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Article

The main distinguishing characteristic of active vibration control

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Abstract: Active Vibration Control (AVC) stands out as a prominent technique in the realm of vibration mitigation and structural dynamics. Unlike passive vibration control methods that rely on dampers or isolators, AVC systems actively manipulate forces or motions within a structure in real-time to counteract undesirable vibrations. In this paper, the main distinguishing characteristic of AVC lies in its proactive approach, wherein control algorithms and actuators are employed to actively sense and respond to dynamic changes in the system. The application of Newton’s second law allows to model of the vibration sensors operation, followed by simulations to improve their performance, contributes to the advancement of the active vibration control system by enabling more precise detection and measurement of vibrations.

Keywords: vibration; sensors; active vibration control

1. Introduction

Vibration analysis for Active Vibration Control (AVC) is a critical aspect of the overall process, involving the assessment and monitoring of vibrations within a structure to inform the dynamic response of the Active Vibration Control system [1–6]. This analysis is essential for designing an effective AVC system and ensuring its optimal performance [7–12].

The process of vibration analysis begins with the strategic placement of sensors throughout the structure [13–18]. These sensors, including accelerometers, strain gauges, and displacement sensors, are selected and positioned carefully to capture comprehensive data on the structure’s vibrations [19–22]. Continuously collecting real-time data on the vibrations, these sensors provide crucial information regarding amplitude, frequency, and phase, forming the basis for understanding the structure’s dynamic behavior and designing an effective Active Vibration Control (AVC) system [23–29].

Vibration analysis entails conducting frequency analysis to identify the natural frequencies of the structure. This analysis helps in determining which frequencies contribute significantly to the vibrations, guiding the tuning of the AVC system to address specific resonant frequencies effectively. By leveraging the insights gained from vibration analysis, engineers can optimize the AVC system’s performance and mitigate structural vibrations efficiently [30–32].

Vibrations in multi-story buildings pose a critical challenge to both structural integrity and occupant comfort. Dynamic forces from sources like wind, earthquakes, and machinery can lead to undesirable oscillations, necessitating advanced solutions for effective mitigation [33–35]. Active Vibration Control (AVC) has emerged as a sophisticated technology designed to address these concerns by actively counteracting vibrations in real-time. This article provides an insightful exploration into the principles of Active Vibration Control and its specific application in three-story buildings [36–41].

In this examination, the article delves into the key components of Active Vibration Control, including sensors, actuators, and advanced control algorithms. The sensors, strategically placed within the building, continuously monitor vibrations, providing real-time data to the AVC system. Electromagnetic, hydraulic, or piezoelectric actuators generate forces to counteract detected vibrations, working in tandem to stabilize the structure. Advanced control algorithms, such as adaptive and predictive strategies, interpret sensor data to ensure precise and dynamic adjustments tailored to specific structural characteristics and environmental conditions [42–47].

The application of Active Vibration Control to a three-story building involves addressing structural resonance, wind-induced vibrations, seismic events, and internal sources of vibrations such as machinery. The technology actively identifies and counteracts resonant frequencies, minimizes wind-induced swaying, enhances seismic resilience, and improves overall occupant comfort by mitigating vibrations caused by internal sources [48–52].

As Active Vibration Control continues to evolve, its integration into building design and construction practices holds significant promise for creating safer, more resilient, and more comfortable structures. This abstract provides a comprehensive overview of the challenges associated with vibrations in multi-story buildings, the principles of AVC, and its specific application in mitigating vibrations in three-story structures [53–55].

2. Understanding active vibration control

The management of vibrations in structures is a critical consideration in the realm of engineering, particularly in the construction of multi-story buildings and industrial facilities. Active Vibration Control (AVC) has emerged as a cutting-edge technology aimed at addressing this challenge with unparalleled precision. By leveraging an intricate interplay of sensors, actuators, and advanced control algorithms, AVC represents a proactive and dynamic approach to counteract and minimize unwanted vibrations in real-time [56].

In stark contrast to passive damping systems, which dissipate energy after vibrations have already occurred, Active Vibration Control intervenes actively as vibrations happen. This proactive strategy enables the system to instantaneously counterbalance the forces responsible for the vibrations, providing a level of responsiveness and precision that traditional methods lack.

At the heart of AVC are sensors strategically placed within the structure to continuously monitor vibrations. These sensors, including accelerometers, strain gauges, and displacement sensors, generate real-time data essential for the system’s timely response. Actuators, the driving force behind AVC, then come into play. Whether electromagnetic, hydraulic, or piezoelectric, these actuators generate forces to actively counteract and mitigate the detected vibrations [56].

The sophistication of Active Vibration Control is further emphasized by the implementation of advanced control algorithms. These algorithms interpret the data provided by sensors, determining the optimal response from the actuators. The proactive nature of AVC, combined with these algorithms, allows for precise control and adjustment, enabling the system to address specific frequencies and amplitudes of vibrations with unparalleled accuracy (see **Figure 1**).

Figure 1. Active vibration control.

In this dynamic landscape of structural engineering, where the integrity of buildings and the comfort of occupants are paramount, Active Vibration Control stands out as a technology that goes beyond traditional passive solutions. This introduction sets the stage for a deeper exploration of the principles and applications of AVC, unveiling its potential to revolutionize the mitigation of structural vibrations and enhance the overall performance of diverse structures.

3. Importance of active vibration control

Active Vibration Control (AVC) plays a pivotal role in various industries and applications due to its significance in mitigating and managing unwanted vibrations in structures. The importance of Active Vibration Control is underscored by several key factors [57]:

Structural stability: Active Vibration Control is crucial for maintaining the structural stability of buildings and infrastructure. By actively countering and minimizing vibrations, it prevents long-term structural damage, ensuring the safety and durability of constructed assets.

Occupant comfort: Uncontrolled vibrations in structures can lead to discomfort for occupants, particularly in tall buildings or those situated in regions prone to seismic activity. AVC contributes to a more comfortable living and working environment by minimizing vibrations caused by external forces like wind or internal sources such as machinery.

Preservation of equipment and machinery: In industrial settings, vibrations can negatively impact the performance and longevity of machinery. Active Vibration Control helps preserve equipment by reducing dynamic forces, preventing premature wear and tear, and maintaining operational efficiency.

Enhanced performance in sensitive environments: In environments where precision is critical, such as laboratories or medical facilities, AVC is essential for protecting sensitive equipment from vibrations. This is crucial for applications where accurate measurements or delicate processes are integral to operations.

Seismic resilience: In earthquake-prone areas, AVC becomes a vital technology for enhancing a structure's resilience. By actively responding to seismic forces in real-time, it minimizes the potential damage caused by ground motion, ensuring the safety of occupants and protecting against structural failures.

Optimization of industrial processes: Active Vibration Control is instrumental in optimizing industrial processes by reducing vibrations that could affect manufacturing accuracy and efficiency. It contributes to smoother and more reliable production processes, minimizing disruptions and improving overall operational performance.

Compliance with regulations: Many industries are subject to regulations and standards related to vibrations to ensure the safety and well-being of occupants and the surrounding environment. AVC systems assist in meeting these regulatory requirements, preventing legal and safety issues.

Cost efficiency: While the initial investment in AVC systems may be substantial, the long-term benefits include significant cost savings. By minimizing structural damage, reducing maintenance costs, and prolonging the lifespan of equipment, AVC contributes to overall cost efficiency in both construction and industrial sectors.

4. Dynamic response spectrum

A dynamic response spectrum is a graphical representation of a structure's response to seismic ground motion over a range of frequencies [57]. This spectrum is a fundamental tool in structural engineering and earthquake analysis, providing a visual depiction of how a structure is likely to react to various seismic inputs (see **Figure 2**).

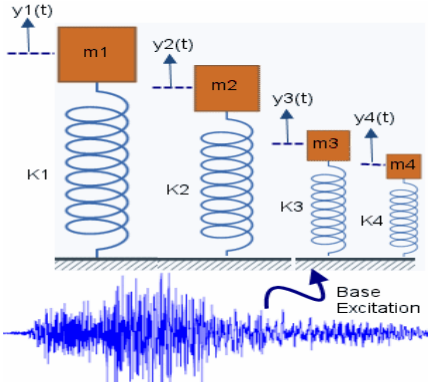

Figure 2. Structure is likely to react to various seismic inputs.

In simpler terms, the dynamic response spectrum illustrates how a building or structure responds to ground shaking at different frequencies during an earthquake. It plots the maximum responses, such as accelerations, velocities, or displacements, that the structure experiences at different natural frequencies [57–58].

The dynamic response spectrum is a graphical representation of how the structure responds to different frequencies of ground motion or external forces. Analyzing the dynamic response spectrum assists in identifying critical frequencies that need attention in the AVC system design (see **Figure 3**).

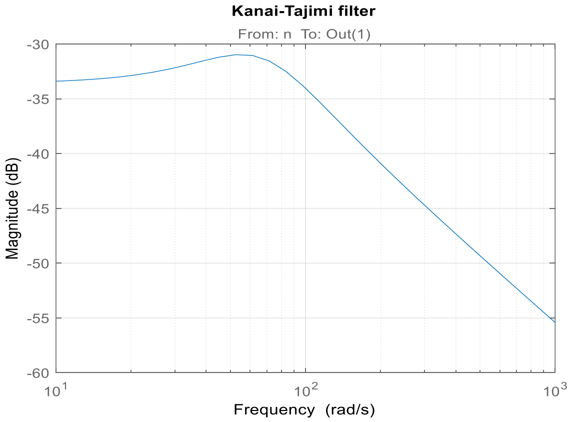

Figure 3. Response spectrum.

The horizontal axis of the spectrum represents the range of frequencies, while the vertical axis depicts the corresponding response amplitudes. Engineers use this information to assess the vulnerability of a structure to different seismic frequencies, aiding in the design and optimization of structures for earthquake resistance.

Dynamic response spectra are crucial in seismic design because they help engineers understand the potential vulnerabilities and weaknesses of a structure under specific earthquake scenarios. By analyzing these spectra, engineers can make informed decisions about the design parameters and materials to enhance a structure’s seismic resilience and ensure the safety of its occupants.

5. Components of active vibration control

Active Vibration Control (AVC) systems consist of several key components working in tandem to actively counteract and minimize unwanted vibrations in structures. These components include sensors, actuators, and control algorithms, each playing a crucial role in the overall functionality of the system.

5.1. Sensors

Sensors are integral to the Active Vibration Control system, as they continuously monitor and measure vibrations in real time. Various types of sensors, such as accelerometers, strain gauges, and displacement sensors, are strategically placed throughout the structure to capture data on the dynamic forces affecting the building. This real-time information is essential for the system to make prompt and accurate adjustments (see **Figure 4**).

Figure 4. Vibration sensor.

A vibration sensor is a sensor affixed directly to a vibrating structure to gauge its vibrations. Operating in tandem with the structure, it captures not the absolute movement $y(t)$ but rather the relative movement $z(t)$. This relative movement is subject to analysis to derive insights into the absolute movement [58].

The vibration sensor itself functions as a system, comprised of a mass, a spring, and a damper, denoted by m, K, and C, respectively.

The established accelerometer model operates on the fundamental principle of motion. This model, elaborated in references [58], is expressed through Equations (1) and (2). The objective of this model is to enhance measurement accuracy by minimizing measurement errors to 1%, achieved through the judicious selection of the damping rate.

$$Z = Y\, \omega^2/\omega_n{}^2\, [(1 - (\omega/\omega_n)^2)^2 + (2\zeta\omega/\omega_n)^2]^{1/2} \tag{1}$$

$$E = (\ddot{z}/\ddot{Y}) - 1 = [1/(1 - (\omega/\omega_n)^2)^2 + (2\zeta\omega/\omega_n)^2] - 1 \tag{2}$$

Z: The relative movement modulus of the sensor; E: The measurement error; Y: The amplitude of movement; ξ: The damping rate, ω_n: The natural frequency of the sensor; ω: Relative frequency.

It's noteworthy that when the relative frequency value approaches the natural frequency of the accelerometer, a resonant frequency ($\omega = \omega_n$) emerges. To ensure proper accelerometer operation while averting resonance, it is imperative that the relative frequency remains equal to or less than one-third of the natural frequency ($\omega_n/3$). The selection of the accelerometer is contingent upon the gain of the vibration frequency.

In order to ascertain the most effective damping rate that minimizes measurement errors, two tests were systematically conducted. The outcomes of these tests were graphically represented in curves illustrating the sensor's damping rate.

In general, commercial accelerometers typically exhibit a damping rate of approximately 0.65, which effectively minimizes measurement error to a value equal to 2%. Damping is a critical characteristic of accelerometers, as it influences the sensor's ability to accurately measure vibrations. A damping rate of 0.65 indicates that the accelerometer's response to vibrations is sufficiently damped, allowing it to provide precise measurements while minimizing errors. This level of damping ensures that the accelerometer's output accurately reflects the true vibration levels experienced by the system under observation. Additionally, the 2% measurement error represents the degree of deviation between the accelerometer's measurements and the actual vibration levels, indicating a high level of accuracy and reliability in the sensor's performance. In this paper, by closely examining and comparing the data presented in **Figures 5** and **6**, it becomes evident that the optimal damping rate, which effectively limits the measurement error to 1%, is identified as 0.675. This specific damping rate has proven to be the most advantageous in achieving the desired precision and accuracy in measurements, making it the preferred parameter for optimizing the performance of the accelerometer in the given context.

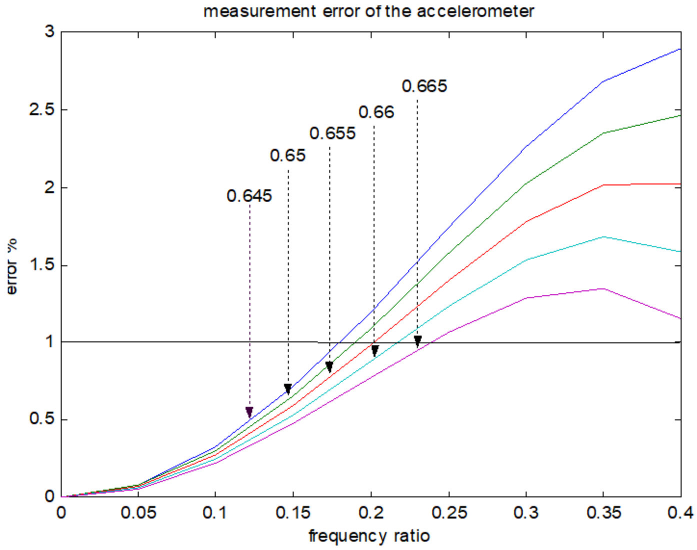

Figure 5. Results of first test.

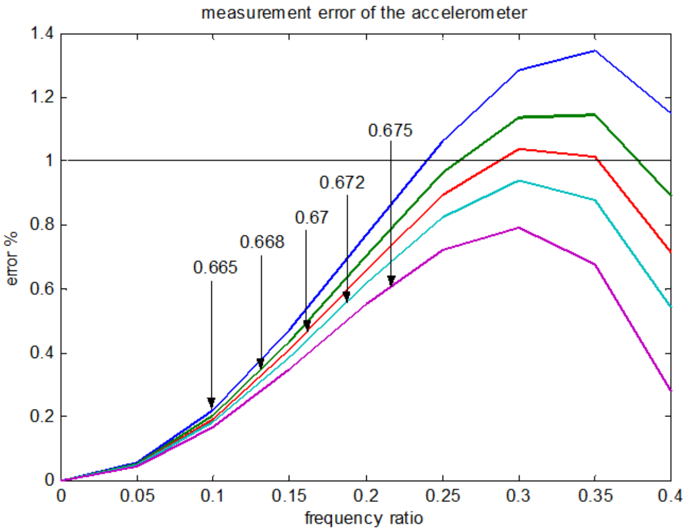

Figure 6. Results of second test.

From **Figures 5** and **6**, the acquired results have the potential to enhance measurement precision to its maximum capacity, thereby contributing to the advancement of accelerometer performance. By identifying and implementing the optimal damping rate, as determined through careful testing and analysis, the accuracy of measurements can be significantly improved. This improvement in precision is essential for obtaining reliable and precise data from the accelerometer, ultimately leading to enhanced performance in various applications and fields. The refined measurement precision ensures that the accelerometer operates at its best, providing more accurate and reliable information about the vibrations and movements of the monitored structure. This, in turn, supports the overall effectiveness and functionality of the accelerometer in its intended use.

The ultimate goal of this approach was to enhance the operation of the Active Vibration Control (AVC) system. By obtaining a precise and reliable mathematical model of the vibration sensor, and ensuring high-precision measurement performance with low error, we were able to contribute to the overall improvement of the AVC system. A more efficient and precise AVC system enables faster and more accurate detection and correction of undesirable vibrations, resulting in better protection of structures and equipment, reduced damage, and increased safety and reliability of the systems.

5.2. Actuators

Actuators are devices responsible for generating forces to actively counteract the detected vibrations. These devices come in different forms, including electromagnetic, hydraulic, and piezoelectric actuators, depending on the specific application and requirements [59,60]. Actuators are strategically positioned within the structure to apply dynamic forces that oppose and mitigate the effects of external and internal vibrations (see **Figure 7**).

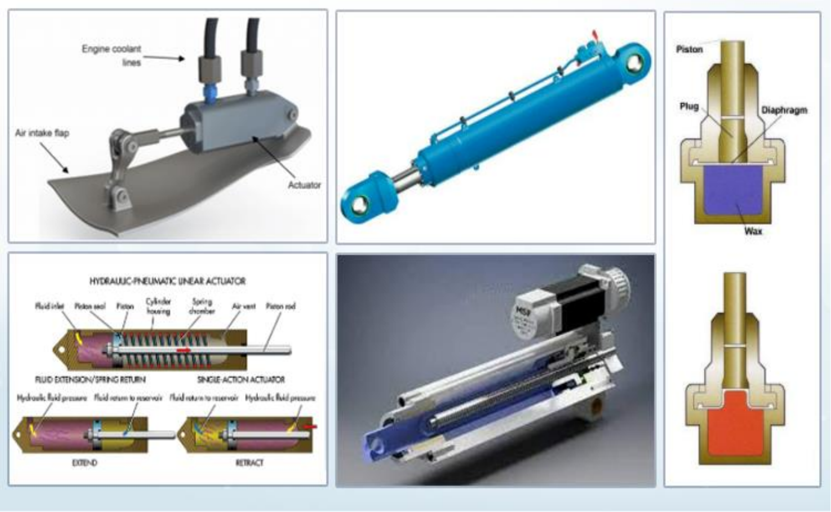

Figure 7. Different type of actuators.

5.3. Control algorithms

The effectiveness of Active Vibration Control relies on advanced control algorithms. These algorithms interpret the data provided by the sensors and determine the appropriate response from the actuators. Two common types of control strategies are adaptive control and predictive control. Adaptive control allows the system to adjust its parameters based on changing conditions, while predictive control anticipates future vibrations, enabling proactive measures. These algorithms ensure precise and dynamic adjustments tailored to specific structural characteristics and environmental conditions (see **Figure 8**).

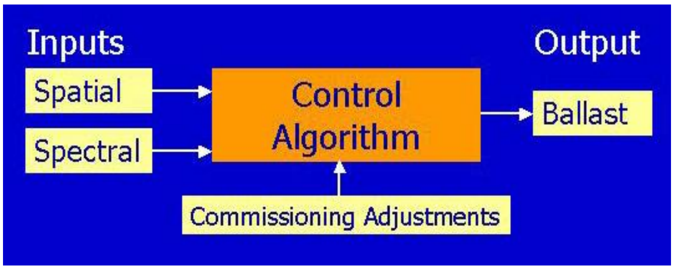

Figure 8. Control algorithms.

The collaboration of these components enables Active Vibration Control systems to function proactively in real-time. Sensors continuously gather data, control algorithms analyze this information, and actuators generate forces to actively counterbalance the forces causing vibrations. This holistic approach allows for precise control and adjustment, providing a highly effective solution to mitigate structural vibrations in diverse settings, from buildings to industrial facilities [61–63].

6. Conclusion

Vibration analysis for Active Vibration Control is a comprehensive process that involves sensor deployment, data collection, frequency and mode shapes analysis, dynamic response spectrum examination, algorithmic processing, and system design optimization. This meticulous analysis ensures that the AVC system is tailored to effectively counteract vibrations and enhance the structural performance of the targeted system or building.

In this study, we began by dissecting the operation of vibration sensors using fundamental principles of physics, notably Newton’s second law. This law states that the force applied to an object is equal to the mass of the object multiplied by its acceleration. By applying this law to the context of vibration sensors, we were able to establish a mathematical model describing the relationship between the force applied to the sensor, its mass, and the acceleration it measures.

Once the mathematical model was established, we subjected it to simulation tests. These simulations allowed us to analyze the behavior of the sensor in various vibration scenarios and verify the validity of the model. We adjusted the parameters of the model to optimize the sensor’s performance, aiming to minimize measurement error to a value below 1% and increase precision to 99%.

Author contributions: Conceptualization, ZG and SB; methodology, ZG; software, ZG; validation, ZG and SB; formal analysis, SB; investigation, ZG and SB; resources, ZG; data curation, ZG; writing—original draft preparation, ZG; writing—review and editing, ZG; visualization, SB; supervision, ZG; project administration, SB; funding acquisition, SB. All authors have read and agreed to the published version of the manuscript.

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