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Enhanced Seismic and Vibration Control with Magnetorheological Fluid Dampers: Applications, Efficiency, and Energy Savings

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ABSTRACT :

In recent years, Magnetorheological (MR) Fluid Damper technology, highlighting its versatile applications in various engineering fields, particularly in vibration reduction and seismic protection. It discusses the advantages of MR dampers over passive and active systems, focusing on their controllable rheological properties, efficient control ability, and low power consumption. The review covers the diverse applications of MR dampers in civil engineering, vehicle suspensions, and bio-engineering mechanisms, as well as their use for seismic-induced vibration mitigation in building structures. Additionally, it discusses energy-saving capabilities of MR dampers, along with their integration for energy harvesting. It demonstrates the effectiveness of MR dampers in seismic protection, indicating their potential for practical implementation in safeguarding civil infrastructure systems against earthquake and wind loading.

Keywords: Magnetorheological (MR) Fluid Dampers, Vibration Reduction, Seismic Protection, semi active control systems,

1. Introduction :

Vibration control devices have been developed to reduce or eliminate excessive system vibrations. Magnetorheological (MR) dampers are employed for vibration control in various civil structures. Vibration control devices, focusing on dampers categorized as passive, active, and semi-active. It discusses the limitations of passive dampers and the advantages of active and semi-active systems. Magnetorheological (MR) dampers are highlighted as advanced semi-active devices, utilizing smart fluids for effective vibration control. The paper aims to optimization of MR dampers to meet increasing demand for versatile vibration control solutions [2].

Highlighting the imperative need for seismic-resistant building design traditional approaches and ongoing efforts in earthquake prevention and mitigation. It discusses seismic design practices, including the consideration of wind and earthquake forces, and the distinction between force-type and displacement-type loading. The role of smart structure technologies, including MR dampers, in seismic response control is emphasized, along with the importance of control systems for flexible structures [5].

Advantages such as uncomplicated design, low power usage, and cost-effectiveness are highlighted. This aims on large MR dampers, their classification, design strategies, implementation, and development, along with mathematical models and control systems [1,6].

discusses the use of MR fluids in structural engineering, particularly in earthquake protection, emphasizing the semi-active control concept using MR dampers. The Bingham model is introduced to describe MR fluid behaviour, with focus on factors affecting durability and performance degradation over time. The study aims to investigate the long-term behaviour of MR dampers for seismic protection, analysing changes in damper performance over a five-year period [7].

2. Description

Magnetorheological (MR) fluid consists of a carrier liquid with iron particles suspended within it. In its inactive state, MR fluid behaves like regular damper oil. However, when an electromagnetic force is applied, the iron particles in the MR fluid align into linear chain-like structures, significantly enhancing its vibration absorption capacity. MR dampers can be linear or rotary. Rotary types include continuous angle (e.g., MR brakes) and limited angle (e.g., vane type)[1,2].

Magnetorheological (MR) fluids change viscosity in response to magnetic fields, useful for electromechanical devices. They transition from Newtonian to chain-like structures, altering yield stress. Carbonyl iron is often used for magnetic particles due to its properties. Silicone oil is a common carrier fluid for its viscosity and non-reactivity. Additives like surfactants prevent particle agglomeration and settling. Proper surface materials are crucial due to the abrasive nature of MR fluids [5].

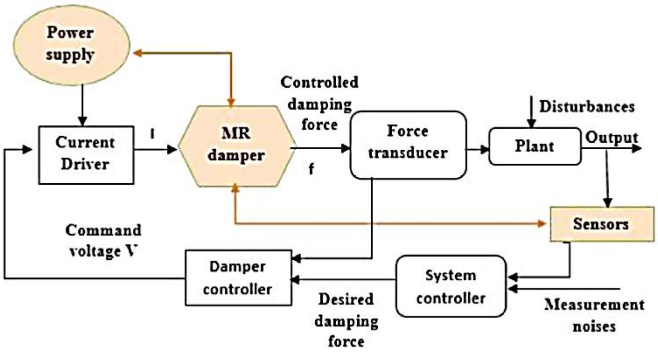

Fig.1-Illustration of a semi-active system based on MR damper (1)

3. Classification

The optimization of MR damper design can significantly enhance performance by altering factors such as the number of coils, including single-coil, double coil, and multi-coil configurations. MR dampers are categorized under a different term based on design features like coil turns, piston coils, bypass valves, control valves, and power-producing capacity. [6]

Basic types include monotube and twin-tube MR dampers, which can be further categorized as double-ended or single-ended. Monotube dampers have one fluid reservoir, while twin-tube dampers have two. Single-ended structures feature one piston rod, while double-ended structures have extended piston rods at both ends. [1,2,6]

3.1.Mono Tube MR Damper

This MR damper consists of only one tube or reservoir and is known as a Mono tube MR damper. It is the most commonly used type due to its compact size and versatility in installation locations. The motion of the piston rod results in a volume change within the reservoir, which.

is balanced by an accumulator mechanism.

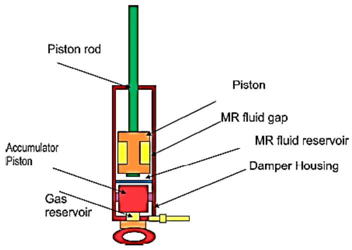

Fig.2-Mono-tube MR damper (2)

3.2.Twin Tube MR damper

An MR damper that contains two fluid reservoirs is called a twin tube MR damper. For two separate reservoirs this damper has an inner and outer housing. The inner reservoir is filled with MR fluid without any air gap. The outer reservoir is partially filled with MR fluid to accommodate the fluid from the inner reservoir during piston movement. The foot valve mechanism includes two valves.

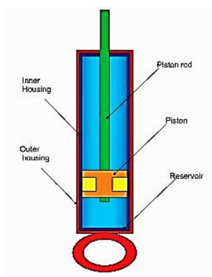

Fig.3-Twin-tube MR damper (2)

3.3.Double Ended MR Damper

In a double-ended MR damper, two piston rods of the same diameter enter the reservoir from both ends. This design results in no volume change due to the piston's movement, eliminating the need for an accumulator mechanism. Double-ended MR dampers are commonly used in gun recoil systems, bicycles, and for controlling sway motion in buildings caused by strong.

winds or earthquakes.

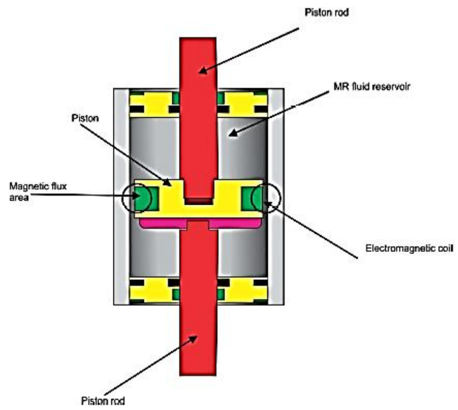

Fig.4-Double-ended MR damper (2)

Flow channel configurations classify MR dampers as inner bypass or outer bypass, which can be single-ended, double-ended, or piston bypass type. Outer bypass dampers have subtypes like outer tube bypass, double-ended bypass, bypass MR valve, meandering type valve, and bypass spool valve. Size classifications include short stroke, long stroke, and large MR dampers, with stroke lengths varying accordingly. Short and long stroke dampers typically have stroke lengths ranging from 55 to 74 mm, while large stroke dampers have lengths from 160 to 300 mm [6].

4. Operative modes

MR dampers may employ either inner or outer coil mechanisms. Inner coil mechanisms have coils wound inside the piston, while external coils are wound on the outer structure. Control valves determine flow mode [1,6].

Large MR dampers utilize a larger stroke to develop shear stress in the MR fluid region. They operate based on principles such as shear mode, flow mode, squeeze mode, and mixed-mode operation. MR damper operations are categorized into single flow mode, mixed-mode, and multimode. Mixed mode involves the hybrid operation of the valve and direct shear mode, while squeeze mode, direct shear mode, and valve mode are considered multimode operations. Shear mode occurs when the fluid moves parallel to the wall, causing shear stress development. In flow mode MR dampers, the bi-fold mode generates high-pressure differences for increased damping force in a compact volume. Mixed-mode MR dampers combine shear and squeeze modes to generate higher damping forces compared to standard MR dampers. Squeeze mode MR dampers involve wall sliding movement and fluid squeezing.

Among these damping operations, mixed-mode MR dampers offer increased controllability and produce higher damping forces[6].

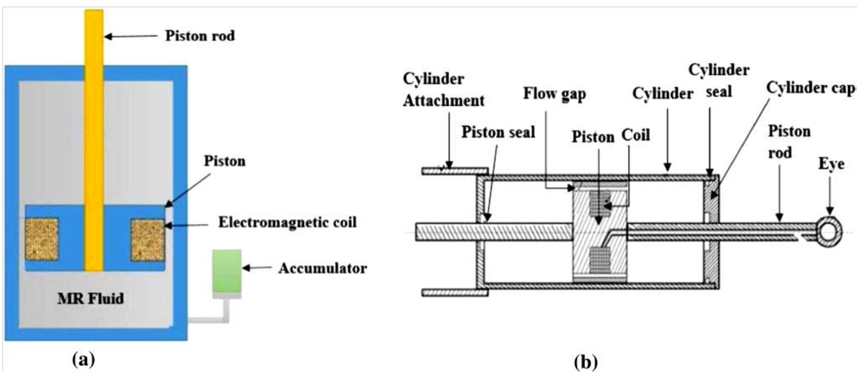

Fig.5-(a) Shear mode operation, (b) flow mode operation in MR damper (6)

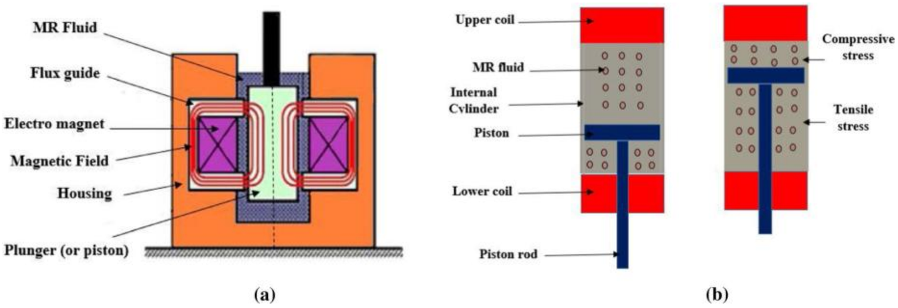

Fig.6-(a) mixed mode,(b) squeeze mode of MR damper (6)

5. Working Principle

The design of MR dampers is influenced by traditional shock absorbers and functions as a semi-active damper, providing control over the input current for regulation. Its composition typically comprises a damper housing, piston shaft, inner and outer pistons, piston guide, floating piston, MR fluid, and a gas chamber. The damper's functionality relies on an MR valve structure created by inner and outer pistons, piston housing, and a coil, dividing the damper into upper and lower chambers filled with MR fluid. The maximum force exerted by the MR damper depends on the properties of the MR fluid, its flow mode, and the damper's dimensions.

MR dampers operate through three primary modes: valve mode, direct shear mode, and squeeze mode. Valve mode restricts MR fluid flow between reservoirs, shear mode is advantageous for applications requiring minimal forces, and squeeze mode involves a thin film of MR fluid between pole surfaces. A recent advancement, the magnetic gradient pinch mode, functions similarly to valve mode but with a non-uniform magnetic field, offering two control modes: pinch mode and reversible jamming mode[1,6].

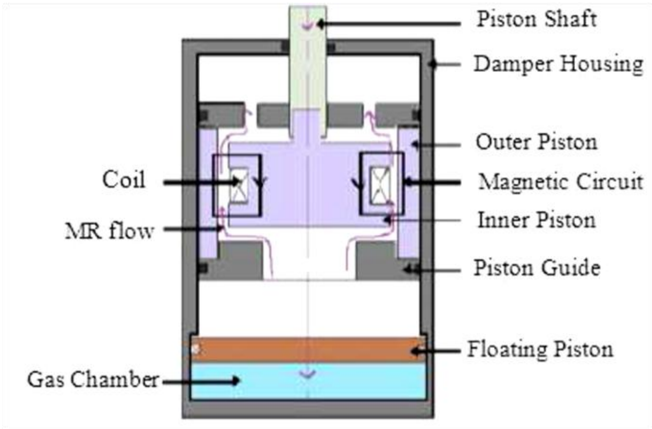

Fig.7-Typical MR damper configuration (1)

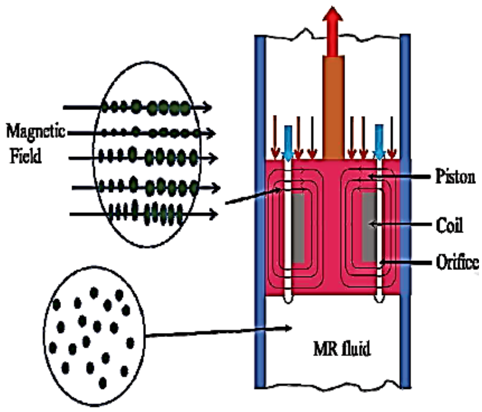

Fig.8-Basic functional principle of MR dampers(1)

6. Properties

Magnetorheological Fluids (MRFs) consist of iron particles dispersed in a carrier liquid, often silicon oil, with additives. Properties like particle size, sedimentation stability, and rheological behaviour affect MRF performance. Additives, such as graphene nanoparticles, can enhance stability. MRF composition, including carrier fluid type and particle concentration, influences viscosity, sedimentation ratio, and thermal conductivity. MRFs have quick response times to magnetic fields, making them ideal for automotive dampers, seismic protection systems, and robotics. Other MRF devices include MR brakes, clutches, valves, and beams, all aimed at reducing vibration in various industries [2,3,4].

MR fluids typically comprise paramagnetic or soft ferromagnetic particles dispersed in a carrier fluid, often silicone or mineral oil. In the absence of a magnetic field, these particles are dispersed within the fluid. However, under the influence of a magnetic field, they exhibit distinct Bingham behaviour [3,4,5].

MR fluids typically consist of liquid carriers and magnetic particles, with additives often used to improve performance by addressing issues like particle sedimentation and oxidation. Ferrofluids, which are suspensions of iron-containing particles in carrier oils, pioneered the development of MR fluids. The key difference lies in the particle size, with MR fluids using micron-sized iron particles while ferrofluids utilize nanometre-sized iron oxide particles, making them less sensitive to magnetic fields. Carbonyl iron is commonly used for particles due to its spherical shape, with diameters typically ranging from 0.1 to 10 micrometres. Carrier fluid composition varies, initially including silicone and petroleum oils and later expanding to mineral oils, polyesters, polyether, water, and synthetic hydrocarbon oils. Achieving a low viscosity is crucial for MR fluid effectiveness, as it influences the controllability and suitability for civil engineering, such as semi-active control of seismic-induced vibrations. The ratio of particle weight to carrier fluid weight strongly influences the maximum yield stress and off-state viscosity of the MR fluid, with the particle fraction chosen to balance these effects [7].

7. Durability

MR dampers are highly effective devices for semi-active structural control in civil construction, but long-term changes in their behaviour pose significant concerns, especially in the context of earthquake engineering. Several durability issues affect MR dampers, including particle settling, fluid thickening, particle oxidation, and seal wearing.

Particle sedimentation occurs when particles settle in the nonexistence of a magnetic field, altering the fluid properties and potentially leading to unexpected responses to dynamic loads. Strategies to mitigate sedimentation include reducing particle size, modifying carrier fluid viscosity, and using stabilizing additives or particle coatings.

Fluid thickening over time can increase off-state viscosity and reacting force, primarily due to the fragmentation of the oxide layer on particle surfaces. Particle oxidation can also occur, leading to decreased mechanical performance. Seal wear can affect device lifetime, and proper seal design and material selection are critical.

MR dampers may include an accumulator with pressurized gas to prevent cavitation and account for fluid volume changes, but its role in altering mechanical response is not fully understood. Durability testing typically involves evaluating settling rates, fluid properties, and particle behaviour over time, with longer rest periods allowing durability phenomena to fully develop [7,8].

8. Advancement in MR Damper

Continuous operation of electromagnets in MR dampers can lead to energy consumption and heat generation, affecting the efficiency of the damper due to temperature-induced changes in MR fluid viscosity. Research has focused on decreased energy consumption and heat generation, with the concept of hybrid magnetic circuits combining permanent magnets and coils emerging as an innovative approach. These hybrid circuits allow control over the base magnetic field strength, affecting damping force. Harnessing this wasted energy through self-powered MR dampers could eliminate the need for external power supplies and additional sensors, improving system reliability. Advantages includes weight and size reduction, simplified maintenance, and enhanced performance in scenarios like earthquakes when external power may be unavailable. Recent developments in self-powered and self-sensing MR dampers offer promising solutions for various applications [1].

Advancements in magnetorheological (MR) damper technology have led to significant improvements in vibration control. Integration of permanent magnets addresses fail-safe concerns, while magnetic valves enhance damping force regulation. Self-sensing MR dampers offer compact solutions with inherent sensing capabilities, validated through mathematical algorithms and testing. Tunable MR dampers functioned by permanent magnets provide efficient alternatives without electromagnetic coils. Hybrid magnet and MR fluid technology in a 2 Degree of freedom quarter car model demonstrate reduced tire deflection and enhanced passenger comfort, marking substantial progress in MR damper applications for vibration control [2].

9. Future Research

The study explores earthquake mitigation technologies, focusing on various dampers like FDs, TMDs, VDs, and especially MR dampers. It highlights challenges such as manufacturing difficulties, fluid leakage, and wear issues in MR dampers, which are not extensively discussed. Despite using iron powder fluid, wear and tear are rarely addressed, impacting performance due to increased viscosity and friction [5].

10. Application

Magnetorheological (MR) dampers are crucial in semi-active vehicle suspensions, offering improved ride comfort, stability, and suspension strength. They outperform passive dampers due to their adaptability and dynamic range. Finite element analysis aids in optimizing MR damper designs for specific vibration reduction applications. MR dampers also find utility in heavy vehicles, military defence vehicles, and vehicle bumpers, enhancing peak amplitude reduction, settlement time, and safety in various collision scenarios [2,6].

MR dampers are highly sought after for scientific and industrial applications due to their reliability, unaffected by temperature changes or fluid impurities. However, their nonlinear characteristics pose challenges in modelling and algorithm development. For the last 15 years, they have been widely employed in various fields including building structures, bridges, automotive and train suspensions, artificial limbs, washing machines, airplane landing gears, vehicle seats, mechanical systems, and helicopter rotors. Despite their advantages, commercializing MR dampers is hindered by their complex structures and user-dependent configurations [5].

11. Advantages

MR dampers offer controllability, low weight, and low power consumption. Semi-active system allows design changes post-installation, unlike passive systems.MR dampers have uses over passive and active damping systems [1].

MR fluid offers quick shear yield stress change for vibration control.MR damper provides heavy damping force with low energy consumption. MR fluid enhances vibration absorption capacity in on-state condition [2]

MR dampers are applied in various fields for vibration control. Semi-active systems minimize structural damage and guarantee stability [5].

Higher damping force capabilities in large MR dampers. Effective in civil, structural, and mining engineering applications [6].

MR dampers show acceptable performance decay after years of inactivity. Fluid stabilizers reduce sedimentation in MR fluid, enhancing device longevity. Proper seal design crucial for MR device durability and wear resistance. Particle oxidation affects MR fluid properties, leading to reduced mechanical performance [7]

12. Conclusion

Magnetorheological (MR) Fluid Damper technology emphasizes the significant advancements and versatile uses of MR dampers in various engineering fields. MR dampers have proven to be effective in vibration reduction, seismic protection, and energy-saving applications due to their controllable rheological properties, efficient control ability, and low power consumption. The usage of MR dampers over passive and active systems are highlighted, displaying their adaptability and dynamic range, which make them superior in terms of ride comfort, stability, and suspension strength. These dampers offer controllability, low weight, and low power consumption, making them a preferred choice for semi-active vehicle suspensions and other engineering applications. The review also discusses the challenges and limitations associated with MR dampers are durability issues related to wear and tear, particle settling, fluid thickening, and seal wear. However, ongoing research and developments in MR damper technology, including hybrid magnetic circuits and self-sensing capabilities, aim to address these concerns and enhance the performance and dependability of MR dampers. Furthermore, the paper highlights the diverse uses of MR dampers in civil engineering, vehicle suspensions, bio-engineering mechanisms, and seismic-induced vibration mitigation in building structures. MR dampers have demonstrated their effectiveness in safeguarding civil infrastructure systems against earthquake and wind loading, displaying their potential for practical implementation in structural control and seismic protection. Overall, MR Fluid Dampers represent a promising technology with a wide range of applications and benefits in engineering fields. Continued research and innovation in MR damper technology are essential to further optimize their performance, durability, and applicability in various engineering scenarios, ensuring enhanced vibration control, seismic protection, and energy efficiency in engineering systems.

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