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Existing Vibration Control Techniques Applied in Construction and Mechanical Engineering

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Abstract. Vibration control techniques are various methods and devices designed to suppress unwanted vibrations, ultimately enhancing system performance and mitigating potential adverse effects. These techniques are widely applied in modern engineering, deducting the detrimental consequences of excessive vibrations, such as structural damage, noise generation, energy waste, and compromised functionality. The general classification of vibration control techniques includes passive, active, and semi-active control. Specifically, passive techniques like Tuned Mass Dampers (TMDs), active techniques like inertia mass actuators, and semi-active control devices such as magnetorheological dampers (MR dampers) are examined in this paper. Meanwhile, structural characteristics, mathematical models using formulas, and applications across diverse fields are analysed for each category. Moreover, efficiency analysis of all the discussed devices for vibration control is conducted through comparative analysis and detailed evaluation. In this case, valuable insights are gained regarding the overall effectiveness of these devices in different scenarios, enabling informed decision-making and potential advancements in the field. Furthermore, the paper extends its scope by prospecting future trends based on the identified advantages and disadvantages of the presented vibration control techniques. These insights shed light on the potential directions for further development, providing a roadmap for advancing vibration control techniques.

Keywords. Mechanical vibration; Vibration control techniques; Passive control; Active control; Semi-active control.

1. Introduction

The measurement of a periodic sequence of oscillations concerning an equilibrium point is known as mechanical vibration [1]. Free vibration, forced vibration, and self-excited vibration (also known as flutter) are the broad categories into which mechanical vibrations can be divided [2]. While vibrations can have beneficial applications, such as generating sound in musical instruments, unpredictable vibrations like earthquakes and tsunamis can cause significant damage to buildings, bridges, and other structures. More

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in detail, vibrations can cause substantial implications in the integrity of structure mechanisms and influence the accuracy of processing industries like semiconductor manufacturing, resulting in severe issues, such as equipment failure, safety hazards, foundation settling, and structural damage. For example, as highlighted in Goyder's research on the vibration caused by flow in heat exchangers, excessive vibration can lead to the failure of bundles of heat exchanger tubes [3]. Therefore, unpredictable and large-scale vibrations can disrupt and impact people's daily activities, safety, comfort, and well-being.

Although undesirable vibrations cannot be eliminated, the risk of causing breakdown can be minimized through vibration control techniques, which have been extensively researched over an extended period. During the early 20th century, Frahm created a dynamic vibration absorber (DVA), a passive vibration control mechanism, which decreased the amplitude of oscillations in the structures and essentially promoted safety [4]. Nevertheless, DVAs have limited effectiveness for attenuating vibrations since they are designed for specific frequencies, and their performance decreases significantly outside this range. Subsequently, scholars such as Ormondroyd and Den Hartog developed additional passive vibration control techniques, which could change the content and frequency of the vibrations [5, 6], overcoming the limitation of reduced effectiveness in the presence of deviations. However, the advanced characteristics of these techniques still restricted their adaptability to varying vibration scenarios, including fixed properties that cannot be adjusted in real-time, less efficiency in attenuating vibrations, and lack of adjustability, making it harder to fine-tune the system.

In the 1920s, electrical contacts and a solenoid valve were used in shock absorbers, contributing to modern active vibration control schemes [7]. Then in the 1950s and 1960s, the first operational control system idea was enacted by Kobori and Minai, which was considered more advanced due to their ability to adapt in real-time to changing road conditions, improve ride quality, enhance safety, optimize vehicle performance, and offer potential for future advancements and integration with vehicle systems. [8, 9]. Meanwhile, in 1972, Yao demonstrated active control in civil engineering structures in practice [10]. These systems were developed for aerospace applications, including active controllers for isolating helicopter rotors with displacement sensors, accelerometers, and communication interfaces [11]. In this case, active controllers offered performance capabilities that passive structures could not provide, such as optimization of performance trade-offs, fault tolerance, and redundancy. Nevertheless, advances in computations and simulation led to more complex structural vibration analysis, like exerting control of electrical equipment with variable vibrations. This highlights the enormous demand for more effective vibration control algorithms.

During the 1980s and 1990s, scholars such as Crawley and De Luis began applying piezoelectric materials like quartz and lead zirconate titanate (PZT) to active control systems, further advancing the field of vibration control [12]. The modified vibration control approaches can more accurately and dynamically adapt to changing vibration conditions using accurate sensors and actuators. The need for semi-active control systems has dramatically expanded while active and passive control systems continually evolve. Significant research has focused on using semi-active control systems since they offered a compromise between passive and active control systems, combining the dependability of passive control with the customizable parameter features of dynamic control systems (e.g., Hrovat et al. [13]).

Vibration control techniques have continued evolving with new materials and innovative applications with more sophisticated and effective methods. They are still considering factors like high costs, massive energy consumption, and maintenance; modern vibration control techniques must be analyzed and reassessed to ensure safety and the long-term sustainability of critical infrastructure and equipment.

This paper analyzes the applications of vibration control techniques, classified based on different categories, including active, passive, and semi-active systems. Furthermore, future trends in developing vibration control techniques are discussed and predicted to manifest the evolving role of vibration control techniques in scientific and industrial applications, reinforcing their significance in these fields.

2. Passive Vibration Control Techniques

2.1. General Summary of Passive Vibration Control

Passive control systems involve passive devices, which run independently without external power and use the structure's intrinsic motion to generate control forces. Passive vibration control techniques commonly employ apparatus and methods for isolating energy. Typical energy absorbers and energy dissipation devices include Tuned Mass Dampers (TMDs), Tuned Liquid Dampers (TLDs), metallic dampers, friction dampers, viscoelastic dampers (VEDs), viscous fluid dampers, Shifted piezoceramic dampers, magnetic dampers, and dynamic absorbers are all intended to dissipate or absorb energy and reduce undesirable vibrations [14]. These devices are installed in structures to absorb seismic or wind-induced energy [15] effectively. Several passive control devices are usually combined and implemented in systems. In the subsequent sections, an examination of the leading passive control devices and their applications will be conducted. The analysis will encompass both the positive aspects and negative ones of these devices.

2.2. Typical Passive Control Devices

2.2.1. Tuned Mass Dampers (TMDs).

TMDs are widely recognized and utilized as damping devices in passive control techniques for structural vibration control. Dating back to 1909, the dynamic vibration absorber invented by Frahm as a prototype of early TMDs to suppress ship rolling motion, TMDs have evolved into various types to absorb vibrations effectively [4]. The four main categories of TMDs include conventional TMDs, pendulum TMDs (PTMDs), bi-directional TMDs (BTMDs), and tuned liquid column dampers (TLCDs) [16].

A TMD works by having a mass tuned to the structural vibration frequency. In figure 1(a), the equations of motion for this SDOF-mass damper system can be written as Eq. 1 [17].

$$[m_0 + m_2\ m_3\ m_3\ m_1\ ]\{\ddot{x}\ \ddot{y}\ \} + [c_0\ 0\ 0\ c_1\ ]\{\dot{x}\ \dot{y}\ \} + [k_0\ 0\ 0\ k_1\ ]\{x\ y\ \} = \{f\ 0\ \} \quad (1)$$

where mass m_0, damping coefficient c_0, and stiffness constant k0 describe the characteristics of the SDOF system. f is the external excitation force, x is the displacement of the SDOF, and y is the relative displacement between the SDOF and the mass damper.

For a TMD given in figure 1(b), the parameters can be written as Eq. 2 [17]:

$$m_1 = m_2 = m_3 = m_{TMD} \tag{2}$$

Where m_1, m_2, and m_3 are equivalent to the actual mass of the TMD, m_{TMD}; the ratio of damping c_1 and the spring constant k_1 are equal to the damper's and the spring's physical values, respectively. When the structures' vibration occurs, the mass moves in the opposite way, absorbing and consuming the vibration energy, thereby reducing the structural response and advancing stability.

Additionally, TLCDs can be considered a specific type of TMDs. For a TLCD in figure 1(c), the parameters can be written as Eq. 3, 4, 5 and 6 [17]:

$$m_1 = m_2 = \rho AL = m_{TLCD} \tag{3}$$

$$m_3 = \rho Ab \tag{4}$$

$$c_1 = \frac{1}{2}\rho A\delta|\dot{y}| \tag{5}$$

$$k_1 = 2\rho Ag \tag{6}$$

The mass coefficients m_1 and m_2 correspond to the combined liquid mass of the TLCD, denoted as m_{TLCD}, while m_3 represents the fluid mass of the horizontal section exclusively. The TLCD is characterized by the following parameters: liquid density ρ, cross-sectional area A, total length L, flat width b, head loss coefficient δ, and liquid level velocity $\dot{y}$. g represents the acceleration due to gravity.

TLCDs use the resonance effect within a vertical liquid column to control vibrations. By precisely designing the liquid's mass and the container's geometry, TLCDs achieve targeted vibration control effects. The tuning of the liquid column's resonant frequency matches the structure's vibration frequency, resulting in a reduction in vibration magnitude [18].

TMDs and TLCDs are crucial in mitigating excessive vibration energy and preventing the initiation, propagation, and detrimental consequences of mechanical issues in structures. TMDs are commonly installed at the upper portions of tall buildings, while TLCDs offer effective vibration control by manipulating liquid column resonance. By integrating these passive control devices, structures can enjoy increased longevity and improved performance by effectively managing vibrations [19].

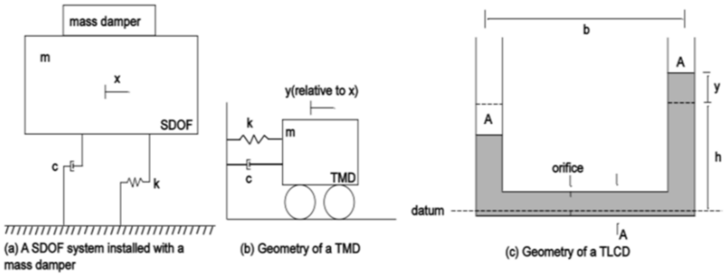

Figure 1. Modeling of an SDOF system and mass dampers

2.2.2. Tuned Liquid Dampers (TLDs)

In 1966, Banning et al. conducted a study that focused on the dynamic characteristics of sloshing liquids. Several nutation dampers have been created as a result of this research. Therefore, these innovative dampers effectively take in and expel energy through the oscillation or liquid sloshing motion confined within a container [20]. Among notable devices developed from the research are the TLD and the TLCD.

TLDs share a significant similarity with TCLDs in their liquid utilization to control structures' vibrations. In the experiment by Gardarsson in figure 2, the shaking table had a $1.2m \times 1.2m$ platform that could move horizontally in one direction through a servo-hydraulic system [21]. A model of a TLD was affixed to a load cell, which was securely bolted to the shaking table. Wave response was assessed using capacitance-type wave gauges and laser-induced fluorescent imagery. The laser-induced fluorescent imagery employed a thin laser sheet and fluorescein dye dissolved in water to visualize water surface profiles and gradients to investigate the temporal and spatial variations in water surface response within the TLDs. It was recorded that TLDs utilize the movement of a shallow liquid within the tank to modify a structure's dynamic characteristics and dissipate its vibrational energy—the liquid sloshing motion within the tank counterbalances external vibrations, reducing their impact.

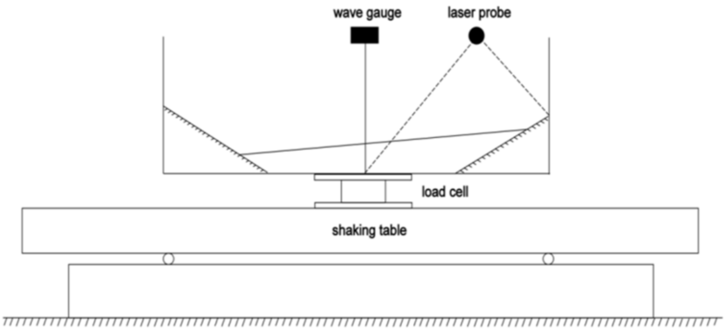

Figure 2. Schematic view of an experimental setup

2.2.3. Hysteresis Devices

Metallic and friction dampers are the two primary forms of hysteresis devices. Metallic dampers' effectiveness and damping mechanism depend heavily on the specific material used, including steel, aluminum, copper, and other options. As depicted in figure 3(a), a straightforward bi-linear hysteretic model of force-deformation is employed [22]. The device-brace assembly, consisting of the device, the supporting brace elements, and an additional hysteresis damper, is installed in the structural frame bay. In this arrangement, metallic dampers lose energy by deforming inelastically inside the constituent material of the damper.

As given in figure 3(b), when deformation occurs in a building installed with the device, the yield force P_y can be described as Eq. 7 [22]:

$$P_y = k_d \Delta_{yd} = SRk_s \left(1 + \frac{1}{k_b/k_d}\right) \Delta_{yd} \tag{7}$$

Where ks represents the story stiffness, Δ_{yd} represents the yield displacement, kd and kb stand for the device stiffness and bracing stiffness, respectively, and $SR = k_{bd}/k_s$ is the ratio of the assembly stiffness k_{bd} to story stiffness k_s.

Moreover, the combined stiffness of device–brace k_{bd} assembly in figure 3(c) can be expressed as Eq. 8:

$$k_{bd} = \frac{1}{(1/k_b)+(1/k_d)} \tag{8}$$

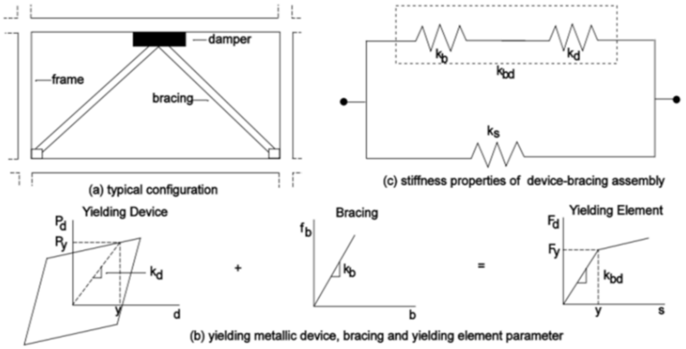

Figure 3. Yielding metallic damper

A friction damper is another type of hysteresis device. Friction dampers are usually made of steel, aluminum alloy, or other friction material (such as polytetrafluoroethylene). By allowing relative motion within the device in response to the structural signal, friction forces are induced, and the energy is effectively dissipated, thereby diminishing the amplitude and response of the structure [23].

The equation for friction dampers can also be derived from Eq. 7. As shown in figure 4(a), the stiffness kd of the device can be regarded as infinitely large in this case; hence k_{bd} is equal to k_b, as shown in Eq. 9 [22]:

$$k_{bd} = k_b;\ SR = \frac{k_b}{k_s} \tag{9}$$

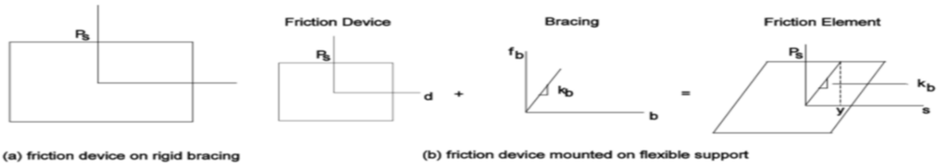

Figure 4. Idealized hysteretic behavior of friction damper

Figure 4(b) illustrates that the yield or slip load P_s is dependent on the deformation Δ_y encountered by the device-brace assembly as written in Eq. 10 [22]:

$$P_s = k_b\Delta_y = \frac{k_b}{k_s}k_s\Delta_y = SRk_s\Delta_y \tag{10}$$

The fundamental equation that creates the relationship between the mechanical characteristics of a friction element is Equation 10. It is apparent that the behavior of a friction element is determined by the slip load P_s, the stiffness ratio SR, and the displacement of the brace Δ_y where the apparatus begins to budge. Only two are considered independent among these variables, as Δ_y can be found in Eq. 10 [22].

2.2.4. Viscoelastic Dampers (VEDs)

Viscoelastic (VE) layers are joined to steel plates by sulphuration to form VEDs. When VEDs are used in structures subjected to dynamic loads, the vibration of the systems will cause shear deformation of the VE layers, which will subsequently cause energy dissipation and lessen the emotional responses of the structures [24]. According to figure 5 [25], the vibratory energy is dissipated in the two systems due to shear strains in the case of the restricted VE materials and direct stresses in the case of the unconstrained VE materials that adhere to the elastic layer. It is known that some high polymers display VE behavior.

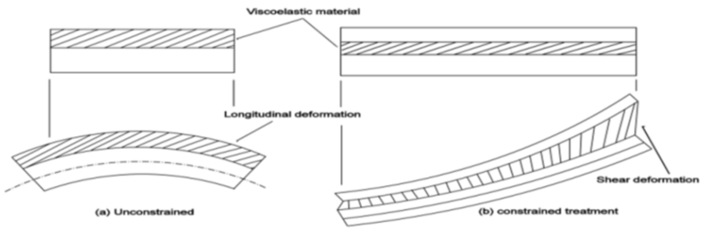

Figure 5. Basic viscoelastic damping arrangements

There are two distinct categories of fundamental configurations, as seen in figure 5. Direct stresses cause the vibratory energy of unconstrained viscoelastic materials linked to the elastic layer to be lost, whereas shear strains prevail in the case of constrained viscoelastic materials.

In the case of unconstrained treatment, viscoelastic materials are applied directly to the structure without additional constraints. This allows the viscoelastic material to freely deform in response to the applied forces, mainly longitudinal deformation, which occurs within the viscoelastic layer in direct contact with the vibrating structure, as shown in part (a) of figure 5, represented by the shade.

However, the constrained treatment situation is different. The viscoelastic material is sandwiched between rigid layers or confined within a cavity formed by wooden structures, represented by the shade in part (b) of figure 5; the shear deformation primarily occurs within the viscoelastic layer due to the constraints imposed by the surrounding rigid layers or structures. The constrained treatment configuration ensures that the viscoelastic material is kept within a defined space, allowing for controlled deformation and enhanced energy dissipation. By confining the viscoelastic material, the constrained treatment effectively dampens shear deformation in the structure.

2.2.5. Base Isolation Systems

Base isolation systems are designed to isolate a sensitive component or equipment from vibrations transmitted through a supporting structure. Various passive isolators and dampers are traditionally utilized to reduce mechanical vibrations [26].

Seismic base isolation is a well-established seismic protection method that has been employed for over a century. It uses flexible bearings or isolators between the structure and its foundation, serving as shock absorbers to dampen seismic forces and vibrations transmitted from the ground. The primary objective of base isolation is to protect the structure and its contents from potentially detrimental ground motion by mitigating inter-story drifts and floor accelerations, particularly in the frequency range that exerts the most significant impact on the building. This approach offers a cost-effective solution that enhances structural resilience and ensures the integrity of buildings [27].

2.3. Assessment of Passive Control Devices

2.3.1. Assessment of TMDs

TMDs are frequently employed in buildings, particularly to withstand seismic activity and wind-induced vibrations in high-rise construction, towers, chimneys, and bridges. TMD installation successfully lowers structural response and enhances occupant comfort [28]. Two notable applications of TMD in buildings include the John Hancock Building in Boston and the Citicorp Center in New York City [29]. On the other hand, Wang et al. researched the vibration control of high-speed railway bridges using TMDs. The study demonstrated the effectiveness of TMDs in reducing bridge vibrations and improving the overall dynamic behavior of the structures [30].

TMDs provide excellent vibration reduction in vibration reduction within a minimal frequency range where the mass and stiffness parameters can be adjusted to achieve optimal results [31]. However, they are less effective for multi-modal or wide-band vibration systems. They cannot adapt to changing vibration characteristics of the primary structure and lose their performance in vibration control [32].

TMDs have higher design, manufacturing, and installation costs, requiring precise parameter tuning and structural adaptation [33].

2.3.2. Assessment of TLDs

TLDs utilizing liquid motion have found wide-ranging applications in various industries. They have been successfully implemented not only in space satellites [34], but also in marine vessels [35] and ground structures [36]. These dampers reduce and absorb vibration energy, particularly during severe wind or earthquake events [18].

TLDs perform excellently attenuate vibrations with extremely low amplitudes barely perceptible to humans. These devices offer simple frequency adjustment, unrestricted vibration amplitude tolerance, and adaptability to existing structures through container distribution. Additionally, the water contained within the vessels can serve various purposes following severe calamities [37]. However, regular maintenance is required.

TLDs require higher manufacturing and installation costs than passive damping devices, but low fluid columns and masses maintenance cost is needed [37].

2.3.3. Assessment of Hysteresis Devices

Hysteresis devices, including metallic and friction dampers, are adopted in buildings, bridges, automobiles, rail and road vehicle systems, and space structures to reduce unwanted excitation forces [38].

Hysteresis devices provide several benefits over active and semi-active dampers. These include robust and constant hysteresis behavior, insensitivity to loading rates, resistance to ambient temperature, dependability, and engineers' expertise with their material characteristics [39]. Long-term upkeep is necessary, though.

Metallic and friction dampers are extensively utilized, owing to their capacity to efficiently dissipate energy at an affordable cost while offering simple installation and maintenance procedures [40]. The components of these devices need to be checked and replaced regularly to ensure optimum performance.

2.3.4. Assessment of VEDs

VEDs are suitable for various building and bridge constructions, especially high-rise buildings and long-span bridges [41]. The World Trade Center's twin towers in New York, the Columbia Seafirst Building in Seattle, and the Two Union Square Buildings in Seattle are three examples of well-known uses [42].

VEDs are suitable for vibration systems in a wide frequency range, with the ability to adapt to different vibration requirements by choosing the right shape and material. However, the performance of the VE material may degrade at high temperatures and over long periods of usage, so its implementation should be monitored to ensure long-term stability [24].

VEDs are moderately expensive to manufacture and install but require regular inspection and maintenance of VE material properties because these properties are affected by factors such as frequency and temperature [24].

2.3.5. Assessment of Base Isolation Systems

Base isolation systems are commonly used in structures with sensitivity to vibrations, such as laboratories, hospitals, and industrial facilities, effectively reducing the transmission of vibrations. Frank Lloyd Wright's Imperial Hotel in Tokyo is a well-known illustration of the efficacy of isolation mechanisms [43]. This ancient structure, finished in 1921, was built on a thin layer of hard soil, further stabilized by a layer of mud. The hotel survived the 1923 Tokyo earthquake by acting as a protective barrier against destructive ground motion.

Base isolation systems are widely used to mitigate vibrations with high amplitudes and a wide range of frequencies, isolating the structure from the source of vibration through resilient materials or mechanical systems. However, they may be less effective when the frequency is low [44].

Base isolation systems may provide long-term benefits by reducing structural damage and maintenance costs [45].

3. Active Vibration Control Techniques

3.1. General Summary of Active Vibration Control

Active Vibration Control refers to techniques and methods to reduce or control unwanted vibrations in mechanical, electrical, and structural systems, particularly those of large size or high impact. It uses an active feedback control system that continuously measures and detects vibrations and quickly responds by generating counteracting forces to neutralize or offset them. As a result, active vibration control systems aid in getting over the restrictions of addressing a single structural resonance or a particular disturbance frequency, and incorporating active components allows for system parameter adaptability [46]. Hence, significant attention has been devoted to employing active control methods for both machinery mounting and structural control. This has resulted in extensive research and development efforts spanning more than two decades, leading to the proposal of various systems and methods (e.g., Inman, 1989; Fuller, Elliott, & Nelson, 1996) [47]. In 2003, active vibration control was reviewed by Alkhatib and Golnaraghi and showed the potential for real-time adjustments to counteract vibrations by utilizing algorithms and actuators [48]. In these cases, active control uses adjustable damping elements or variable stiffness devices to achieve improved adaptability and energy efficiency in controlling vibrations. The most representative instances of active vibration control techniques are addressed in the demonstration of inertia mass actuators, electronic damping, and piezoelectric devices.

3.2. Inertial Mass Actuators

Inertial mass actuators are devices used in active vibration control systems to counteract and control unwanted vibrations in a mechanical system. These utilize the inertial mass principle to generate forces that dampen or eliminate vibrations. These actuators use the principle of inertia to create details that effectively reduce vibrations and improve the overall system's stability and performance [46].

For calculations, inertial mass actuators employ feedback control algorithms to continuously monitor and analyze the vibrations in a structure or system. Based on the measured data, the control system commands the inertia mass actuators to produce forces that counteract the unwanted vibrations.

As shown in figure 6, inertia mass actuators consist of a mass element that can be moved in response to vibrations, along with a mechanism to generate the necessary acceleration. The mass piece can be a separate block or a part of the structure. The actuator is strategically positioned and mounted within the system to sense and counteract the vibrations effectively.

A proof mass, supported by a spring, forms the core of an inertial actuator and is propelled by an external force. Small actuators typically produce the point through an electromagnetic circuit [49]. Meanwhile, the magnets with a supporting structure or, in certain instances, the coil can serve as the suspended mass [50]. The typical approach for achieving a wide-range actuation involves attaching the inertial mass to the main structure using flexible springs. The system experiences a resonance due to this configuration, which results in the force acting on the primary form having dynamic properties. Therefore, only when the inertial mass actuator runs far above the resonance frequency can it be said to be a reliable force generator. [46].

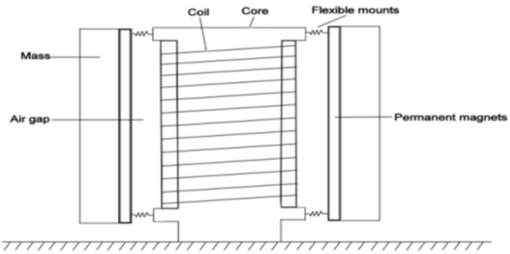

Figure 6. A sketch of the inertial actuator

The actuator consists of a fixed core to which a cylindrical coil of electronic components is attached, as shown in figure 6. The body is surrounded by a cylindrical object shaped like a tube containing a permanent magnet. It is usually made of aluminum alloy for maximum strength and weight and is surrounded by copper wire coils to obtain a high magnetic field between the air gaps. The mechanical system will denote the mass and the flexible mounts. The air gap between the core and permanent magnets ensures magnetic coupling without interference. Finally, the permanent magnets generate a static field, interacting with the coil to achieve the desired actuation of the inertia mass.

Modeling the mechanical system as a mass connected to the coil by a spring and a damper is possible. The spring and the damper are flexible mounts on each side of the group for the actuator. The equation of motion for a single-degree-of-freedom oscillator of mass m, damping constant c, stiffness k, displacement $u(t)$, and driving force on the mass $p(t)$ can be written as Eq. 11 [51]:

$$m\ddot{u} + c\dot{u} + ku(t) = p(t) \tag{11}$$

The derivative of the displacement $u(t)$ is denoted $\dot{u}$, which is the velocity of the mass, and the second derivative of $u(t)$ is the acceleration, which is characterized $\ddot{u}$. For sinusoidal motion, the equation can be transformed into the frequency domain, which is given as Eq. 12 [51]:

$$q\omega mU(\omega) + cU(\omega) + \frac{1}{q\omega}kU(\omega) = P(\omega) \tag{12}$$

where the acceleration is given by $q\omega$U(ω) and the displacement is $\frac{1}{q\omega}U(\omega)$. The mechanical impedance, $I_m(\omega)$, is defined as the ratio between the force $P(\omega)$ and the velocity $U(\omega)$. For a single-degree-of-freedom system, the mechanical impedance is given by Eq. 13 [51]:

$$I_M(\omega) = \frac{P(\omega)}{U(\omega)} = q\omega m + c + \frac{1}{q\omega}k \tag{13}$$

In order to obtain the undamped natural frequency f_0, equation is solved with $P(\omega)$= 0 and $c = 0$

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{14}$$

Additionally, it can be demonstrated that the resonance frequency is influenced by damping c rather than the input force. Suppose the actuator is to be used in an active vibration control application since the resonance frequency will cause the actuator to create a 180-degree phase shift. In that case, it must be below the lower frequency limit where the actuator should operate. A controller has difficulty working effectively when there is such a significant phase change [51].

3.3. Electronic Damping

3.3.1. General Summary of Electronic Damping.

Electronic damping is used in vibration control systems to mitigate or suppress unwanted vibrations in mechanical structures. The fundamental principle of electronic damping can be described as follows: sensitive piezoelectric ceramic transducers are strategically positioned on a system to detect the dynamic strains caused by structural vibrations. When the sensing transducer undergoes deformation, it generates an electric current fed into a negative feedback amplifier. This amplifier both amplifies and alters the phase of the signal. Subsequently, the output voltage from the amplifier is applied to a separate piezoelectric transducer located elsewhere in the structure. It involves using electronic devices and control algorithms to monitor and respond to the vibrations in real time actively. Under impact excitation conditions, experiments have been carried out on a cantilever beam to investigate electronic damping. Piezoceramic transducers were utilized as sensors and drivers, employing velocity feedback [52].

3.3.2. The Controlled Electronic Suspension System.

One of the most common examples of electronic damping is the Controlled Electronic Suspension System (CES), a technology designed to control and dampen vibrations in mechanisms actively. A potent Electronic Control Unit (ECU) [53] activates the CES system. The ECU, the brain of the CES unit, is created to fully use the electro-hydraulic valving system by analyzing input data given by several sensors positioned at strategic points on the vehicle.

The basic principle of the CES system works by utilizing various sensors to monitor the vehicle's dynamics, including acceleration, velocity, and wheel position. These sensors provide continuous feedback to a central control unit, which analyzes the data and determines the appropriate damping adjustments needed to reduce vibrations and improve ride comfort [53].

Based on the sensor inputs, the CES system can adjust the damping characteristics of each suspension component in real-time. It can vary the stiffness or damping force of the shocks or dampers, allowing the system to respond rapidly to changes in road conditions, vehicle speed, or driver inputs [54].

For example, when encountering a pothole or an uneven road surface, the CES system can detect the disturbance through the sensors and quickly adjust the damping forces to mitigate the vibrations. It can stiffen the suspension to minimize body roll during cornering or soften it to absorb bumps and enhance ride comfort.

The Controlled Electronic Suspension System is of significant importance in modern vehicle engineering. By actively adjusting the damping characteristics of the suspension, it enhances ride comfort, handling, and overall vehicle stability, which implies that the mechanism plays a vital role in providing a smooth and controlled driving experience, improving both safety and performance in vehicles [55].

3.3.3. Digital Ride Control Valve Technology ($DRiV$™).

Derived from the CES model, Digital Ride Control Valve Technology ($DRiV$™) incorporates a cost-effective adjustable damper technology tailored for the mechanism segment. In contrast to CES, it eliminates the need for a dedicated ECU, reducing system costs. The system's design includes an internal valve and integrates the electronics directly into the damper, ensuring minimal dead length and efficient packaging [53, 54].

3.3.4. Piezoelectric Devices.

The capacity of some materials to produce an electric charge in response to applied mechanical stress or deformation is known as the piezoelectric effect, and piezoelectric devices are transducers that use this property and vice versa [56]. These devices use piezoelectric materials such as quartz, ceramics, or specific polymers.

Piezoelectric materials (like lead zirconate titanate or PZT), have a crystalline structure with an asymmetrical arrangement of positive and negative charges. The charges balance each other out in their natural state, resulting in no net electric polarization [57].

In active vibration control, piezoelectric devices play a significant role in generating controlled forces for vibration suppression. The first advantage is in sensing. When subjected to mechanical vibrations, the piezoelectric material generates an electrical charge proportional to the applied stress [58]. These sensors provide valuable real-time data about the vibrations' amplitude, frequency, and other characteristics, enabling effective control system feedback.

Piezoelectric devices can also act as actuators in active vibration control systems. Applying an electric field to the piezoelectric material undergoes mechanical deformation or displacement [59]. This controlled deformation can generate forces that counteract and actively suppress the vibrations.

The piezoelectric materials enable the design and implementation of effective vibration control systems that can adapt and actively mitigate vibrations in real-time, leading to improved structural integrity, reduced vibrations, enhanced performance, and increased comfort in a wide range of applications like ultrasonic cleaning and drilling, piezoelectric accelerometers [60], and the active suspension systems which have been mentioned earlier.

3.4. Assessment of Active Vibration Control

3.4.1. Applications of Active Vibration Control.

Active control systems have various applications in civil engineering, aerospace, automotive, and mechanical engineering. They effectively mitigate vibrations in tall buildings, long-span bridges, aerospace structures, and high-performance vehicles. For instance, large telescopes can incorporate a flexible primary mirror connected to actuators, compensating for varying loads during star tracking [61].

3.4.2. Applicability and Effectiveness of Active Vibration Control.

Active control systems offer excellent vibration suppression capabilities and effectively mitigate vibrations across a broad frequency range. They can adapt to varying vibration conditions and provide real-time control, making them highly effective in reducing structural responses. Compared to passive control systems, active control systems can be optimized for specific needs, with the number and position of sensors and actuators tailored to the system and vibration source characteristics [62]. However, the stability of active control systems relies heavily on the accuracy of these sensors, actuators, and control algorithms and the power supply and control system reliability.

3.4.3. Costs of Active Vibration Control.

Active control systems typically involve higher initial costs due to sensors, actuators, control algorithms, and power supply requirements. The installation, calibration, and maintenance of these systems are also needed. In situations where spending needs to be cut, and vibration levels are acceptable, other techniques may be preferable to achieve sufficient vibration reduction at a lower cost [62].

4. Semi-Active Vibration Control TECHNIQUES

4.1. General Description

The first application of semi-active control for systems susceptible to environmental stresses appears to have been put out by Hrovat et al. in the field of structural engineering in 1983 [13]. Unwanted vibrations in systems and buildings can be reduced using semi-active vibration control. The versatility and adaptability generally associated with fully active systems are combined with the dependability of passive devices in semi-active control devices [63]. A dynamic control system's disadvantage is that it requires a substantial amount of electricity, unlike semi-active control systems, which run on a smaller amount of power, often from a battery [64].

4.2. Magnetorheological Dampers

For use in civil engineering, new semi-active control mechanisms known as magnetorheological (MR) dampers, which use MR fluids to generate controlled dampers, hold considerable potential [63, 64]. The automobile sector, seismic isolation, aerospace, and aviation are just a few industries that have extensively used magnetorheological fluid (MRF) dampers to control vibration [65].

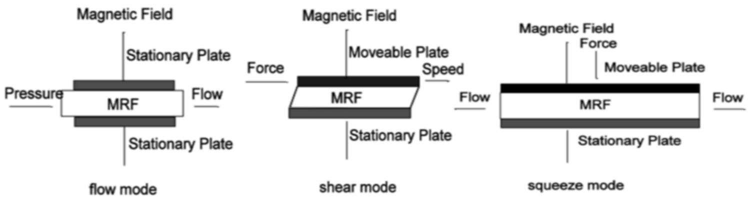

Figure 7. MR dampers under different operating conditions

Figure 7 shows three basic operating modes of MR Dampers: flow mode (valve mode), shear mode, and squeeze mode [66].

In valve mode, the MR damper controls the damping force by regulating the flow of the magnetorheological fluid through a series of flow passages. The direction of pressure and flow in this mode depends on the relative motion between the stationary and moveable plates. When the plates move closer, the fluid pressure increases, and the flow is directed through the damping orifices or gaps. The fixed plate typically houses the flow passages or orifices, while the moveable plate contains the piston or valve that controls the flow.

The MR damper operates in shear mode by subjecting the MR fluid to shear deformation. This mode's direction of pressure and flow is perpendicular to the plates' surface. The moveable plate applies a force to the MR fluid, causing it to shear between the plates. The pressure is exerted perpendicular to the leaves, while the flow occurs parallel to the vessels. The moveable plate typically applies the force or load while the stationary plate remains fixed.

In squeeze mode, the MR damper utilizes the compression of the MR fluid between two solid surfaces. This mode's pressure and flow direction is perpendicular to the plates' surface, similar to the shear method. The moveable plate applies a force that compresses the MR fluid, increasing pressure. The flow occurs parallel to the vessels, allowing the fluid to displace within the confined space. The moveable plate typically generates the compressive force, while the stationary plate remains fixed. By adjusting the magnetic field, the alignment and resistance of the MR particles change, influencing the compression behavior and, hence, the damping force in squeeze mode.

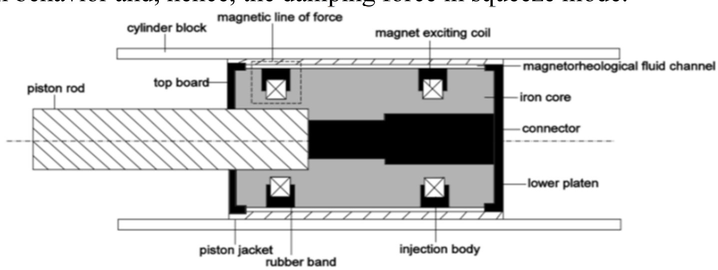

Figure 8. A sketch of the structure of the magnetorheological damper

For the specific structures of the damper, as shown in figure 8, the MR damper mainly comprises a piston rod, an iron core, a coil, a connector, an upper and lower press plate, a piston jacket, a cylinder body, etc. When the coil is energized, a magnetic field line is generated, and the magnetic field forms a closed loop around the ring, passing vertically through the magnetorheological fluid channel. During the operation of the shock absorber, the piston rod drives the piston head to move back and forth, and the magnetorheological fluid passes through the damping gap under pressure. At this time, changing the current can change the magnetic field strength of the coil, resulting in a change in the shear yield strength of the magnetorheological fluid, thus generating a continuous controllable damping force.

The damping force mechanical model of MR Damper is

$$F = \frac{\pi\mu DL}{h} v_0 + \pi DL\tau_y sgn(v_0) \tag{15}$$

μ is the zero-field viscosity of a magnetorheological fluid. D is the diameter of the piston head; L is the length of the piston head; h is the gap width of magnetorheological fluid; v_0 is the relative speed of the piston and cylinder block; τ_y is the shear yield stress of magnetorheological fluid. The coulomb damping force is the second term, and the viscous damping force is the first term on the right side of the equal sign. The ratio of coulomb damping force to viscous damping force may represent the dynamically adjustable coefficient of the MR Damper.

$$\beta = \frac{\tau_y h}{\mu v_0} \tag{16}$$

In MR Dampers, the adjustable damping force caused by the change of excitation current mainly comes from the evolution of shear yield strength of MR Fluid. However, the current damping force calculation formula is quasi-static primarily, and the accurate and reliable transient damping force calculation formula has not been clearly defined. Given this, based on dynamic finite element magnetic field analysis, the response time of damping force is investigated from the change of shear yield strength without calculating emotional damping power [67].

4.3. Disadvantages and Advantages Analysis of Semi-active Control

Semi-active vibration control systems offer several advantages over passive or fully active systems. Firstly, they provide the reliability and robustness of passive systems [63, 64, 65, 68]. Since semi-active devices do not require external power sources or complex control algorithms, they are less prone to failure and require minimal maintenance [65]. This reliability is especially crucial in safety-critical aerospace or civil engineering applications.

Secondly, semi-active control devices maintain the versatility and adaptability typically associated with fully active systems [69]. They can quickly respond to changing vibration conditions and adapt their damping characteristics accordingly. This adaptability allows for real-time optimal vibration control, enabling improved comfort, stability, and safety across various dynamic scenarios [70].

Additionally, semi-active systems offer energy efficiency benefits compared to fully active systems [70]. By modulating the damping characteristics based on the input signals, semi-active devices can reduce energy consumption while effectively suppressing vibrations [71, 72]. This energy-saving aspect makes them appealing in applications where power consumption is a concern, such as automotive or portable devices.

Despite their advantages, semi-active vibration control systems have a few drawbacks. One limitation is the reduced level of control authority compared to fully active systems. While fully functional systems can actively generate forces and actively manipulate the dynamic response of the structure, semi-active devices can only modify the damping properties [73]. As a result, the overall control effectiveness may be lower in some scenarios.

Another disadvantage is the complexity and cost of implementing semi-active control systems [74, 75]. Although generally more cost-effective than fully active systems, semi-active devices still require sophisticated control algorithms and additional hardware components such as sensors, actuators, and controllers. These systems' design, installation, and maintenance can be more challenging and expensive than passive systems.

5. Conclusion

5.1. Exploration of Potential Future Trends in Vibration Techniques

Future trends in vibration control techniques will continue to expand their presence in various industries, such as civil engineering, aerospace, and automotive engineering. There could also be an exploration of emerging fields like healthcare, energy, and the environment. Vibration control systems are becoming increasingly intelligent and adaptive, monitoring and analyzing data in real-time and adjusting control parameters based on actual conditions. This advancement would enhance the effectiveness and adaptability of vibration control systems, enabling them to better respond to different vibration sources and environmental conditions. Furthermore, future vibration control technologies would attach importance to energy efficiency and sustainability. Vibration control systems can reduce energy consumption and minimize environmental impact by optimizing control algorithms, employing energy-saving materials, and incorporating innovative energy recovery systems.

5.2. Discussion of Innovative Methodologies and Technologies

Developing intelligent sensors and actuators would bring advanced functionality to vibration control systems. These devices have higher sensitivity and accuracy, enabling real-time monitoring of structural vibrations and adjustment of control parameters. Additionally, optimizing algorithms is expected to bring better control strategies and parameter settings to minimize structural vibration response. By considering constraints and seeking optimal solutions, these algorithms can enhance the performance of vibration control systems. Multi-modal control techniques could also be applied in more structures, which aim to control multiple vibration modes in the design, resulting in comprehensive vibration suppression.

5.3. Application Areas and Industries That Can Benefit from Advanced Vibration Control Techniques

Advanced vibration control techniques have the potential to revolutionize various application areas and industries, enhancing efficiency, safety, and overall performance. In the automotive sector, these techniques can significantly improve ride comfort, vehicle stability, and noise reduction, enhancing passenger experience and increasing vehicle lifespan. Similarly, in aerospace and aviation, advanced vibration control can minimize structural vibrations, ensuring smoother flights, reducing fatigue damage, and enhancing fuel efficiency. Industries such as manufacturing and robotics can benefit from improved precision and accuracy by minimizing vibrations, resulting in higher-quality products and increased productivity. Additionally, in the construction sector, advanced vibration control techniques can mitigate the impact of ground vibrations on nearby structures, reducing the risk of damage and ensuring the safety of buildings and infrastructure. Advanced vibration control techniques have far-reaching implications across numerous industries, enabling enhanced performance, improved safety, and increased operational efficiency.

5.4. Prediction of Potential Impact and Benefits in Fields

The widespread implementation of advanced vibration control techniques is poised to profoundly impact and benefit various fields, not just mechanisms and structures. In the medical sector, these techniques can revolutionize imaging technologies by reducing vibrations in medical equipment, leading to sharper and more accurate diagnostic imaging. This, in turn, can improve early detection and treatment, ultimately saving lives and improving patient outcomes. In the renewable energy sector, vibration control can enhance wind turbines' and solar panels' performance and longevity, optimizing energy production and making clean energy sources more reliable and cost-effective. Moreover, in structural engineering and civil infrastructure, applying advanced vibration control can enhance the resilience of buildings, bridges, and other critical structures, safeguarding them against natural disasters and reducing maintenance costs.

Furthermore, in consumer electronics, vibration control can enhance the stability and precision of devices like smartphones and cameras, improving user experiences and product longevity. The potential benefits of advanced vibration control techniques are wide-ranging, from improved healthcare and energy efficiency to enhanced safety and performance across various industries and fields. Therefore, the development of future vibration control systems is one thing people should look forward to.

5.5. Limitations and Areas for Improvement

Firstly, due to time and resource constraints, this paper only covers certain aspects of vibration control techniques, neglecting other relevant technologies and methods. The discussion should provide specific details, including advanced approaches such as AI-based algorithms and novel sensors, practical examples, and applications. Failure to address these limitations may lead to omitting significant techniques or providing superficial insights into specific topics.

Secondly, this paper lacks a quantitative evaluation of different methods and technologies. The absence of well-defined standards makes it challenging to comprehensively assess the performance and relative merits of other techniques. Quantitative analysis can make the characteristics of different methods more intuitive.

Thirdly, it is crucial to highlight the limitations, identify future research directions, and offer recommendations to address implementation challenges and technical difficulties. The paper can provide a more comprehensive and in-depth analysis of vibration control techniques by addressing these aspects.

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