International Journal of Enhanced Research in Educational Development (IJERED)
ISSN: 2320-8708, Vol. 13 Issue 1, Jan.-Feb., 2025

Vibration Control in Mechanical Systems Using Smart Materials: Analysis and Applications

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INTRODUCTION

Vibrations occur across various devices and tools, such as engines, machinery, bridges, aircraft wings, and robotic arms. The vibration in these vehicles or settings is often unnerving, making it uncomfortable for the person operating the machinery or driving the car, who needs to factor in the vibration effect to manage it properly. Vibration has been a significant problem in the operation of various things, and it is even harder when the source of the vibration is separate from the actual mechanical system. Engineers and scientists have looked at ways of addressing this problem, but previous attempts have only slightly reduced the vibration and over time, the problem reoccurs.

Vibration has many adverse effects, such as energy loss as the vibrating item generates kinetic energy. Once the kinetic energy is generated, it is lost. Therefore, this machinery that often vibrates uses more energy than it should because of the vibrative effects. Another adverse effect of vibration is that it leads to noise generation that interferes with the work done in the environment (Ghodsi et al., 2022). The vibration also reduces the accuracy in robotics, as they are increasingly being used in automation. Vibration leads to fatigue failure in bridges and aircraft, which puts the lives of people using these services at risk.

Various conventional methods and devices, including rubber dampers, tuned mass dampers, and isolation mounts, have been employed to deal with vibration. These methods have sought to cushion the vibration's impact when it occurs, but have only temporarily reduced its occurrence (Pasupuleti, 2024). Despite their slight effectiveness, these methods lack adaptability when vibration changes, which can happen unexpectedly. This aspect makes it challenging to handle this machinery that plays a vital role in the performance of tasks. Therefore, a new novel approach has emerged where the vibration is controlled through innovative materials (Moutsopoulou et al., 2024). These smart materials are made of alloys and other substances that eliminate the vibration effect. These smart materials work through the use of sensors to detect vibration and generate counteractive forces. These innovative materials allow for real-time adaptive vibration control.

LITERATURE REVIEW

A New Active Anti-Vibration System Using a Magnetostrictive Bimetal Actuator

The innovative vibration reduction system described in this article by Mojtaba Ghodsi, Morteza Mohammadzaheri, Payam Soltani, and Hamidreza Ziaifar uses a magneto-restrictive bimetal actuator. Without knowing the disturbance's dynamics beforehand, this unique and innovative vibration reduction method can eradicate it (Noori & Narjabadifam, 2019). The analytical and FEM results are used to manufacture the magnetically restricted bimetal actuator, which is then experimentally tested at various frequencies. This actuator's control system can reduce the central system's vibration amplitude by 33.6%.

In many applications, such as robotics, suspension systems, noise cancellation, machining operations, or mirror placement in the upcoming generation of space observatories, unwanted vibrations are the most unpleasant. It is crucial to use active vibration control systems in these well-known applications because they get rid of undesirable and problematic vibrations (Chaudhari et al., 2024). An integral part of any active vibration control system is a suitable actuator. Compared to traditional actuators, such as hydraulic, pneumatic, electromagnetic, and electrostatic ones, smart material actuators are more dependable, more miniature, and respond faster. Shape memory alloys (SMA), magnetorheological, piezoelectric, and magnetostrictive materials are some of these vibration control systems' most advanced smart materials. For passive and active anti-vibration systems in mechanical and civil structures, shape memory alloy is one of the most promising smart materials (Ghodsi et al., 2022). This substance was employed by researchers to stabilize gimbal cameras or to control vibrations on satellites with gimbal-type antennas. SMA's lightweight, high-strain, compact design makes it ideal for vibration control systems. However, its hysteretic nature, low frequency response time, and great sensitivity to external temperature perturbations limit its usefulness and efficacy.

Magnetorheological materials are excellent choices for passive damping and semi-active control systems because their damping coefficient varies with the magnetic field. According to Zhang et al. (2024), magnetorheological materials have a high energy density and a massive generated force. However, they also have a low frequency response and need much room for their drive system. Magnetorheological materials are the only smart materials with a high energy density that can function successfully in challenging environments as actuators in an active vibration control system. Sensors, energy harvesters, and actuators in active vibration control structures use giant magnetostrictive materials. Notwithstanding the benefits of this single metal magnetostrictive material, magnetic fields and thermal expansion from the heat produced limit its efficacy (Pasupuleti, 2024). controlling sensors, harvesters, actuators, and devices with a magnetostrictive bimetal actuator. This bimetal actuator operates without thermal strain over a broad range of operating temperatures because it comprises two ferromagnetic layers with extremely near thermal expansion coefficients. As a result, no temperature control system, hardware or software recalibration system is required.

Since their development in the early 2010s, piezo elements have sharply increased usage and application in various vibration control systems. Robot manipulators, wind turbines, and machining used piezo-actuated active control systems, whereas car suspension systems used semi-active ones (Chaudhari et al., 2024). This material can be utilized in passive attenuation systems by using various arrangements. In certain instances, researchers optimized the positioning and orientation of piezo sensors and actuators in active vibration control of planes using evolutionary algorithms or finite element models for active vibration mechanisms. The fact that piezoelectric patches are reasonably priced and suitable for medium-range temperatures between 75 and 200 degrees Celsius is one of their primary characteristics (Zhu et al., 2022). However, their drawbacks are low coupling efficiency, depolarization, and gradual formation of microcracks.

To keep the vibration amplitude of the main structure as low as feasible, anti-vibration systems employ a variety of control mechanisms. A linear-quadratic feedback controller for a linear magnetostrictive actuator was proposed in a real-time application. This can help reduce acceleration and displacement in the first four modes by a 75% margin (Yuan et al., 2023). Furthermore, it was shown that using a feedforward compensator as the controller and a multi-mode adaptive position feedback method might be relatively successful in reducing vibration. The displacement from extreme vibration sources is reduced to zero by vibration attenuation. Vibration-induced displacement is a control disturbance that results from an uncontrollable cause. Feedforward is used to reject the disturbance. Since the disruption is created artificially, this link can be found in a laboratory experiment (Pasupuleti, 2024). However, it is difficult to identify this link, such as the impact of wind.

The findings of this study's laboratory experiment demonstrated that the suggested anti-vibration system is especially well-suited to reduce the impact of external disturbances on beam displacement at frequencies ranging from 55 Hz to 90 Hz (Chaudhari et al., 2024). Understanding the dynamics of disturbances is not used in the suggested control technique.

This study concludes by discussing a novel magnetostrictive bimetal actuator-based active anti-vibration system. The purpose of this technology is to lessen the impact of undesired vibrations on a cantilever beam. There are two main benefits of using this approach over traditional methods. A temperature sensor and recalibration procedure are unnecessary because it employs a magnetostrictive bimetal actuator (Moutsopoulou et al., 2024). The other benefit is suppressing vibrations without knowing the specifics of external vibrations and their source.

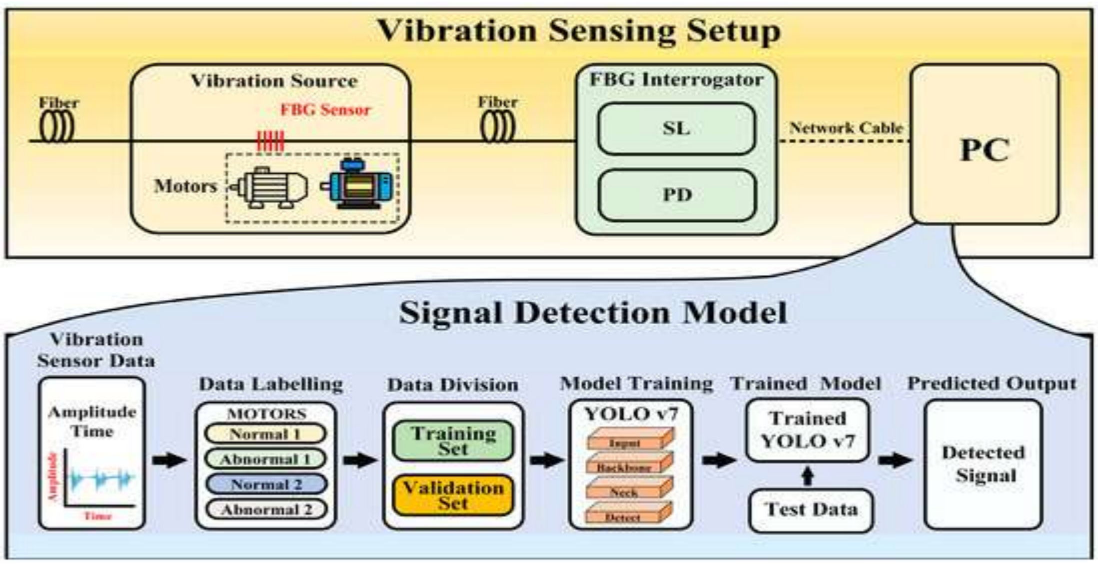
An unbalanced rotating mass system was positioned on the tip of a beam using a simulation that produced an undesired environmental vibration. After outlining the fundamentals of this anti-vibration system, an approximate analytical model was developed for a beam that would be susceptible to both external vibration and the suggested control system. The model demonstrated its ability to forecast the vibrating compound's dynamic behavior (Noori & Narjabadifam, 2019).

Consequently, an inventive three-component control system built, examined, and used shows the potential to reduce the core system's vibration amplitude by roughly 33.6%.

Overview of Smart Materials Used for Vibration Control

The researchers looked at biomimetics, which includes materials, structures, sensor systems, information processing, smart materials, and intelligent buildings. This multidisciplinary technology has emerged as a result of advancements in these fields. In order to reproduce the unique characteristics of nature that are present in the most intelligent of creatures, humans, these advancements have attempted to copy nature in all its forms (Marakakis et al., 2019). The class of sensors and actuators includes intelligent materials and structures. A new generation of high-performance mechanical and structural systems is emerging in engineering. Pasupuleti (2024) states these systems combine sensing, diagnostics, and control capabilities. Numerous smart materials, including shape memory alloys, electrorheological materials, electrostrictive materials, and piezoelectric materials, are employed in active structural applications.

In this new era of material growth, synthetic materials are becoming the most important technology. Thus, creating intelligent materials with brains, nervous systems, and muscular capabilities will be feasible. Because of their potential applications in embedded sensors, autonomous functions, and self-repair, these materials are expected to substantially impact civilization in the coming decades (Pasupuleti, 2024). Built-in or intrinsic sensors, actuators, and control mechanisms that can detect stimuli, react reliably and quickly, and revert to their initial condition when the stimulus has been removed are called smart structures or systems.



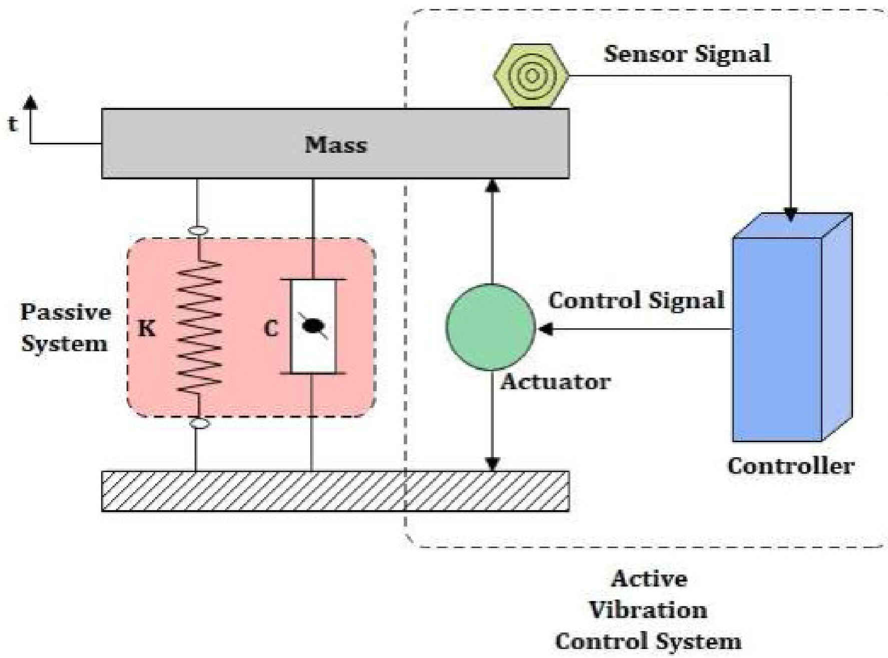
From Intelligent Vibration Monitoring System for Smart Industry Utilizing Optical Fiber Sensor Combined with Machine Learning by Pradeep Kumar

There are two types of smart materials: active and passive. Energy transduction is made possible by active materials' ability to change their geometrical or material characteristics when exposed to electric, thermal, or magnetic fields. Shape memory alloys (SMA), electrorheological (ER) fluids, piezoelectric materials, and magnetostrictive materials are examples of active materials (Zhu et al., 2022). These substances function as actuators and force transducers. SMAs are appropriate for actuation due to their significant recovery force. Conversely, piezoelectrical materials are active and can transform electrical energy into a magnetic force (Qiao et al., 2025). Despite their clever characteristics, the passive Samet materials are not naturally capable of energy transduction. Fiber optic material is an example of a passive smart material. Although these materials have the potential to be sensors, they are neither transducers nor sensors.

Future uses for smart materials include damage arrest materials, which can stop cracks from spreading by automatically creating compressive forces around them. These materials can distinguish between static and shock loading and react by generating significant forces to offset shock stresses in their capacity as shock absorbers (Chaudhari et al., 2024). Over time, any damage can be fixed by these self-healing materials. These intelligent materials might mitigate heat in harsh environments, such as those that space shuttles face when they return to Earth's atmosphere from orbit. These substances are capable of changing their makeup to tolerate extremely high temperatures.

The lightweight nature of piezoelectric materials and their ability to be integrated or affixed to buildings are two of their primary features. They can act as dispersed actuators and sensors. As technology progresses, mechanical systems and components are reduced, notably in the electrical and computer industries (Marakakis et al., 2019). As a result, the mass loading effect of typical transducers makes standard vibration testing impractical at more minor scales. The potential use of piezoelectric materials in buckling control of structures is being investigated (Ghodsi et al., 2022). Bonding piezoceramics to surfaces creates this feature; lateral pressures can change a beam's initially straight profile, forming an anti-symmetrical second mode shape.

Shape memory alloys' capacity to produce intricate movements with few parts is one of their main advantages. They can achieve this with a slight temperature shift, even with the hysteresis effect (Pasupuleti, 2024). However, because SMA actuators rely on heating and cooling for actuation, they have a slow response time. Consequently, rather than high-frequency applications, they are more appropriate for low-frequency and quasi-static response control. Eyeglass frames and cell phone antennae are two successful applications of SMAs (Chaudhari et al., 2024). Taking advantage of their high internal friction, they are also employed as vibration dampers and isolators. They are also employed in robotics to create artificial hands and arms, in passive or active control systems like buckling control, composite structures for form control, and smart or adaptable structures for vibration management.



From Nonlinear Vibration Control Experimental System Design of a Flexible Arm Using Interactive Actuations from Shape Memory Alloy by Ximei Li

A ferromagnetic material undergoes magnetostriction when its shape changes under a magnetic field. Measureable magnetostriction is present in a significant fraction of ferromagnetic materials. A magnetostrictive material's magnetic state changes when an external force strains it; this is crucial to detecting and actuating devices. During normal functioning, magnetostrictive sensors are usually mechanically biased (Pasupuleti, 2024). A compressive load forces the domain structure to align perpendicular to the applied force. When applied magnetic or electric fields drastically alter the rheological properties of magnetorheological (MR) and electro-rheological fluids, they exhibit intriguing behavior (Kumbhar et al., 2014). In semi-active vibration control systems, these fluids function as fast-acting fluid valves devoid of mechanical elements. These materials have great potential for several uses, particularly in bridging the gap between mechanical functionality and electronic control.

METHODOLOGY

Robotic arms are used in various applications such as industrial automation, medical surgery, and aerospace assembly (Zhang et al., 2024). The delicate nature of the function of these robotic arms shows how negatively impactful vibration can be in hindering the effectiveness of this device. The lightweight links make them prone to vibration, especially when they engage in fast movements, or experience external forces or payload changes.

Through dynamic modelling, the creation of a single-degree-of-freedom (SDOF) model is used to describe the joint vibration

$$mx + cx + kx = F (t)$$

where m represents the equivalent mass of the link, c is the damping coefficient, k is the stiffness, and F(t) is the excitation force.

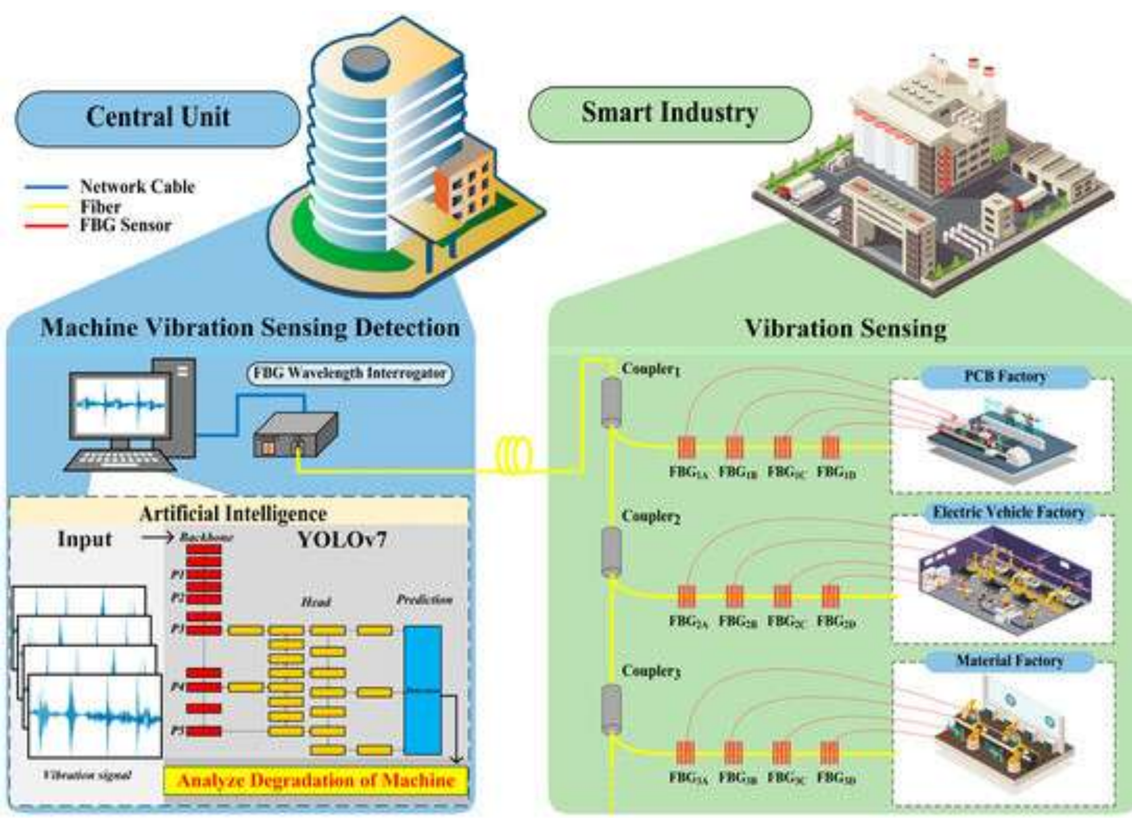
The model is then extended to a multi-degree-of-freedom (MDOF) system to account for multiple links to the robotic arm. The MATLAB Simulink is selected since it can simulate nonlinear dynamics, implement controllers, and visualize vibration responses under varying inputs.

A piezoelectric patch is bonded onto the flexible section of the robotic arm link. When a voltage signal is applied, the actuator generates a counter-vibration force, which cancels the incoming vibration (Pasupuleti, 2024). The piezoelectric actuator is modelled as a force input proportional to applied voltage. The governing equation is:

$$mx + cx + kx = F(t) + \alpha V(t)$$

where α is the piezoelectric coupling coefficient and V(t) is the applied control voltage.

Developing two advanced control algorithms is critical in ensuring efficient and adaptive vibration suppression. One of the algorithms conducts adaptive control that continuously monitors system parameters. It also adjusts actuator input based on real-time feedback. This control system's key advantage is handling uncertainties such as payload variation or material degradation (Qiao et al., 2025). The second algorithm is predictive control, a model based on predictive future vibration trends. It optimizes control inputs over a short prediction horizon. The key benefit of this model is that it prevents vibration buildup before it occurs.



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The system is tested under real-world conditions to evaluate its performance. This aspect is achieved through different vibration frequencies where the excitation forces are applied near and far from the natural frequency to test for resonance handling (Pasupuleti, 2024). Variable payloads are tested by shifting them from light to heavy to simulate robotic tasks in various industries. External disturbances such as random shocks or step disturbances are also applied to evaluate robustness.

RESULTS AND ANALYSIS

The simulation results reveal that smart material-based vibration control is far more effective than conventional methods. For example, the vibration response comparison shows that without control, there are sustained oscillations (Zhu et al., 2022). Passive damping slows decay, but residual oscillations remain. When the smart material is active, it rapidly suppresses the vibration to a few cycles.

CONCLUSION

To sum up, smart materials play a significant role in vibration control in mechanical systems and demonstrate their importance. One of the key findings of this research is that the vibrations reduce performance, accuracy, and safety in mechanical systems. Smart materials provide adaptive, practical solutions, outperforming conventional damping. The simulation results reveal significant improvements in vibration suppression with active control.

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