Developments in vibration control of structures and structural components with magnetorheological fluids

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Vibration isolation and control of structures subjected to different types of dynamic loads due to periodic forces, impact and shock type forces and earthquake forces is an important area in structural engineering. The structures can be machine foundations, buildings, bridges, towers, automobiles, ship structures, military tanks and aeronautical structures. Some of these devices used are elastic springs, viscoelastic dampers, viscous fluid dampers, magnetorheological dampers and friction dampers. This article gives latest developments in vibration control of structures and structural components using magnetorheological fluids. The current status of technology and further research requirements to be studied in these areas are highlighted.

Keywords: Automobile brakes, magnetorheological fluids, structure and structural components, suspension systems, vibration control.

IMPROVEMENT in manufacturing technology has provided machines of higher ratings, longer bridges, taller buildings which requires to satisfy the static, dynamic capacity and serviceability and stability limits for members/ systems prescribed by codes of practice. These machines/ structures give rise to considerable higher dynamic forces and thereby higher stresses. This demands development of advanced control and safety systems to keep the structural members/systems static and dynamic responses within tolerable levels. The performance, safety and stability of structures supporting the machines/structures depend largely on their design of suspension systems and their interaction with the environment. In this article, current status of technology in development of magnetorheological and friction dampers and their use in vibration control of structural and structural components in different fields of engineering applications are presented.

Present status of technology

Seismic forces are of short duration transient accelerations acting on the foundation of the structure and they may occur once or twice in the life time of the structure. The viscous fluid dampers (VFDs), magnetorheological fluid dampers (MRFDs) and friction dampers are used for seismic performance enhancement of structures by increasing the damping in the structure[1]. VFDs reduce the effects of earthquake excitation on a structure and permit it to remain linearly elastic during a seismic event by enhanced damping.

The addition of liquid dampers to a structure does not fundamentally adjust its natural period, but rather it increments damping from around 2–5% of basic (which is regular for structures) to somewhere around 20–30% (refs 1, 2). Damping above 30% brings small decrease in response, and such increments would not lead to utilization of dampers[2]. A methodology of design for seismic performance enhancement of buildings using VFDs has been developed[1]. In this study, a design methodology for finding number, capacity and distribution of viscous VFDs in buildings with different types of damper displacement enhancement mechanisms for seismic performance enhancement of buildings is developed using the numerical methods used/tested for simulation of experimental test results on moment-resisting frames.

The fluids used in the VFDs are silicon oil. With silicon oil with different viscosities different levels of damping are possible. VFDs along with springs are widely used for vibration control systems in automobile and aeronautical vehicles, supporting systems in missile launching, military cannons and machine foundations. Basically they are passive devices. In MRFDs along with silicon oil, carbonyl iron particles and additives to keep the carbon particles in suspension are added and they have a control device mechanism which gives variable current input. VFDs are pure dampers with negligible stiffness. MRFDs act as pure dampers at low current inputs and at high current inputs, they increase the stiffness and friction forces in the damper and make the MRFs in dampers from liquid to semi-solid in 3–10 ms. The typical amount of current input required is 0–2 A in MRFDs. The resisting force for a typical MRFD can be varied from 2 to 200 kPa.

Magnetorheological fluids

MRFs are smart fluids whose properties can be controlled by inducing variable magnetic field in carbonyl iron

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particles with different current inputs. The basic ingredients of MRFs include metal particles, carrier fluids and additives. MRFs belong to the class of controllable fluids. They contain micron-sized, magnetically polarizable particles dispersed in a carrier medium such as mineral or silicone oil. The MR response of MRFs results from the polarization induced in the suspended particles by the application of an external magneticfield. The interaction between the particles results in dipoles which causes the particles to form columnar structures, parallel to the applied field shown in Figure 1. These chain-like structures restrict the motion of the fluid, thereby increasing the viscosity of MRFs. The mechanical energy needed to yield these chain-like structures increases as the applied field increases and results in magnetic field-dependent yield stress. In the absence of an applied field, MRFs exhibit Newtonian-like behaviour. The essential characteristic of MRFs is their ability to reversibly change from free-flowing linear viscous liquids to semi-solids having controllable yield strength in milliseconds when exposed to a magnetic field.

Ingredients of MR fluids

In MRFs, commonly used magnetic particles are carbonyl iron powder and iron alloy powders. In which, the most widely used material is carbonyl iron. Carbonyl iron particles are much used as suspensions because of their high magnetic permeability, low magnetization and also these are magnetically multi domain (M/s Sigma Aldrich). The diameter of these carbonyl iron particles ranges from 3 to 5 μm and their concentration is 20–40% by volume of MRF[4]. Typical cost of carbonyl iron particles manufactured by Sigma Aldrich (C3518), India with a density of 7.86 g/ml at 25°C is about $430 per kg.

Carrier fluids (50–80%) by volume[5,6] are the major constituents of MRFs. Its primary function is to offer a medium for magnetically active particulates to remain suspended during the absence of magnetic field and to undergo realignment with the application of magnetic field. Some of the carrier fluids are poly vinyl-*n*-butyl and naphthol-thickened kerosene[7], silicone oil[8,9], white and light grade mineral oils[10], honge oil[5], a combination of synthetic oil, water and organic liquids[11]. Silicone oil is widely selected as a carrier fluid, due to its superior qualities, such as good temperature stability, good heat transfer characteristics, oxidation resistance[12,13], very low vapour pressure and high flash points. In other words, silicone oil experiences only a little change in physical properties over a wide temperature span (–40°C to 204°C), whereas the vegetable oils (bio-degradable) and their properties are temperature-sensitive[14]. Further research is required for choosing different cost effective carrier fluids for a wide variety of applications. Various silicone oils are available with Sigma Aldrich[15] with viscosities ranging from 5 to 100,000 CPS and with density between 0.91 and 0.97 g/ml at 25°C.

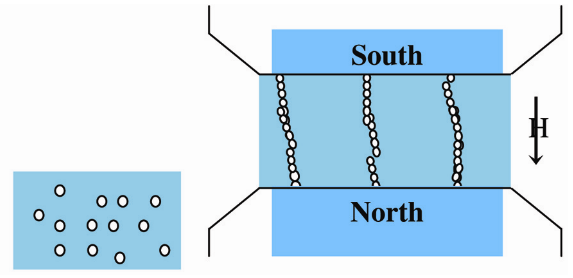

Figure 1. Magnetorheological fluids.

Furthermore, additives are added to control the viscosity of the liquid and reduce the sedimentation rate of the particles. They are mainly used to reduce sedimentation, prevent agglomeration, enhance lubricity, prevent oxidation, modify viscosity and inhibit wear. The various additives in use include Aerosil 200, oleic acid, tetramethylammonium hydroxide solution[16], lecithin, Tween-80, Span-80 (ref. 17), etc.

Studies on MR fluids

Semi-active control devices that possess the advantages of active and passive control devices have been proposed for structural control applications[18,19]. These devices include controllable fluids such as electrorheological (ER) and magnetorheological fluids. Such fluids exhibit rapid change in their rheological properties and thus in the damping and stiffness properties with application of an electric/magnetic field. Generally, active control systems require a significant amount of energy into the system, whereas the semi-active control devices involve modifications of mechanical properties of the system in the preferred manner with only modest exterior energy/current input[20]. Consequently, extensive studies have done on the semi-active devices development in MRF applications.

Choi *et al.*[21] studied the flow behaviour of MRF theoretically and experimentally. The flow behaviour equations (shear stress versus torque and shear rate versus angular velocity) were developed on the basis of the Bingham plastic, bi-viscous and Herscheo–Bulkley constitutive models. Ashour *et al.*[22] developed the new MRF using the modern improved manufacturing process at low cost to demonstrate the engineering feasibility. Laboratory experiment was conducted to optimize the quality and properties of MRF and Haake cone-plate viscometer was utilized to measure the properties of MRF. Compared to other conventional devices, MRF-based devices provide the faster responses, improved performance and are simple to design at reduced cost.

The MRF chains formation was simulated under various magnetic field and the particle motions were determined by the magnetic interaction, contact interaction and viscous force. Simulated results were compared with the experimental results[23]. Carlson *et al.*[24] studied the durability, life and working conditions of MRFs apart from the yield strength to improve or increase the commercial success. Compared to the ER fluids, MRFs are known to exhibit considerably higher dynamic yield strength and greater insensitivity to temperature variation and contaminants[25,26].

The yield stress of MRF lies in the order of 2–3 kPa in the absence of a magnetic field and it rapidly exceeds 80 kPa under the application of a magnetic field in the order of 3000 A/m (ref. 18). With the application of varying magnetic field, these fluids are considered to yield high bandwidth control through rapid variations in the rheological properties. Zhang and Kim *et al.*[27] experimentally studied the material characterization of MRF at high frequency ranges application. The storage modulus and loss modulus were measured based on the wave transmission at frequency ranges of 50–100 kHz. The storage modulus and loss modulus were calculated in two different positions (orthogonal and parallel) of applied magnetic field. The study concluded that orthogonal position of applied magnetic field has the effective method to control the MRF behaviour.

The utilization of MRFs has been increasing in the different semi-active damping control applications in the low to moderate frequency ranges, including automotive suspension[28], civil structures[29–32], fluid clutches[33], optical polishing[34] and a variety of aerospace applications[35–38], vibration isolation[39,40], automobile valves[41] and automotive damping applications[42].

Lord Corporation, the leading supplier of commercially proven MR fluids, devices and systems, manufactures three different MR fluids namely LORD MRF-122EG, LORD MRF-132DG and LORD MRF-140CG (ref. 43). The properties of these fluids vary from each other[44]. The cost of these fluids is the same and is about $750/l. LORD MR fluid has been used in multiple successful demonstrations of MR technology, including demos on Humvees, Stryker and M915A3.

Studies on MR fluid particles

Many experimental tests were carried out to measure the mechanical properties of MRFs such as storage modulus, loss modulus, shear stress and shear strain. Jolly *et al.*[45] studied the formulation of MRF for various applications. They concluded that depending on the application, the properties of MRFs vary in the balanced manner.

Ngatu *et al.*[46] studied MR fluids containing circular iron particles of 6–10 μm in diameter (also called Alfa Aesar). Nanowires having a mean measurement of 230 nm and length of 7.6 ± 5.1 μm were utilized. Silicone oil (GE SF96-200) with a viscosity of 0.175 Pa-s was utilized as the carrier liquid to get ready both ordinary and dimorphic MR liquids. Lecithin (2% of weight of the total metal content) was used to create stable scatterings. It was seen that every single dimorphic liquid has a lower sedimentation proportion, suggesting a smaller extent of sedimentation than routine microsphere-based MR liquids. This decrease in sedimentation proportion brings about a more permeable agglomeration of particles at the holder base, making re-scattering much easier and giving a homogeneous mixture more rapidly.

Sarkar and Hirani[16] prepared MR fluid consisting of 19.5% by weight silicone oil, 0.25% by weight oleic acid, 0.25% by weight tetramethylammonium hydroxide and 80% by weight carbonyl iron powder (Sigma Aldrich 12310, 99% purity and mean size of particle 150 μm)[15] by the method of mechanical mixing. To get high yield strength, large sized particles (0–150 μm compared to commonly used particle size 2–4 μm) were employed. The carbonyl iron based MR fluid prepared by mixing oleic acid and tetramethylammonium hydroxide as additives showed superior performance. This synthesized MR fluid shows better chain strength and less agglomeration compared to MRF 241ES fluid (water-based MR fluid, with 41% volume fraction of iron particles). The synthesized MR fluid gives 9 Nm torque and stops the motion of the disk in 11.85 s (at zero coil current) and in 2.98 s (at 1.5 A coil current). The flywheel inertia based MR brake setup can characterize MR fluids.

Sarkar and Hirani[47] found that for avoiding sedimentation, smaller sized (3–10 μm) particles are favoured, whereas larger sized particles can be utilized as a part of MR brakes, MR clutches, and so on as mechanical stirring in those systems does not permit particles to settle down. Ideally larger sized particles give higher shear stress compared with smaller sized particles. To study the impact of particle sizes, nine MR fluids containing small, large and mixed sized carbonyl iron particles have been combined. Three concentrations (9%, 18% and 36% by volume) for each size of particles have been utilized. The shear stresses of these MRF tests have been measured utilizing ANTON PAAR MCR-102 Rheometer. With increase in volume fraction of iron particles, the MR liquids synthesized utilizing mixed sized particles demonstrated better shear stress compared to the MR fluids containing smaller sized spherical-shaped particles and larger sized flaked-shaped particles at higher shear rate.

Effect on MR fluids with addition of nano silver particles

Sarkar and Hirani[48] synthesized three different compositions of MR fluid samples (no silver, with 0.25% weight and 0.50% weight silver particles). Shear stress and torque performance were characterized using MCR-102 magneto rheometer and developed experimental setup respectively. From the study performed on three different compositions of MR samples, it is observed that: (i) Shear stress of MR fluids reduces with an increase in percentage in silver nano-particles. (ii) Shear stresses of all three different compositions of MR fluids decrease with increase in operating temperature. (iii) At 200 rpm, braking torque of three different compositions of MR fluid samples is within the error bar. No noticeable change in braking torque occurs, but reduction in temperature rise with increase in silver particles has been observed. (iv) At 600 rpm, 0.25% particles silver-based MR fluid give better performance compared to 0.50% particles silver based MR fluid. (v) MR fluid containing low particle percentage (0.25%) of silver nano-particles is preferred for MR braking applications.

Effect on MR fluids with addition of nano copper-based particles

Sarkar and Hirani[49] synthesized four MR fluid samples having variable compositions of nano copper powder-based particles. They observed that 'shear stresses of MR fluids do not decrease with increase in weight of copper nano-powders. To observe the increase in heat transfer rate due to mixing of copper nano powder, MR brake test rig has been developed. Experiments performed on MR brake rig indicate that on increasing copper nano-powder percentage, surface temperature of MR brake decreased. Based on these results it can be concluded that the use of Cu nano-powder is an effective cooling method. It does not require any extra space to cool the MR brake. Cu-based MR fluids shall be used if there is a need to impart the cooling capabilities in MRF devices'.

Application of MR fluids – MRFD

MR dampers contain magnetorheological fluids. MR dampers generally consist of a hydraulic cylinder containing micron-sized magnetically polarizable particles suspended within a fluid[31,32]. In the presence of strong magnetic field, the particles polarize and offer an increased resistance to flow. By varying the magnetic field, the mechanical behaviour of an MR damper (MRFD) can be varied. Since MRF can be changed from a viscous fluid to solid within milliseconds and the resulting damping force can be considerably large with a low-power requirement, MRFDs are applicable to large civil engineering structures.

MRFD offers the advantage of being able to dynamically modify the response of a structure to increase its safety and reliability (Figure 2)[50]. Because there are few moving parts, these devices offer highly reliable operation. Furthermore, they are expected to be competitively priced and can be viewed as fail-safe in that they become passive dampers whenever the control hardware malfunctions. The maximum force that an MRFD can deliver depends on the properties of MRFs, their flow pattern, and the size of the damper. This device also offers highly reliable operation at a modest cost and its performance is in the development of appropriate control algorithm that can take advantage of the unique characteristics of the device[51].

For increasing the safety and reliability of any static and dynamic systems, the vibration control strategies and developments in controllable actuators is important. Therefore, the semi-active MRFDs are being increasingly used in vehicle suspension systems, machineries and structures. They can offer large range of damping force capacity with minimal power requirements to provide improved performance.

Modelling of MR dampers

In MRFDs, the fluid viscosity is continuously controlled by a magnetic field. Different strategies for the control of semi-active MR suspensions have been published[52–54]. Many models were formulated to characterize the dynamic behaviour of MRFDs: The Bingham model[55]; the bi-viscous hysteresis model[38] and the phenomenological Bouc-Wen model[50]. Among these models, the one that describes well not only the bi-viscous behaviour but also the hysteretic behaviour of MRFDs is the Bouc-Wen model (Figure 3). This model takes an 8-parameter first

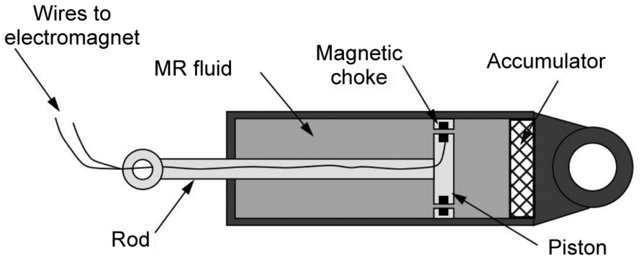

Figure 2. Schematic diagram of MR damper[50].

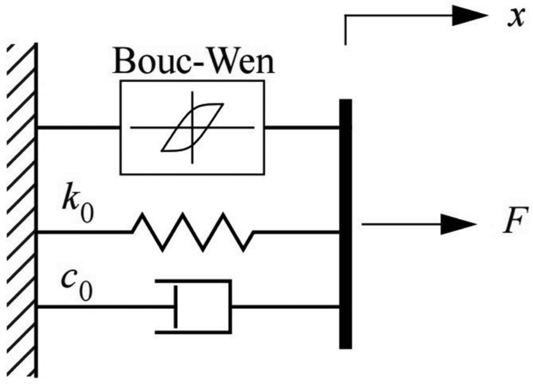

Figure 3. The Bouc-Wen model for MR dampers[50].

order nonlinear differential equation, which is used to analyse the nonlinear hysteretic MR behaviour. The Bouc-Wen model stands out due to its relative simplicity and accurate results. However, to solve the inverse problem, i.e. to obtain a reliable parameter estimation based on experimental data, it has been shown to be a difficult task, mainly due to the high number of parameters involved. In the Bouc-Wen model, the force F generated by MRFD is given by

$$F = C_0\dot{x} + K_0 x + \alpha z, \tag{1}$$

where x is the displacement, C_0 the plastic damping coefficient, K_0 account for the effects of the accumulator in MRFD, which, in a phenomenological perspective, acts as a spring and z is the hysteretic displacement.

A new dynamic model of the overall 20 tonne MRFD system was proposed[56], which comprised two parts: a dynamic model of power supply and a phenomenological model[57] of the MRFD based on the Bouc-Wen hysteresis model. This model was accurate in predicting damper behaviour under a wide variety of operating conditions. To improve the MRFD response time, a force feedback control scheme used in conjunction with a back-driven current approach is proposed and experimentally shown to be effective. Other practical issues related to MRFDs were also studied, including damper piston cantering, voltage surge suppression, temperature effects, voltage power supply versus current driver, etc. And also, two specific applications using ‘smart’ damping technology for vibration mitigation in naval structures. In this study, stress levels in ship supply transfer ramps due to adverse sea conditions are considered; the second study was the reduction in shock vibration. Simulation of results demonstrated that ‘smart’ damping devices used in conjunction with appropriate control strategies are effective and practically implementable in the vibration control applications. The studies reported give insight into the behaviour of MRFDs and their potential applications to large-scale structures. This work is useful to accelerate the implementation of these dampers in areas of natural hazard protection and vibration mitigation in large-scale structures.

The performance of a MRFD integrated in a single-degree-of-freedom (SDOF) suspension system model was studied subjected to a random excitation[58]. The study proposed a control law based on sliding mode controller. Yang *et al.*[59] studied features and performance of MRFDs for structural vibration reduction. These semi-active control devices are used in a number of real world applications because of their simple design, lower power requirement and scalability. A quasi-static axisymmetric model was used to design MRFD and it was validated by simple parallel plate model and experimental results. These results showed that MRFD provides the large controllable damping. Dynamic response of MRFD was also analysed experimentally. It was also concluded that parallel coils damper provides faster response time than the series coil damper. Further, the performance characteristics of the MRF suspension using an H–∞ controller for vibration suppression of a full vehicle system model comprising four independent MRFD suspensions were studied[60].

Pranoto *et al.*[29] developed the shear type linear MRFD for controlling the vibration of flexible structures or plates of aircraft wings. The performance of MRFD was evaluated theoretically and validated experimentally by conducting the test in vibration suppression of the cantilever plate. The study concluded that MRFD provides many advantages compared to other systems and it satisfies all the conditions for plate vibration control.

Wang *et al.*[30] developed the MRF based semi-active tuned liquid column damper (TLCD) for vibration reduction of building structures. It was concluded that MR-TLCD damping performance could be controlled by changing the applied magnetic field depending on loading conditions and structural uncertainty like wind-induced displacement and acceleration. Both Bingham plasticity model and Bouc-Wen hysteresis model were used to develop the simplified inverse dynamics (SID) models for MRFDs. The developed SID model was used to calculate the optimal fluid yield stress and optimal input current by Bingham plasticity model and Bouc-Wen hysteresis model respectively. Also, the piston velocity feedback algorithm and damper force feedback algorithm were developed for both the model to improve the damping performance of MRFD. The mechanical behaviour of MRFD was described experimentally for analysing the seismic control of longitudinal displacements of a suspension bridge under different earthquake conditions[61]. MRFDs were optimized based on two objectives functions such as the target damper force as 1000 N and the maximum magnetic flux density. Finite element analysis was used to get the desired optimal values based on the geometrical magnitudes, current-input excitation and yield stress. MRFD was fabricated and tested based on the optimized parameters.

Weber[62] developed a semi-active vibration absorber (SVA) based on the real time controlled MRFD for reduction of structural vibrations. The stiffness force and damping force are controlled by adjusting the natural frequency and minimizing internal damping of the MR–SVA to improve the performance of the system. The results showed that the MR–SVA has higher dynamic performance than the passive type dampers. The vibration reduction of MR–SVA has been improved between 12.4% and 60% depending on the level of excitation compared to passive methods.

Performance enhancement of steel moment resisting frames with MRFD

Experimental design and analytical studies on steel moment resisting frames (SMRF) for their improved performance of structures using viscous fluid and MRFDs have been carried out[31,32,63,64]. Two types of a one-quarter models of a steel moment resisting frame were designed and fabricated with toggle brace and scissor-jack-mechanisms for damper displacement enhancement in the frame model. Dynamic properties of two MRFDs containing MRFs were documented. The responses (force–displacement, force–velocity) for both the RD-1005-3 dampers (from Lord Corporation) due to 2, 2.55 and 3 Hz sinusoidal with amplitude of 3, 4 and 5 mm at 0, 0.5, 0.75 and 1 A are found with the help of experiments[65].

Experimental and analytical studies on seismic performance enhancement of SMRFs with MRFDs fitted in toggle and scissor-jack brace mechanisms have been carried out. It is experimentally demonstrated that, the semi-active control of the three-storey SMRF, up to current-input of 0.25 A to MRFDs is not effective in seismic performance enhancement of frame subjected to seismic forces, because the MRFDs lose their natural characteristics of giving damping to the system beyond 0.25 A current input and inducing additional forces in the system. However, MRFs at higher current inputs increase the stiffness and friction forces in the dampers which increases the resistance force in the dampers. Because of this, forces of the members in the frame with MRFDs increase, and they are more than the bare frame. So, it is essential that the members in the moment resisting frame with MRFDs at higher current inputs, should keep the responses within the limits prescribed by codes of practice. Then the SMRF with MRFDs resist higher seismic forces than the pure viscous fluid dampers (MRFDs at zero current input). Hence, further studies are needed to find the range of input-currents to be effective in instantaneous vibration control of structures for consistent performance at any time. For some specific dynamic performance requirement, the current-input in MRFD can be kept constant.

Dyke *et al.*[66,67] carried out analytical and experimental studies using clipped-optimal control algorithm based on acceleration feedback. In their approach, a linear optimal controller combined with a force feedback loop was designed to adjust the command voltage of MRFD. A new neuro-genetic control algorithm[68] is presented for finding optimum control forces. The control algorithm does not need the pre-training required in a neural network-based controller, which improves the efficiency of general control methodology significantly. Neural network (NN) models[69] proposed to emulate inverse dynamics of MRFD which calculates voltage signals based on a few previous time steps of displacement, damper force, voltage signal and the desirable control force. These models were based on the input–output generated using phenomenological model[57].

An analytical methodology for neuro semi-active control of a 3-storey SMRF with MRFDs has been developed[63]. The authors developed an optimal semi-active neuro-controller for capturing the phenomenological model of a MRFD using linear quadratic regulator (LQR) algorithm for controlling a 3-storey SMRF model. One of the important aspects of the structural control is the time delay associated with the control algorithm used to predict the control force. Artificial neural network (ANN) was used to improve the efficiency/performance of the control module. A feed forward neural network was trained and implemented using LQR algorithm for semi-active control of MRFD in SMRF. An explicit relation between control force and command signals (voltage) has been developed for the given MRFD. The neuro-controller is trained and tested with six types of earthquake records scaled to peak ground acceleration (PGA) of design basis earthquake (DBE). This methodology can be further extended to train the ANN corresponding to site-specific earthquakes based on the location of the building.

From the literature review, it is found that MRFDs can provide effective control of vibration in various applications such as vehicle suspension, machineries mountings, buildings and bridge structures. A wide range of controllers and control algorithms were used in the reported studies to achieve the controlled damping force for realizing the objectives of the respective studies. The MRFDs could be effectively applied in a semi-active control manner with only minimal external power.

MRFD integrated with air spring

The air spring is a suspension element that consists of two chambers (primary and additional volume) filled with air at a desired pressure and connected to each other by means of a pipeline system. The stiffness of the air spring depends on the total volume and an electromagnetic valve is adopted to link the additional volume and, so, to change the stiffness. The change of the spring stiffness is controlled by an electromagnetic valve, while damping ratio is defined by dimensions and construction characteristics of the interconnection pipeline[70].

Hong *et al.*[70] studied the development of a liquid spring shock absorber with controllable MRF damping through a bypass comprising tubing and an MR valve. The spring force is developed by compressing the MRF hydrostatically due to varying shaft volume. Liu *et al.*[71] proposed a variable damping and stiffness system using two MRFDs and two springs. By controlling the damping of the MRFD, the total stiffness of this system can be varied in step less. Meanwhile, due to the fast response characteristic of MRF, this system provides the possibility to apply real time control on it. However, two MRFDs increase the complexity of the system and the fallibility.

The idea proposed by Renno *et al.*[72] is characterized by the integration of an air spring with an MRFD. The idea takes place starting from the passive device and based on the combination of an air spring with a common viscous damper. The architecture of the device is based on the parallel connection between the spring and the damper. The proposed device employs an air spring integrated with an MRFD. The scheme is illustrated in Figure 4. The MRF flows through the annular gap between the piston and the cylinder. A magnetic circuit, supplied by the excitation coil located in the piston, is used to generate controllable magnetic field by varying the coil current. The resultant damping force is due to both shear damping and valve damping forces. It changes dynamically with the magnetic field generated by the input current. The combined employment of an air spring and an MRFD is characterized to find the possibility of changing stiffness and damping and making them fully versatile and functional to overcome the several issues related to vibration control. The integrated solution is based on the parallel of both an air spring and an MRFD. The solution allows to select the better compromise to enhance the opposite aspects of ride and handling. The possibility of changing both the stiffness and the damping represents a functional solution for several issues concerning the vibration control.

Usage of MR fluids suspension systems in automobile industry

Lord Corporation, the world's leading supplier of commercially proven MR fluids, states that, 'MRF technology has proven capability to reduce topping and bottoming; bottoming that can injure drivers and topping that can lead to loss of control of the vehicle. Seating equipped with MRFDs offers both safety and health benefits for drivers. Unlike standard air suspended seats, which compromise shock and vibration control, the MR technology is one of the solutions that automatically adopts to both the drivers body weight and continually changing levels of shock and road vibration, improving driver responsiveness and control while reducing fatigue and risk of injury[44,73].

MR technology enables new levels of performance in automotive primary suspension systems. In an MR suspension, controllable MRF replaces traditional hydraulic fluid in each shock absorber. As sensors monitor road and vehicle conditions, a controller modifies the damping characteristics up to one thousand times per second. This enables dramatic improvements in both ride comfort and handling and can be used to improve the driving characteristics of any vehicle, from high-end sports cars, to sedans and sports utility vehicles (SUVs). First introduced in the 2002 model year, the system now appears on more than a dozen models from a wide variety of original equipment manufacturers (OEMs), including Acura MDX, Audi R8, Cadillac DTS, Chevrolet Corvette, Ferrari 599 GTB and Holden HSV Commodore. The MagneRide shock absorber system using MRF technology developed by Lord Corporation is available on a number of Cadillac and Corvette models. MagneRide is an automotive adaptive suspension with MRFD system developed by the Delphi Automotive Corporation in 2003 (Figure 5)[74], which is now owned by Beijing West Industries that utilizes MRFDs for a highly adaptive ride. As opposed to traditional suspension systems, MagneRide has no mechanical valves or small moving parts that can wear out. This system consists of four mono tube dampers, one on each corner of the vehicle, a sensor set,

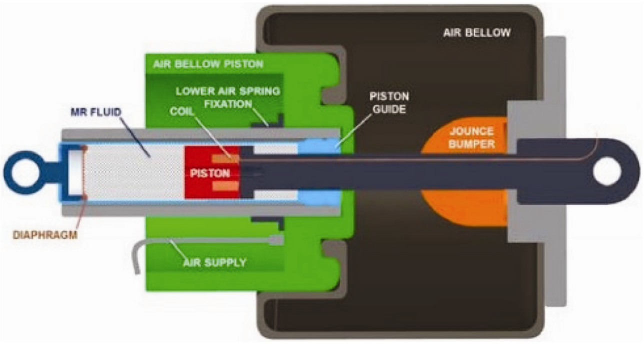

Figure 4. Air spring integrated with an MR damper[67].

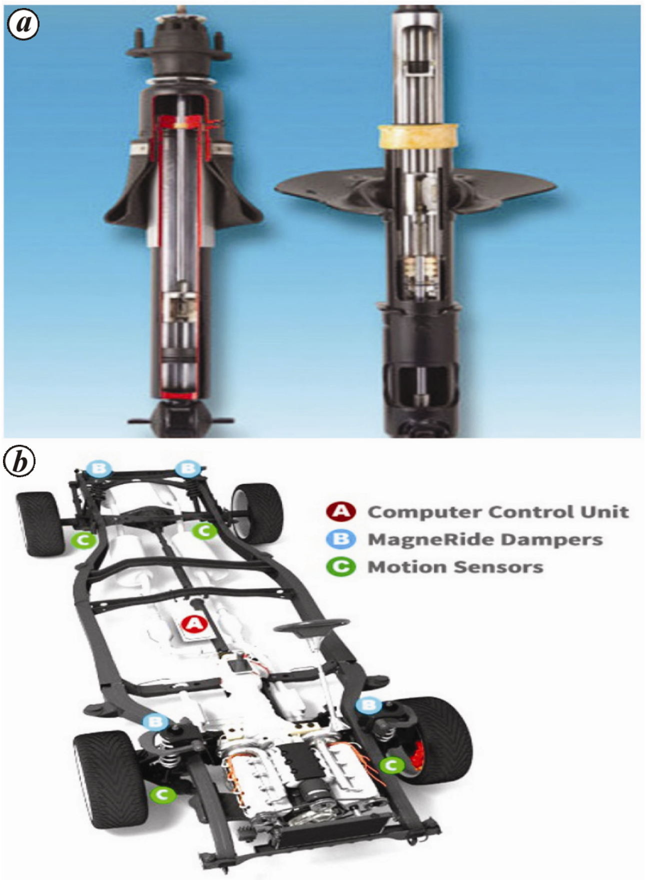

Figure 5. Parts of a MagneRide controlled suspension system[74]. ***a***, Cutaway of a Delphi MagneRide rear shock absorber and a suspension strut. ***b***, The MagneRide system.

Figure 6. Viscous fluid dampers with springs. ***a***, GERB vibration control; ***b***, Vibrodynamics Corporation.

and an electronic control unit (ECU) to maintain the system. MagneRide is suitable for vehicles in which premium ride and handling characteristics are desired, including luxury automobiles, sports cars, light trucks and SUVs. MagneRide as an integral part of the vehicle's ride and handling system, results in enhanced vehicle performance, safety, comfort and reliability.

Rod Millen Special Vehicles, a California-based engineering company, has developed and tested a robust, MRF based, computer controlled suspension upgrade for the army's high mobility multipurpose wheeled vehicle (HMMWV) hummer. The new system was developed to improve the performance and mobility of the army's hummer that uses a stock suspension system. rod millen special vehicles calls its system magneto rheological fluid optimized active damper suspension (MROADS). Developed for the army's tank and armaments command (TACOM), the MROADS system, designed for bolt-on retrofitting, consists of one MRF computer-controlled damper at each of the vehicle's wheel positions. The active damper with MRFs suspension modulates the forces in a damper as a function of sensed variables, such as the vehicle speed, body movements and position of a particular wheel. The new active damper suspension system is lighter, smaller, less expensive and uses much less power than a fully active system while providing similar levels of performance. Tests showed significant (70% on certain terrain) reduction in driver absorbed power, excellent reliability and no failures. Other advantages of the MRF system include higher mobility speeds over a given terrain, improved tyre traction and tyre life, reduced fatigue loading of vehicle structure and payload, reduced driver, vehicle and payload damage from terrain impacts at speed, improved vehicle stability and handling, improved accuracy during surveillance, targeting, or weapons firing, etc'.

Viscous fluid dampers/MRFD with springs

Viscous fluid dampers used in impact hammer systems and large stamping presses are shown in Figure 6. Here, viscous fluid dampers can be substituted with MRFDs for vibration isolation of high capacity loads for these applications.

R&D requirements in developing MRFs for vibration control of structures and components

The latest developments in vibration control of structures and structural components using MRFs and the current status of technology are discussed. The constitution of various particles and their size, various fluids and their viscosity in MRFs for different industrial applications such as brakes, suspension systems and clutches in automobiles, vibration control and performance enhancement of structures of buildings, bridges, suspension systems subjected to seismic loads, are active areas of research and required to be developed cost effective products way for the same. Development of products with MRFs with combination of other conventional suspension technologies (springs, air bellows) is also described.

The challenges in using MRFDs structural seismic performance enhancement are, MRFs used in MRFDs are costly. So there is a need to reduce the cost which can be done by choosing cost effective ingredients based on the functionality (e.g. for carrier fluids such as honge oil can be used in place of silicon oil) without compromise in the performance requirements. At present, the cost of all components in MRFs is expensive. Manufacturing in large scale after the design and usage of MRFs are well established, the cost can be reduced. Another major issue in MRFs is the sedimentation of dense carbonyl iron particles which tend to settle. In some cases, this is not a significant issue as long as there is a means within the device to re-disperse particles that have settled (for example in automobiles). However, for seismic performance enhancement of structures, the MRFDs are required to be used for long time, and they are required to perform instantly at any time. Here, allowing time for the particles to be re-dispersed is not an option. Thus, overcoming sedimentation remains a challenge in usage of MRFDs in structures such as buildings and bridges; for which, further research is required.

There is also requirement to find the range of input-currents to be effective in instantaneous vibration control of structures with different natural frequencies for consistent performance at any time. For some specific dynamic performance requirement, the current-input in MRFDs can be kept constant. Research and development in this direction is important for effective vibration control of structures and structural components based on their specific requirement.

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