machine components.

Actuators—such as hydraulic, pneumatic, or electric drives—generate forces opposite to the unwanted dynamic forces, effectively reducing motion.

The control strategy of an active system relies on information gathered by a measurement system, which includes sensors, amplifiers, and signal conditioning elements. Based on this data, the controller directs the actuator to produce the necessary corrective force. Depending on how energy is supplied and managed, active vibration systems can be categorized as passive, semi-active, hybrid, or adaptive. Based on the driving mechanism, they may use pneumatic, hydraulic, electromagnetic, or hybrid actuators.

This system consist of mechanical, electronic, and computer-controlled components. It consists of four key parts: the mechanical structure affected by vibrations, sensors to detect disturbances, a controller to process feedback and generate control signals, and actuators to counteract the vibrations. The actuator's opposing force creates destructive interference, reducing or eliminating unwanted motion.

There are two categories of Active Vibration control method:

1. **Feedback Active Vibration Control**, where corrective action depends on real-time vibration data.
2. **Feedforward Active Vibration Control**, where disturbances are predicted and compensated in advance.

Each method has its own advantages and limitations, and their selection depends on the system's performance requirements and operating environment.

In this project, a finite element model (FEM) of the piezoelectric material was developed using ANSYS software to determine its modal frequencies and identify the dominant vibration modes through a model reduction technique based on modal cost. Based on the obtained modal data, the optimal size and placement of the piezoelectric actuators were established. Subsequently, a simply supported smart beam integrated with piezoelectric sensors and actuators was analysed, and its impulse response was evaluated. The results revealed that the proposed optimisation methodology significantly enhances the efficiency and accuracy of active vibrations control in piezoelectric smart structures.

LITERATURE REVIEW

Qinglei Hu and Guangfu Ma [1], highlighted that vibration reduction was a major challenge in the design and manufacturing of flexible spacecraft, especially those with large and lightweight structures. These structures generally had low damping properties and low natural frequencies, which made them more susceptible to excessive vibrations. The results showed that all three control methods GNUF, PPF, and LQG effectively handled both single mode and multi-mode vibrations, proving that the proposed approach was successful for active vibration control in flexible spacecraft. **Jaques Lottin et al. [2]** conducted a study to determine the most efficient placement of sensors and actuators for active vibration control in flexible structures. They explained that the optimal locations depend on the type of control scheme used, as different control strategies require specific arrangements to achieve the best vibration suppression results. The results showed that the dynamic behavior of the beam varied with the location and mass of the sensors and actuators. **Deepak Chhabra et al. [3]** the main aim of this research was to understand how the placement of piezoelectric patches—at the free end, middle, or fixed end, influences the vibration control performance. To evaluate the control performance, different control algorithms such as Proportional Output Feedback, PID, and Pole Placement methods were implemented. Overall, this work successfully developed a computational model and control strategy for designing piezoelectric smart structures with improved vibration control performance. **Yavuz Yaman et al. [4]** conducted a study on smart plates made of rectangular aluminum plates configured as cantilever structures with piezoelectric sensor and actuator patches bounded to their surfaces. The patches were placed on the top and bottom surfaces of the plate. The results showed that the controller effectively suppressed vibrations corresponding to the first two flexural modes and provided robust performance even in the presence of modeling uncertainties. Overall, the research successfully determined the optimal actuator size, placement, and sensor configuration for achieving efficient vibration control in smart plate structures. **S. Raja et al. [5],** examined the effectiveness of shear actuators compared to extension bending actuators in active vibration control of sandwich beams. Their study revealed that shear actuators, which generate distributed forces and moments, were more efficient in reducing vibrations than extension bending actuators that create concentrated forces and moments. In conclusion, the study demonstrated that shear actuators are more effective and efficient in distributing control forces for vibration suppression in smart composite sandwich beams, especially when the actuator geometry and material layering are properly optimized. **R. Setola [6],** developed an active vibration control method for flexible beams using a spline based reconstruction approach integrated with an LQ (Linear Quadratic) regulator. The spline function was employed to interpolate sensor measurements while satisfying boundary conditions, effectively introducing spatial filtering that enhances robustness by minimizing high frequency spillover effects. The study demonstrated that the combination of spline reconstruction and LQ regulation provides a robust and efficient framework for vibration suppression in flexible beam structures, offering improved stability and performance against persistent external disturbances. **Te'o Lenquist da Rocha [7]** conducted a study on active vibration control using smart material technology, focusing on the optimal placement of piezoelectric sensors and actuators to achieve the best control performance. The study focused on the first two modes of vibration, revealing that actuators placed at these optimized positions exhibit stronger electromechanical coupling and improved vibration suppression. Overall, Rocha's research presented a robust methodology for optimal actuator/sensor placement in smart structures, enabling efficient vibration control and contributing to the advancement of lightweight, intelligent structural systems. **Zeki Kiral et al. [8]** conducted both experimental and numerical investigations on the active vibration control of a cantilever smart beam subjected to a moving load. The primary objective was to reduce residual vibrations that appeared after the load moved off the beam. The study found that proportional control effectively suppressed the residual vibrations of the smart beam. The findings demonstrated that finite element methods are highly effective for designing active vibration control strategies, particularly when piezoelectric actuators and feedback control systems are integrated. **C. Mei [9],** explored a hybrid active vibration control approach that combines both waves based and mode based control techniques to enhance vibration suppression in mechanical structures. In the proposed hybrid method, wave control is primarily designed for high frequency vibrations, focusing on managing the distribution and transmission of vibrational energy within the structure. The study concluded that this hybrid control framework effectively minimizes vibrations across a wide frequency range and enhances the dynamic stability and efficiency of advanced lightweight structural systems. **Chih Liang Chu et al. [10]** conducted a study on active vibration control of a flexible beam mounted on an elastic base using the Independent Modal Space Control (IMSC) method. In the analysis, a model comprising 32 finite elements was developed and validated through numerical comparisons with ANSYS simulations, demonstrating strong agreement. The study concluded that the optimal IMSC based control approach provides superior dynamic performance and enhanced vibration attenuation for flexible beam systems mounted on elastic foundations, making it a promising method for advanced structural vibration control applications. **Juntao Fei [11]** conducted a study on active vibration control of a flexible steel cantilever beam using intelligent piezoelectric actuators. The research aimed to develop and test real-time feedback control schemes to suppress unwanted vibrations. This study confirmed that bonded piezoelectric actuators, when integrated with real-time control systems, provide a reliable and efficient solution for vibration suppression in flexible structures. **Yavuz Yaman et al. [12]** conducted a study on active vibration control of a smart cantilever aluminum beam integrated with surface-bonded piezoelectric (PZT) patches. The study demonstrated that integrating smart materials, such as PZT sensors and actuators, provides an efficient active control mechanism to reduce vibration levels and preserve structural integrity. Overall, the study concluded that the H∞ control technique, when combined with a properly reduced finite element model, offers a robust and efficient method for active vibration suppression in smart structures. **K. B. Waghulde et al. [13]** carried out both experimental and numerical investigations on the active vibration control of a cantilever smart beam embedded with piezoelectric sensors and actuators. In their experimental setup, a white noise excitation was applied to the actuator to replicate real-world vibration sources, such as those caused by human activity or surrounding machinery. The study emphasized that the developed spatial H∞ control methodology is not limited to piezoelectric laminate beams but can be extended to various vibration suppression applications, including aerospace structures such as airplane wings, helicopter propellers, and other slender structural components where vibration control is critical for performance and reliability. **Pradeep Kumar Sharma et. al. [14],** focused their study on the application of piezoelectric materials for active vibration control of structural systems. They highlighted that piezoceramics are lightweight, cost effective, and easy to implement, making them ideal for minimizing the amplitude of structural vibrations. They examined how piezoelectric materials respond to externally applied forces and electrical inputs, and how their placement and configuration influence vibration control efficiency. **K. Chau et al. [15]** introduced an advanced method that uses high-speed Wavelength Division Multiplexing (WDM) to multiplex Fiber Bragg Grating (FBG) sensors for structural vibration control and strain measurement. The experimental results confirmed that the FBG-based sensing system provided highly accurate, real-time feedback, leading to effective and reliable vibration suppression. The integration of FBG sensors with active control techniques proved to be a reliable and high-performance solution for vibration monitoring and control, showing strong potential for smart structural systems in aerospace and mechanical engineering applications. **A. P. Parameswaran et al. [16],** investigated the problem of undesirable vibrations in mechanical systems and emphasized the necessity of maintaining them within acceptable limits for efficient performance. Their research demonstrated that combining piezoelectric sensors and actuators with feedback control algorithms can achieve lightweight, fast, and effective multi-mode vibration control. The study attributed this limitation to the time-multiplexed nature of the general-purpose operating system (GPOS), which sequentially handled internal and external interrupts, limiting processor performance.

PROBLEM STATEMENT AND OBJECTIVES

Controlling Mechanical and structural vibrations is a major concern in many engineering fields. In manufacturing systems, excessive vibrations can reduce accuracy, efficiency, and product quality. In civil structures, unwanted vibrations can affect occupant comfort and compromise structural integrity, while in automotive and aerospace systems, vibrations can shorten component life and contribute to noise and instability.

To tackle these challenges, Active Vibration Control (AVC) systems have become an effective solution. This project focuses on developing and optimizing an active vibration control system for a smart cantilever beam using Piezoelectric (PZT) patches as both sensors and actuators. The main goal is to achieve effective vibration suppression with minimal control effort by optimizing the placement, size, and configuration of the PZT patches. Additionally, a comparative study will be conducted to evaluate the beam’s performance with the sensor on the top surface and actuator on the bottom, and vice versa, to identify the most efficient configuration for vibration control.

Objectives

1. To identify vibration of cantilever beam without active vibration.
2. To damp the vibration of cantilever beam by using piezoelectric sensors & Actuators.
3. To find out optimum position for piezoelectric patches for maximum vibration control of cantilever beam with the help of ANSYS Software
4. To validate the effective position of the patches of cantilever beam with the help of prototype model.
5. To find out the effectiveness of piezoelectric patches with proportional integral derivative controlling system.

ANALYSIS OF CANTILEVER BEAM

In this study, the cantilever beam model was systematically analyzed to evaluate its dynamic response under different loading conditions, which is essential for designing and optimizing active vibration control (AVC) strategies using piezoelectric (PZT) sensors and actuators. The model was analyzed for various combinations of the following excitation parameters:

Force Acting at the free end of beam: A Force of 10 N has been applied at end of the cantilever beam. This type of loading simulates realistic operational scenarios where the beam may experience tip loads due to attached components, payloads, or external disturbances. The magnitude of 10 N was chosen to represent moderate excitation, sufficient to induce measurable vibrations while remaining within the elastic range of the beam material. The response to this force helps in understanding the deflection characteristics, natural frequencies, and the potential locations for optimal placement of PZT actuators and sensors.

Frequency Range of Excitation: The analysis has been performed over a frequency of 1 Hz to 100 Hz, which encompasses the fundamental and several higher order vibrational modes of the cantilever beam. This range is selected to capture the resonance conditions that significantly amplify beam vibrations, which is crucial for designing an effective active control system. Studying the frequency response allows identification of dominant modes where PZT based active vibration suppression can be most effective.

1. Analysis of Cantilever beam without Active Vibration

The boundary conditions applied to the cantilever beam model are as shown in the enclosed figure:

- One end of the beam is fixed in all three directions: $F_x = 0, F_y = 0, F_z = 0$.
- A vertical downward force of $F = 10$ Nis applied at the free end.

Boundary Conditions

The following figure shows boundary conditions applied in the Ansys software.

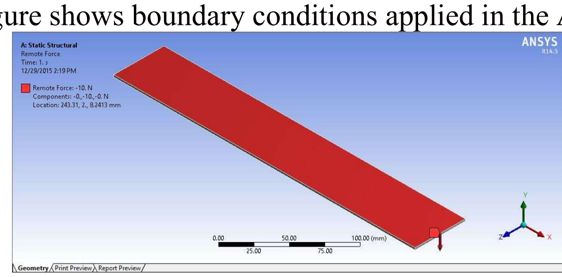

Figure no. 1: Boundary conditions

Stress Result

After Application of force on beam the maximum stress developed in beam was 100.35 Mpa, which is shown in red colour and minimum stress was 0.0017969 Mpa which is shown in blue colour.

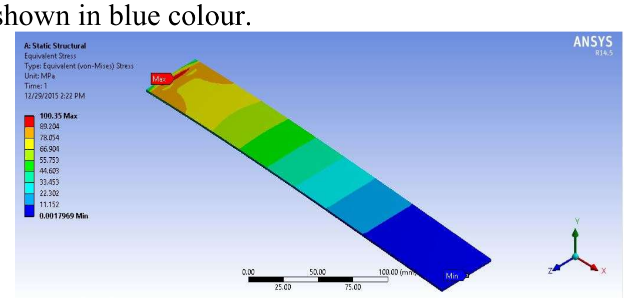

Figure no. 2: Stress on beam

Strain Result

After applying a 10 N force on the beam, the maximum strain developed was 0.0014336 mm/mm, shown in red, while the minimum strain was 2.0747×10^{-7} mm/mm, shown in blue.

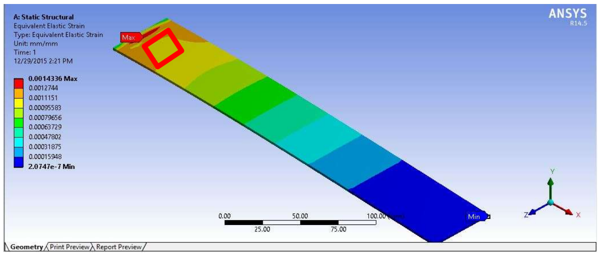

Figure no. 3: Strain results in beam

Deformation Result

After applying a 10 N force on the beam, the maximum deformation observed was 33.849 mm, shown in red, while the minimum deformation was 0 mm, shown in blue.

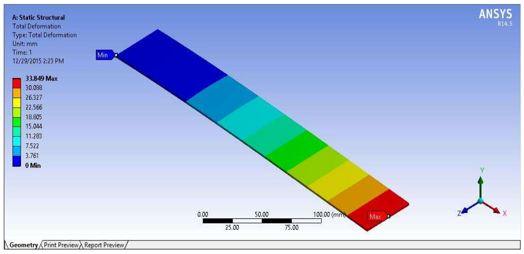

Figure no. 4: Deflection in the Cantilever beam model

2. Analysis of Cantilever beam with PZT Patches

This analysis focuses on the **static structural behavior** of a beam with PZT patches. The goal is to establish a structural baseline by quantifying the stress, strain, and deformation when a simple static load is applied.

Boundary Conditions

The analysis utilizes a Finite Element Method model of a cantilever beam with PZT patches bonded to its surface.

- **Boundary Condition:** One end of the cantilever beam is fixed
- **Loading Condition:** The force of 10 N is applied at the free end of the beam.

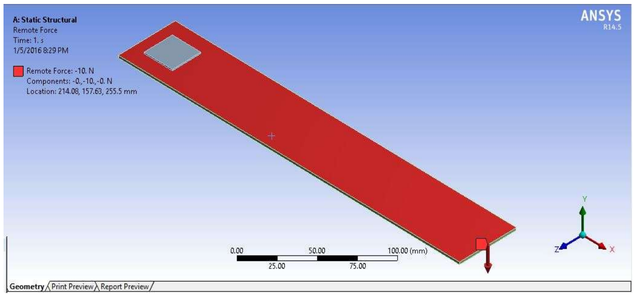

Figure no. 5: Boundary conditions on Cantilever beam with PZT patches

Stress Result

After applying a force on the beam with PZT patches, the maximum stress developed was 92.854 MPa, shown in red, while the minimum stress was

0.0028286 MPa, shown in blue. The maximum stress occurs at the fixed end on both the top and bottom surfaces of the beam, which is consistent with the location of the maximum bending moment in a cantilever beam. The minimum stress is nearly zero and appears near the free end or along the neutral axis (center line), where bending stresses are minimal.

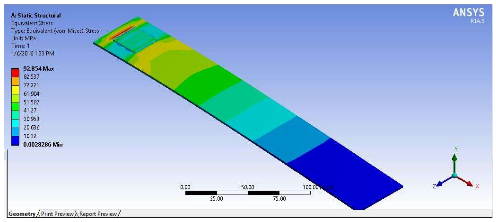

Figure no. 6: Stress on Cantilever beam with PZT patches

Strain Result

After applying a 10 N force on the beam, the maximum strain developed was 0.0014139 mm/mm, shown in red, while the minimum strain was 3.997×10^{-7} mm/mm, shown in blue. The maximum strain occurs at the fixed end, where the bending moment is highest, resulting in the greatest material deformation. This strain is dimensionless and remains well within the elastic limits of both the aluminum beam and the PZT patches, indicating that the applied load is non-destructive.

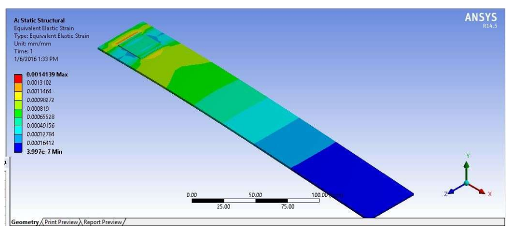

Figure no. 7: Strain on Cantilever beam with PZT patches

Deformation Result

After applying a 10 N force on the beam with PZT patches, the maximum deformation observed was 25.175 mm, shown in red, while the minimum deformation was 0 mm, shown in blue. The maximum deformation occurs at the free end, where the load is applied, and the minimum deformation is at the fixed end, consistent with the cantilever boundary conditions.

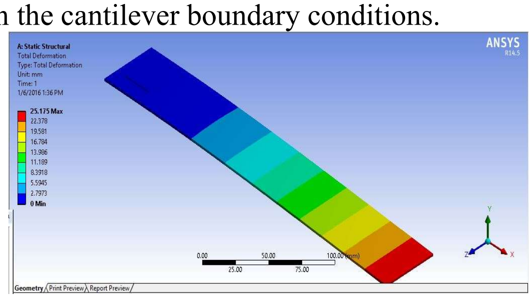

Figure no. 8: Deformation on Cantilever beam with PZT patches

The results clearly indicate that the presence of PZT patches significantly improved the performance of the cantilever beam. Even in this static analysis, the patches provided a stiffening effect, reducing deflection and strain compared to a beam without PZT patches. This demonstrates that PZT patches not only enable active vibration control but also contribute to the structural rigidity of the system, enhancing its overall dynamic performance.

EXPERIMENTAL SETUP

Active vibration control (AVC) is a method used to reduce or manage vibrations in a structure by applying a counteracting force that is equal in strength but opposite in phase to the original vibration. When these forces interact, they cancel each other out, stopping the structure from vibrating. Earlier, methods such as springs, pads, and dampers were used to control vibrations, these are called passive vibration control techniques. However, passive techniques are limited because they can only control vibrations within a specific frequency range.

Active vibration control is a modern solution that overcomes these limitations. Traditional control methods can be bulky, difficult to maintain, and expensive, especially in machines where space is limited. AVC, on the other hand, is compact, cost effective, requires minimal maintenance, and typically lasts longer than passive systems.

AVC relies on smart structures, which consist of actuators, sensors, a power source, and a compensator that respond when vibrations occur. Smart structures are increasingly used in bridges, trusses, buildings, and mechanical systems. Studying and analyzing a basic structure using AVC can improve its performance, especially under challenging conditions that involve beam vibrations.

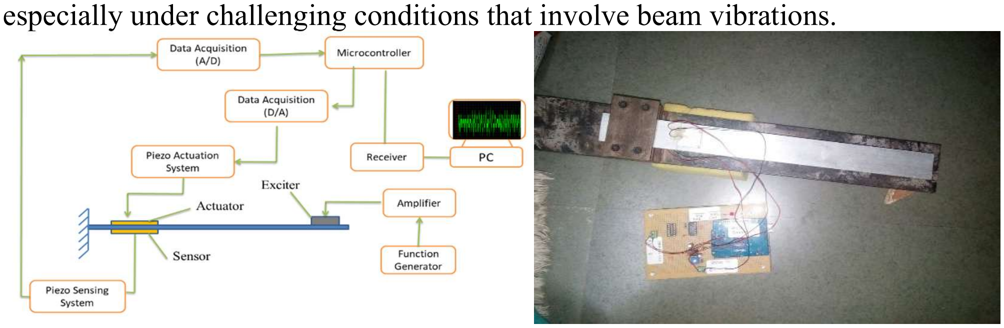

Figure no. 9: Experimental Setup

In the present work, a smart aluminum plate with a pair of piezoelectric laminations is used to study the principles of AVC. The experimental setup includes a rectangular aluminum beam arranged in a cantilever configuration, with piezoelectric patches bonded to its surface. A finite element model (FEM) of the smart beam is created in ANSYS 14.5 to identify the most effective sensor locations. Using the simulation results, the physical model of the beam is fabricated. The experiment then aims to select a suitable control method and fine-tune the controller gain to achieve maximum vibration reduction with minimum input effort.

Experimental Procedure

1. The aluminum cantilever beam tip was displaced by 5 mm. The sensor was placed above the beam, and the actuator below.
2. The sensor detected the vibrations and sent signals to a microcontroller unit equipped with both PID and SRF controllers.
3. For the PID controller, readings were taken with the beam displaced 5 mm above and below, while the sensor and actuator positions were kept as above.
4. The procedure was repeated for the SRF controller.
5. Graphs were plotted using Arduino Serial Plotter, and data could be saved using serial oscilloscope software at a baud rate of 9600.

6. To study the effect of sensor and actuator placement, their positions were interchanged, and results were recorded.
7. The actuation time required to achieve 70% vibration suppression was noted for both controllers.

RESULTS AND DISCUSSIONS

The active vibration control (AVC) study was carried out on a cantilever aluminum beam with surface-bonded piezoelectric (PZT) patches. The main goal was to examine how the placement of sensors and actuators, along with different control strategies, affects vibration suppression. Both PID and Strain Rate Feedback (SRF) controllers were tested, and finite element analysis (FEA) was used to determine the optimal positions for the PZT patches.

Analysis of Beam

1. Cantilever Beam Analysis

The initial FEA of the beam without patches showed that the maximum strain occurs near the fixed end of the cantilever. This region was identified as the most effective for actuator placement. Stress and deflection distributions are shown in Figures no 4. and 4.5. The deflection plot confirmed that the free end experiences the highest displacement, which is typical of cantilever structures under tip loading.

2. Effect of PZT Patches

After attaching the piezoelectric patches at the identified locations (Figure no 4.6), the beam was reanalyzed under the same loading conditions. The results indicate a significant reduction in strain in the patched areas (Figure no 4.8), while stress concentrations remained within safe limits (Figure 4.9). The reduction in strain demonstrates the effectiveness of the patches in modifying the dynamic response of the beam and providing localized vibration damping.

Table no. 1: Analysis Result

Formation in beam	**Beam without Patches**		**Beam with patches at 10 mm from Fixed end**	
	Min	Max	Min	Max
Deformation	0	33.849	0	25.175
Stress	0.0017969	100.35	0.0018286	92.854
Strain	2.0747E-07	0.0014336	3.997E-07	0.0014139

Controller Performance

1. PID Controller

The PID controller was optimized to achieve effective vibration suppression with minimal control input. The proportional gain (K_p) and derivative gain (K_d) were tuned based on experimental observations. It was found that:

- Optimal $K_p = 75$for $K_d = 0$.
- Increasing $K_d$above 0.02 degraded the control performance.

With these settings, the PID controller achieved rapid suppression of vibrations at the beam tip and maintained stability across the tested frequency range.

2. SRF Controller

The SRF controller was tested at the dominant frequency of 11.1 Hz with a damping ratio (ζ_c) of 0.5 and controller gain $K = 1.1$. The controller effectively suppressed vibrations by producing counteracting shear forces in real time. Compared to the PID controller, the SRF controller showed slightly faster response for targeted frequency modes, demonstrating its suitability for frequency specific vibration control.

Experimental Observations

- Displacement tests at the beam tip confirmed that both controllers could significantly reduce vibration amplitude.
- Sensor and actuator placement had a notable effect on the actuation efficiency. Optimal placement above and below the beam produced faster suppression.
- Time required for 70% vibration suppression was recorded for both controllers, showing the faster response of the SRF controller in specific frequency modes.
- Graphs plotted using Arduino Serial Plotter and oscilloscope software confirmed the real time feedback and damping performance of the system.
- All the graphs are plotted with time on X-axis and millivolt on Y-axis.

A) Graph Plotted using PID controller

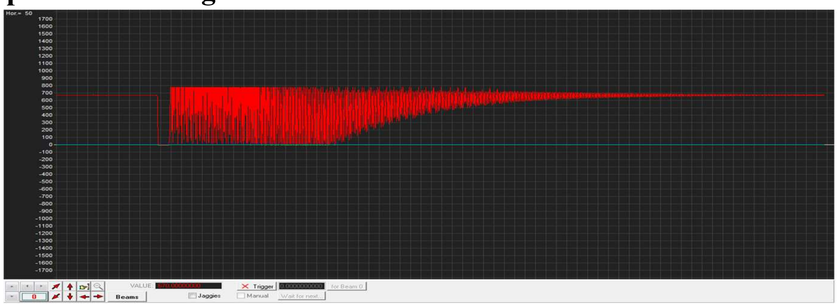

Figure no. 10: Sensor placed below the beam and actuator above the beam and the tip is pushed by 5 mm

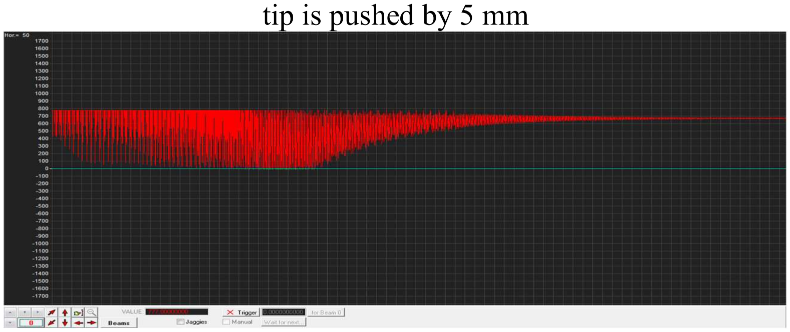

Figure no. 11: Sensor placed below the beam and actuator above the beam and the tip is pushed up by 5 mm

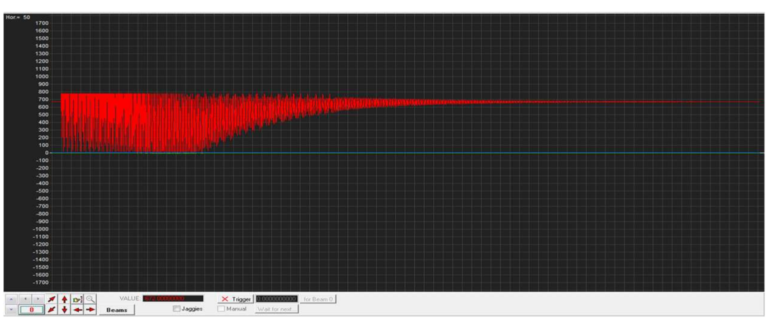

Figure no. 12: Sensor placed above the beam and actuator below the beam and tip is pushed down by 5 mm

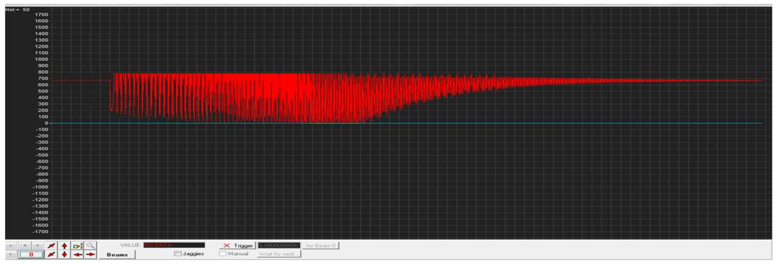

Figure no. 13: Sensor placed above the beam and actuator below the beam and the tip is pushed up by 5 mm

B) Graph Plotted using SRF controller

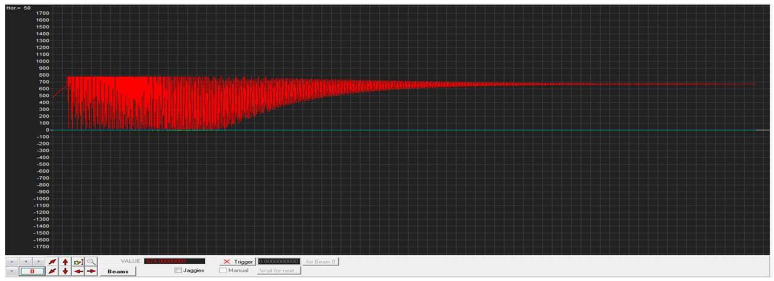

Figure no. 14: Sensor placed below the beam and actuator above the beam and the tip is pushed by 5 mm

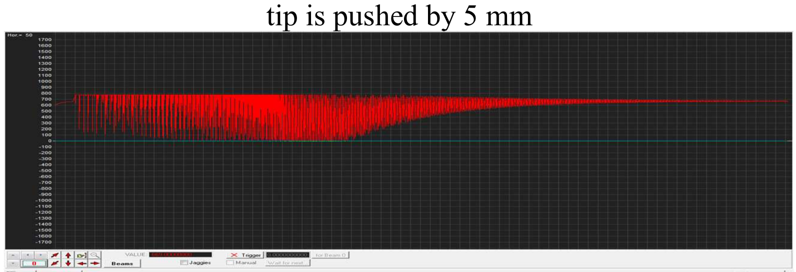

Figure no. 15: Sensor placed below the beam and actuator above the beam and the tip is pushed by 5 mm

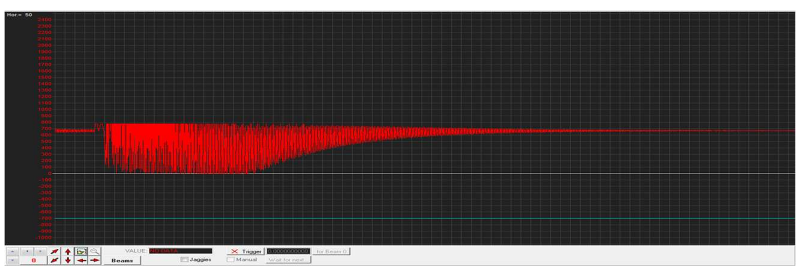

Figure no. 16: Sensor placed above the beam and actuator below the beam and the tip is pushed down by 5mm.

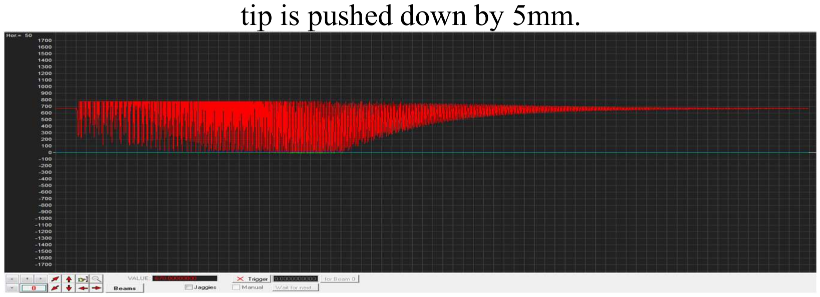

Figure no. 17: Sensor placed above the beam and actuator below the beam and the tip is pushed up by 5mm.

Table no. 2: Experimental Result

Readings	**PID**		**SRF**	
Displacement by 5 mm	Top Sensor	Bottom Sensor	Top Sensor	Bottom Sensor
Push up	21 Sec	21 Sec	20 Sec	20 Sec
Push Down	16 Sec	17 Sec	15 Sec	15 Sec

The results, summarized in the table, represent the time required to achieve 70% vibration suppression for different sensor and actuator placements. Both top and bottom sensor positions were tested to determine the optimized configuration. It was observed that placing the sensor on the top of the beam and the actuator at the bottom produced the most effective vibration suppression. Additionally, the SRF controller outperformed the PID controller, achieving faster and more efficient damping under the same experimental conditions.

Validation Results Using FFT

The result obtained through the Serial Plotter is validated using FFT analyzer. It can be seen that result obtained from Serial Plotter are matched by FFT results.

Table no. 3: 8 FFT Results

Readings	**PID**		**SRF**	
Displacement by 1 mm	Top Sensor	Bottom Sensor	Top Sensor	Bottom Sensor
Push up	18.9 Sec	22.8 Sec	16.7 Sec	14.3 Sec
Push Down	12.2 Sec	16.5 Sec	12 Sec	11 Sec

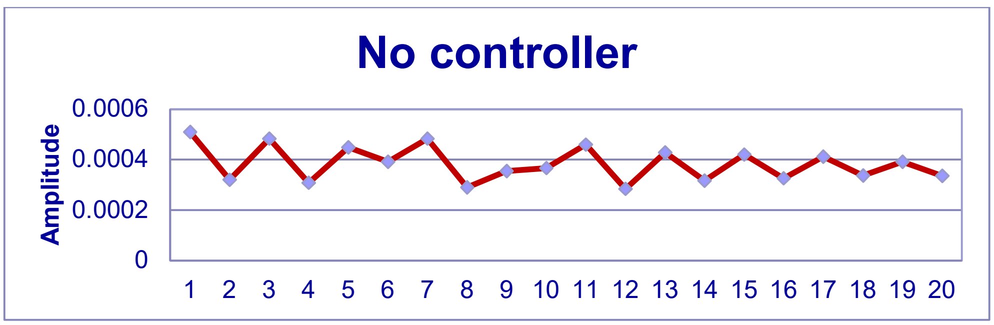

Figure no 18: FFT readings when no controller is used.

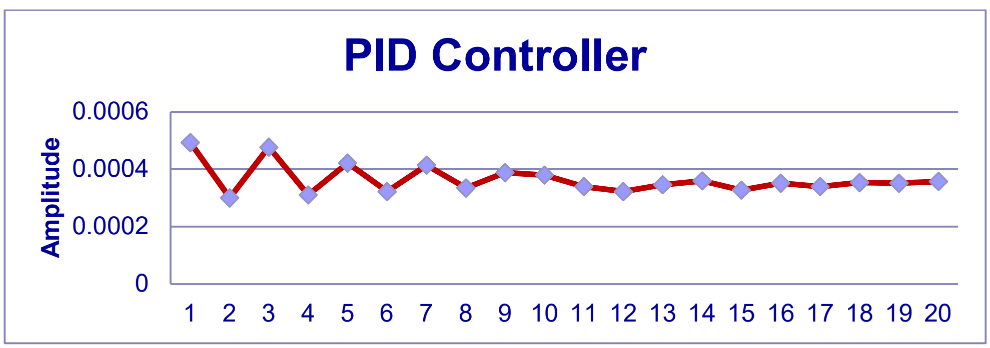

Figure no 19: FFT readings when PID controller is used.

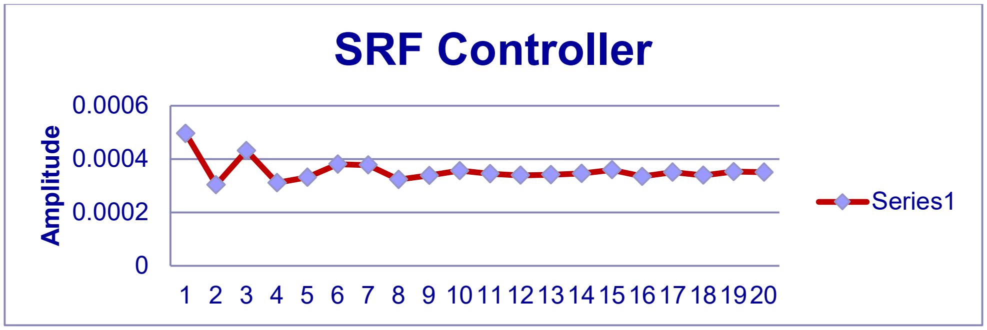

Figure no 20: FFT readings when SRF controller is used.

From Figures 18, 19, 20, it is evident that vibration suppression improves significantly with the use of controllers. Without any controller, the beam exhibits a logarithmic decrement of 0.053364 (Figure no 18). When the PID controller is applied, the vibrations are suppressed more effectively, with a logarithmic decrement of 0.15824 (Figure no 19). The SRF controller demonstrates the best performance (Figure no 20), achieving the highest vibration suppression with a logarithmic decrement of 0.303769. These results clearly indicate that the SRF controller is more effective than both the PID controller and the uncontrolled case.
Additional dynamic properties of the system were also calculated:

- Modal mass: 0.0168990 kg
- Stiffness: 1762.02 N/m
- Mass moment of inertia: 236.69 × 10^-12 kg·m²
- Natural frequency: 51.40 Hz

These parameters are consistent with the observed vibration characteristics and confirm the effectiveness of active vibration control in enhancing the dynamic performance of the cantilever beam.

In conclusion, the study demonstrates that active vibration control using PZT sensors and actuators is a highly effective approach for suppressing vibrations in cantilever beams. The methodology and results provide a solid foundation for extending AVC techniques to other engineering structures, mechanical systems, and smart devices.

CONCLUSION

The present work effectively demonstrates active vibration control (AVC) of a cantilever beam integrated with PZT patches. The study combines finite element modeling and experimental testing to analyze how the positioning of sensors and actuators, together with various control strategies, affects the efficiency of vibration suppression.

The main conclusions of the study are:

- Effectiveness of SRF Controller: Among the control strategies tested, the Strain Rate Feedback (SRF) controller was found to be more effective than the PID controller, achieving faster and higher vibration suppression for the cantilever beam.
- Optimal Sensor-Actuator Placement: Sensor and actuator positions were systematically tested. It was observed that placing the sensor on the top of the beam and the actuator at the bottom provides the best performance, resulting in efficient damping and reduced actuation time.
- Role of PZT Patches: Piezoelectric patches, when bonded near the regions of maximum strain, significantly reduce strain in the beam, effectively

suppressing vibrations and improving the dynamic behavior of the structure.

Overall, the study confirms that active vibration control using PZT patches is a highly effective method for controlling vibrations in cantilever beams. The findings highlight the importance of controller selection and optimal sensor-actuator placement in enhancing performance, making this approach suitable for modern engineering applications in machinery, smart structures, and precision devices.

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