

SMART FLUIDS: PROPERTIES AND APPLICATIONS IN VIBRATION CONTROL SYSTEMS

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ABSTRACT

This paper aims to present the properties and application of smart materials which are to be used in vibration control systems. The vibration control can be carried out by three strategies namely passive, semi-active and active control systems. Smart fluids belong to the class of field responsive composites and they have the capacity to undergo significant, reversible and controllable transformations with respect to their material characteristics. These materials have the ability to change from a liquid to a solid almost instantly when subjected to electric or magnetic field. Smart fluid comprises a suspension of micro-meter-sized particles in a dielectric carrier liquid. These smart materials are commonly referred as Magneto-rheological (MR) fluids, Electro-rheological (ER) fluids and Ferro-fluids. MR fluids are the dispersions of fine, magnetically soft, multi-domain particles, in a hydraulic or silicone oil carrier fluid. The apparent yield strength of these fluids can be changed significantly within milliseconds on the application of an external magnetic field. MR fluids possess rheological properties, which can be changed in a controlled way. ER fluid also exhibit changes in their behavior under the influence of an applied electric field. ER fluids are also known as electro-viscous fluids, where rheological effects were used to depict the changes observed in the mechanical properties of the fluid due to electrostatic stress. Ferro-fluids consist of colloidal suspension of mono domain ultra-fine magnetic particles dispersed in either aqueous or non-aqueous liquids.

Keywords: *Electro-rheological fluids, Ferro-fluids, Magneto-rheological fluids, Semi-active control systems*

I. INTRODUCTION

The vibration control can be carried out by three strategies namely passive, semi-active and active control systems and are shown in Fig. 1. A passive vibration-control unit consists of a resilient member (stiffness) and an energy dissipator (damper) of constant value to absorb vibratory energy of the disturbing vibration and is shown in Fig. 1 (a). This configuration has found to have significant limitations in structural applications where broadband disturbances of highly uncertain nature are encountered. In order to compensate these limitations, active vibration-control systems are designed and utilized. With an additional active force introduced as a part of a suspension unit, $u(t)$, Fig. 1 (b), the vibration-control system is then controlled using different algorithms to

make it more responsive to sources of disturbance. A combination of active/passive treatment is intended to reduce the amount of external power requirement which is necessary to achieve the desired performance characteristics.

In view of the above, if a system is required to be operated over a broadband of frequency range, then it is impossible to operate it with a single choice of stiffness and damping. If the desired response characteristics cannot be obtained, then an active vibration-control system can provide an alternative for such broadband disturbances. However, such active configurations suffer from control-induced instability in addition to the requirement of large control effort. Because of this, it is not in common usage in most of the industrial applications. On the other hand, passive vibration-control systems (especially vibration absorbers) are often hampered by a phenomenon known as “de-tuning”.

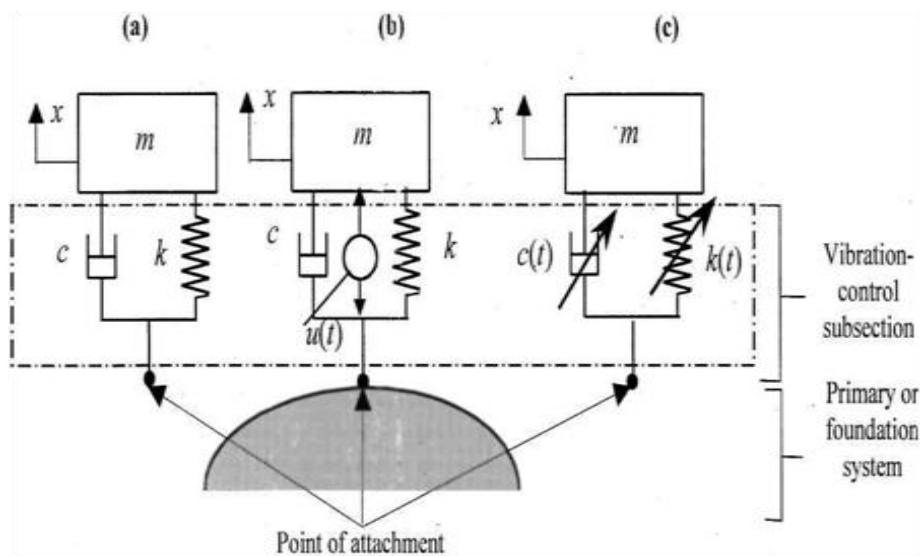


Fig. 1 Three versions of vibration-control systems: (a) Passive, (b) Active and (c) Semi-active configuration [1]

Semi-active (also known as adaptive-passive) configuration addresses these extreme limitations by effectively integrating a tuning control scheme with tunable passive devices. For this, active force generators are replaced by modulated variable compartments such as variable rate damper and stiffness, Fig. 1 (c). These variable components are referred as “tunable parameters” of the vibration-control system, which are re-tailored via a tuning control. Much attention is being paid to these arrangements for their low energy consumption and cost [1]. The behavior of the semi-active devices is often highly nonlinear one, and it poses main challenges in its application. The semi-active control systems are, thus, potentially very good techniques of controlling suspensions and to improve its performance.

Recent development of smart materials and structures has led to the design of various semi-active suspension systems. Examples of various semi-active suspension systems include electro-rheological (ER), magneto-rheological (MR) fluid dampers variable orifice dampers controllable friction braces, controllable friction isolators and variable stiffness devices including pneumatic isolators etc.

Science and technology have made marvelous developments in the design of electronics and machinery using standard materials, which do not have particularly special properties. The range of applications is still wider for special materials whose properties scientists, engineers can manipulate. Some of these materials have the ability to change shape or size simply by adding a little heat or to change from a liquid to a solid almost instantly when placed near a magnet; these materials are commonly called Smart materials/fluids. These materials have multiple properties (chemical, electrical, magnetic, mechanical and thermal) or can transform energy which can be altered or tuned using external fields. Most everyday materials have physical properties, which cannot be significantly altered; for example if oil is heated it will become a little thinner, whereas a smart material with variable may turn from a liquid state which flows easily to a solid. Each individual type of smart material has a different property which can be significantly altered, such as viscosity, volume or conductivity [2]. As each smart material has a different properties which can significantly be altered. Thus, the property that can be altered significantly determines what type of applications a particular smart material can be used most effectively. Varieties of smart materials exist and are still being researched extensively. These include piezoelectric materials, magneto-rheostatic materials, electro-rheostatic materials and shape memory alloys. Some everyday items have already incorporating smart materials and the number of application is still growing steadily. There are some smart fluids; MR fluids, ER fluids and Ferro-fluids which under the influence of applied magnetic/electric fields change their rheological properties [3]. The smart fluids i.e. MR fluids, ER fluids and Ferro-fluids are used in the dampers to achieve the objective of vibration control. These smart fluids have been reviewed in terms of their properties and applications in this paper.

II. MAGNETO-RHEOLOGICAL FLUIDS AND ITS PROPERTIES

Magneto-rheological (MR) fluids are one of the smart fluids that exhibit dramatic reversible change in its rheological properties (elasticity, plasticity or viscosity) either in solid-like state or free-flowing liquid state depending on the presence or absence of a magnetic field. The discovery of MR fluids is credited to Jacob Rabinow at the US National Bureau of Standard in 1948 [4].

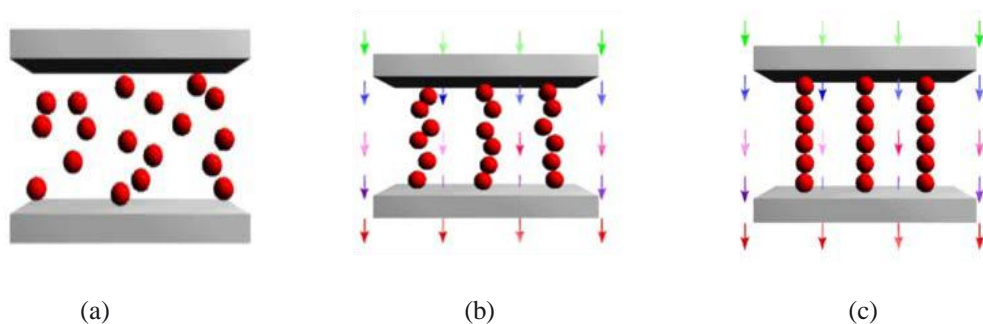


Fig. 2 Activation illustration of MR fluid: (a) No magnetic field applied, (b) Magnetic field just applied and (c) ferrous particles chains formed after full activation of magnetic field

Figure 2 shows the activation of the MR fluid. The MR fluids consist of magnetically permeable micron-sized particles dispersed throughout the carrier medium either a polar or non-polar fluid, which influence the viscosity of the fluids under no external magnetic field. The Figure 2(a) shows that the particles in the fluid are randomly

dispersed in the medium when there is no magnetic field applied. In the presence of a magnetic field, the particles start to move to align themselves along the lines of magnetic flux i.e. Fig.2 (b). Fig.2 (c) shows the formation of chains of the particles thus creating yield strength. As this change in its rheology occurs instantly and also reversible in nature, the MR fluids are attractive for real-time control applications [5].

The magneto-rheological fluids are the suspensions of micron sized, magnetizable particles (mainly iron) suspended in an appropriate carrier liquid such as mineral oil, synthetic oil, water or ethylene glycol. The carrier fluid serves as a dispersed medium and ensures the homogeneity of particles in the fluid. A variety of additives (stabilizers and surfactants) are used to prevent gravitational settling and promote stable particles suspension, enhance lubricity and change initial viscosity of the MR fluids. The stabilizers serve to keep the particles suspended in the fluid, whilst the surfactants are absorbed on the surface of the magnetic particles to enhance the polarization induced in the suspended particles upon the application of a magnetic field.

In the absence of an applied field, the MR fluids are reasonably well approximated as Newtonian liquids. For most engineering applications a simple Bingham plastic model is effective at describing the essential, field-dependent fluid characteristics. A Bingham plastic is a non-Newtonian fluid whose yield stress must be exceeded before flow can begin [6]. Thereafter, the rate-of-shear versus shear stress curve is linear. In this model, the total yield stress is given by

$$\tau = \tau_0(H) + \eta\dot{\gamma} \quad (1)$$

where τ_0 is the yield stress caused by applied magnetic field [Pa], H is the Magnetic field strength [A/m], γ is the Shear rate [s⁻¹] and η is the Plastic viscosity [pa.s]. Typical magneto-rheological materials can achieve yield strengths up to 50–100 kPa at magnetic field strength of about 150–250 kA/m. The MR effect is immediately reversible if the magnetic field is reduced or removed. Generally response time of 6.5 millisecond has been recorded for this fluid. The magneto-rheological fluids that have been already developed are stable in temperature ranges from –50° C to 150°C. There are slight changes in the volume fraction and hence slight reductions in the yield strength at these temperatures but they are small. Also size distribution of the suspended particles affects the change in properties of the MR fluid when placed in a magnetic field.

The MR applications in the field of are semi-active control devices which offer the flexibility and versatility of the active systems and the reliability of the passive ones. There are many ways to exploit the MR fluids in engineering applications [7].

As the state of MR materials can be controlled and reversed by the strength of an applied magnetic field, so it is useful in applications where variable performance is desired. Microprocessors, sensor technologies, increasing electronic content and processing speeds have created real-time control possibilities of smart systems using MR devices. The commercialization of the MR technology begins in 1995 with the use of rotary brakes in aerobic exercise equipment. From this moment onward, the application of magneto-rheological material technology in real-world systems has grown steadily. During the past few years a number of commercially available products (or near commercialization) have been developed [8-11]: e.g. Linear MR dampers for vibrational control systems in heavy duty trucks, Linear and rotary brakes for low-cost, accurate, positional and velocity control of pneumatic actuator systems, Rotary brakes to provide tactile force-feedback in steer-by-wire systems, Linear dampers for real-time control in advanced prosthetic devices, Adjustable real-time controlled shock absorbers for automobiles, MR sponge dampers for washing machines, Magneto-rheological fluid polishing tools, Very

large MR fluid dampers for seismic damage mitigation in civil engineering structures, Large MR fluid dampers to control wind-induced vibrations in cable-stayed bridges.

III. ELECTRO-RHEOLOGICAL FLUIDS AND ITS PROPERTIES

Another attractive field-responsive fluid, similar to MR fluid, is Electro-rheological (ER) fluid which also exhibits its rheological change or ability to alter their flow characteristics under the influence of an applied electric field. In the earlier era, the ER fluids have long been known as electro-viscous fluids [12] where rheological effects were used to depict the changes as observed in the mechanical properties of the fluid due to electrostatic stress. Nevertheless, the initial discovery of electro-rheological fluids is credited to the American inventor Willis M. Winslow [13] who, in the 1947 described the effects of the ER fluids in his patent. The ER effect was ascribed to Klass and Martinek [14] regarding the study on electro-viscous properties of suspensions, where a large change in electro-viscosity as a function of many parameters was found.

The ER fluids comprise of electrical polarizable particles dispersed in carrier fluid (electrically insulating oil) with complement of additives or surfactants [15]. An ER fluid consists of particles containing mobile charge carriers such as polyacene quinines, polymeric electrolytes of Bayer, carbonaceous fluid of Bridgestone, zeolites and poly-electrolytes. When an electric field is applied, the particles inside the ER fluid become polarized and have a higher dielectric constant than its surrounding carrier fluids. At the greatest field concentration, the number of polarized particles is increased by the movement of the mobile charges to those areas. This results in inducement of dipole moments that attract one another. The particles alignment takes place to minimize the dipole-dipole interaction energy in the field direction (Fig. 3). This process is reversible, with a transition time of less than 1 microsecond. For a certain particle like silica, in order to increase the performance of ER effect, poly-electrolytes are added for the purpose of absorbing water onto the particulate material. This process increases the electrostatic force of attraction between the particles, where the effect decreases as the amount of water absorbed decreases. The ER fluids had not created much interest until Block and Kelly [16] discovered water-free ER fluids. These materials are classified as intrinsically polarizable materials. For instance ferroelectric, inorganic, semiconductor polymer, metal, coated conductor and liquid crystal materials are water-free ER materials, which perform as a function of bulk polarization or interfacial polarization. Furthermore, particle shape was also found to affect the performance of ER fluids.

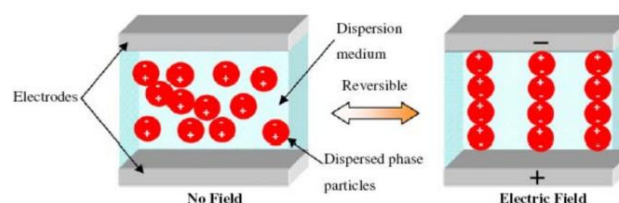


Fig. 3. Formation of chain-like formation of particles in ER fluids in the direction of an applied electric field

The normal application of ER fluids is in fast acting hydraulic valves and clutches, with the separation between plates being in the order of 1 mm while the applied potential being in the order of 1 kV. When the electric field is applied, an ER hydraulic valve is shut or the plates of an ER clutch are locked together and when the electric field is removed the ER hydraulic valve is open or the clutch plates are disengaged. Other common applications of the ER technologies are in the brakes and shock absorbers. Other potential uses are in the accurate abrasive polishing, and tactile displays. The ER fluid has also have a potential applications in flexible electronics with the fluid incorporated in elements such as rollable screens and keypads, in which the viscosity-changing qualities of the fluid allowing the rollable elements to become rigid for use and flexible to roll and retract for storing when not in use.

IV. FERRO FLUIDS AND ITS PROPERTIES

A magnetic colloid, also known as a Ferro-fluid, is a colloidal suspension of single-domain magnetic particles, with typical dimensions of about 10nm, dispersed in a liquid carrier [17]. Ferro-fluids were discovered in the 1960s at the NASA Research Center, where scientists were investigating different possible methods of controlling liquids in space. Figure 4 shows the sketch of Ferro-fluid grains in single-layered grains as well as double-layered grains.

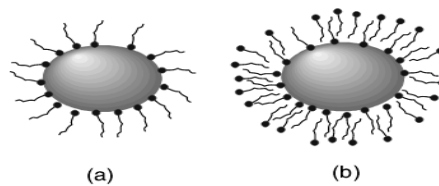


Fig. 4 Sketch of surfacted Ferro-fluid grains: a) single-layered grains; b) double-layered grains.

The benefits of a magnetic fluid were immediately obvious: The location of the fluid could be precisely controlled through the application of a magnetic field and by varying the strength of the field; the fluids could be forced to flow. Researchers have prepared Ferro-fluids containing small particles of ferromagnetic metals, such as cobalt and iron, as well as magnetic compounds, such as manganese zinc ferrite, $Zn_xMn_{1-x}Fe_2O_4$ ($0 < x < 1$); this is a family of solid solutions). But by far, the most work has been conducted on Ferro-fluids containing small particles of magnetite, Fe_3O_4 . Ferro-fluids consist of colloidal suspension of mono-domain ultra-fine magnetic particles (typically less than 10 nm), dispersed in either aqueous or non-aqueous liquids [18-19]. Basically, particle types of super-paramagnetic materials such as iron oxides, Mn-Zn Ferrites, Ferrum and Cobalt is chosen together with a carrier fluid, such as water, oil to produce a stable colloidal suspension. When an external magnetic field is applied, dipolar interactions are induced within the particles causing them to align in the field direction. Forces exerted from the magnetic field are transmitted through viscous friction to the Ferro-fluids, which leads to various interesting phenomena. However, Ferro-fluids do not exhibit yield stress (like MR fluids), but instead they have field dependent viscosity. Ferro-fluids commonly keep their viscosity with high magnetic fields without forming any chain. However, since Ferro-fluids are synthesized by colloidal magnetic particles, they are more stable as compared to the MR fluids, which are based on non-colloidal

magnetic particles. Practical applications of this property include automotive, mechanical engineering, optics, electronic devices, biomedical and heat dissipation.

Ferro-fluids have found a wide variety of applications e.g. use in rotating shaft seals. A Ferro-fluid can behave as a liquid O-ring where a rotating shaft enters either a low- or high-pressure chamber. The Ferro-fluid is held in place by permanent magnets and forms a tight seal, eliminating most of the friction produced in a traditional mechanical seal. These rotating shaft seals are found in rotating anode X-ray generators and in vacuum chambers used in the semiconductor industry. Ferro-fluid seals are used in high-speed computer disk drives to eliminate harmful dust particles or other impurities that can cause the data-reading heads to crash into the disks. Another application of Ferro-fluids is in improving the performance of loudspeakers. In a loudspeaker, electric energy is sent through a coil located at the center of a circular permanent magnet. The magnetic field induced by the electric energy causes the coil to vibrate and thus produces sound and heat. Bathing the electric coil in a Ferro-fluid, which is held in place by circular permanent magnets, dampens unwanted resonances and also provides a mechanism to dissipate heat from the excess energy supplied to the coil. Both of these factors lead to an overall improved sound quality too. The researchers are attempting to design Ferro-fluids that can carry medications to specific locations in the human body through the use of applied magnetic fields. Other research work ongoing is regarding the possible uses of Ferro-fluids as contrast agents for magnetic resonance imaging (MRI).

V. COMPARISON OF SMART FLUIDS

The working mechanism of the MR fluids is assumed to be similar to that of the ER fluids except that the MR fluids are limited by magnetic saturation while ER fluids are limited by dielectric strength. In contrast to the ER fluid, the MR fluids are more useful because the change in their rheological properties is, larger than that in the ER fluids e.g. increase of yield stress by 20-50 times stronger. Unlike the ER fluid, the MR fluids are also less sensitive to moisture and contaminants and thus the MR fluids are the right candidates for the use in dirty or contaminated environments. They are also not affected by the surface chemistry of surfactants as the ER fluid does. The power (50 W) and voltage (12–24 V) requirements for MR materials activation are relatively smaller as compared with the ER fluid. Table 1 shows the basic comparison of the smart fluids.

Table1 Comparison of Smart Fluids [20]

	MR Fluids	ER Fluids	Ferro fluids
Particulate Material	Iron, ferrites, etc	Zeolites, Polymers, SiO ₂ , BaTiO ₃	Ceramics, Ferrites, iron, cobalt, etc.
Particle size	0.1-10 μm	0.1-10μm	2-10 nm
Suspending fluid	Non polar oils, polar liquids, water and other	Oils	Oils, Water
Density (g/cc)	3-5	1-2	1-2

Off viscosity (mPa-s)	100-1000	50-1000	2-500
Device excitation	Electromagnets or permanent magnets	High voltage	Permanent magnet

Further, the MR fluids are found to be superior to the ER fluids in terms of the yield stress, current consumption and the stability. In addition, the amount of active fluids required in the MR fluids in order to execute a mechanical performance is less than the requirement of the ER fluids. Even though the ER and the MR fluids require almost the same magnitude of power, the MR fluids need only small voltages and high currents, while the ER fluids demand high voltages and low currents. Thus, the extremely high voltage requirements and inability to withstand contamination of the ER fluids make them unpractical for most of commercial applications. In contrast, the ER fluids have a distinctive feature where they show higher response characteristics as compared to the MR fluids. Researchers have discovered that the ER devices appeared to provide more viable means (in terms of input displacement and transmitted force) of achieving fixing relaxation subjected to various magnitudes of impact loading. In contrast, the MR fluids have larger particles and react differently as compared to the Ferro-fluids under the same influence of the magnetic field. The MR fluids can change their viscosity with the formation of a chain structure and solidify when a magnetic field is applied. However, Ferro-fluids commonly keep their viscosity with high magnetic fields without forming any chain. However, since Ferro-fluids are synthesized by colloidal magnetic particles, they are more stable as compared to the MR fluids, which are based on non-colloidal magnetic particles.

VI. CONCLUSIONS

The development of smart fluids will undoubtedly be an essential task in many fields of science and technology such as medical treatment, energy, transportation, safety engineering, vibration control and military technologies. In future the materials development, therefore, should be directed toward creation of hyper-functional materials which surpass even biological organ in some aspects. The current smart materials research is to develop various pathways that will lead the modern technology toward a smart system. These smart fluids can reversibly and instantaneously change from a free-flowing liquid to a semi-solid with controllable yield strength when exposed to a magnetic/electric field. The world of dissipative and damping device is full of potential smart fluid applications, especially when it is desirable for vibration control.

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