Conference Proceedings of the Academy of Romanian Scientists
PRODUCTICA Scientific Session
Online ISSN 2067-9564 Volume **10**, Number **1**/**2018**

MAGNETOREHOLOGICAL FLUIDS FOR ACTIVE VIBRATION CONTROL

Sorin BURDUCEA[1], Miron ZAPCIU[2]

Rezumat. *Lucrarea de față își propune să ilustreze proprietățile mecanice, reologice și magnetice ale fluidelor magnetoreologice sub ipoteza utilizării lor în aplicații industriale. Soluțiile dezvoltate până la acest moment de timp în cadrul problematicii amortizării active a vibrațiilor sunt expuse împreună cu avantajele aduse de această tehnologie.*

Abstract. *This is a brief introduction that describes the mechanical, rheological and magnetic properties of the magnetorheological (MR) fluids for feasible engineering applications. The typical ways in which this technology may be used are shown and discussed. As an increasing number of industrial applications take advantage of MR's fluids special properties, the technology gets improved every day in order to provide optimal performance in active damping and dissipative devices. The special case of active squeeze film damping based on MR fluid is also discussed.*

Keywords: magnetorheological fluids, MR fluid, ER fluid, active vibration damping.

1. Introduction

Rheology is a science that focuses on the flow and deformation of materials. Rheological fluids have properties that can be modified using electrical current or magnetic field, giving them the ability to be controlled with the aid of external components. Magneto-Rheological (MR) and Electro-Rheological (ER) fluids are controlled by varying the strength of the magnetic or electric field. The fluid's viscosity can be adjusted between thinner-than-water to almost-solid state and any stage in between. The modifications are almost instantaneous, completely reversible and giving today's possibilities for digital control of electric and magnetic field, the process renders itself as highly controllable.

Both fluids act as suspension medium carrying micrometer or nanometer scale particles. Both may use silicone, glycol, oil or water as the base medium and since they may not be activated for long periods of time, different additives are needed to keep the particles in suspension. The fluids contain polarisable particles that can be forced to align in a specific way. The polarisable particles are the basic difference between ER and MR fluids. ER fluid uses particles that polarize when

[1] Eng., PhD student, SC Siemens Romania SRL, E-mail: sorin.burducea@siemens.com
[2] Professor, Politehnica University of Bucharest, Corresponding Member of the Academy of Romanian Scientists, Spl. Independentei 54, sector 1, Bucharest, E-mail: miron.zapciu@upb.ro

directly exposed to an electric current. MR fluid uses larger particles based on soft iron that polarizes when exposed to a magnetic field.

The typical MR fluid particles measure 3 to 5 microns (3 to 5 thousandths of a millimetre) in diameter. The application will dictate the additives that will be used to control particle settling, mixing, fluid friction and fluid viscosity. The fluid is normally 20 to 40 percent saturated with the iron particles. Specific gravity is generally between 3 and 4; for reference, water's specific gravity is 1. Thus, a 250 litres drum of MR fluid can weigh close to a full ton.

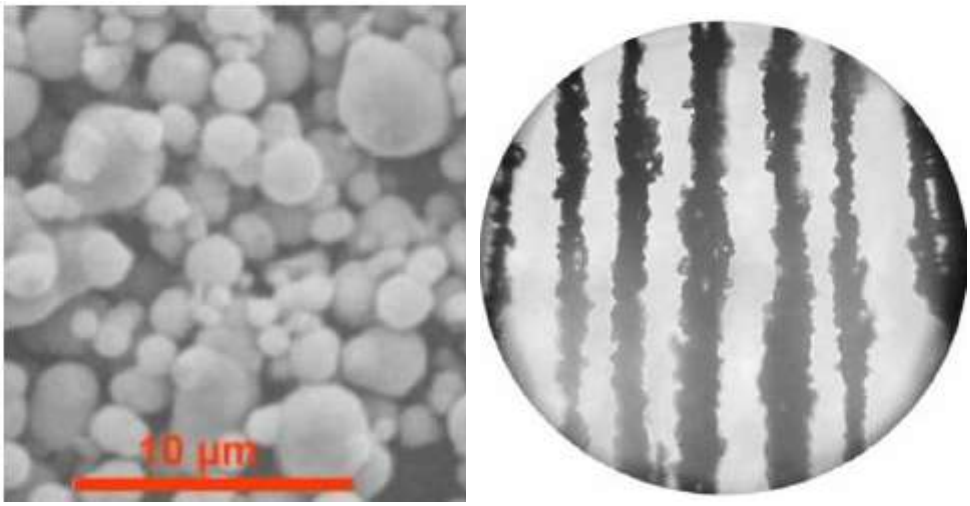
In a normal state, the particles are located in a random manner inside the carrier fluids. In this state, MR and ER fluids behave like liquids. It is when they are subjected to external (magnetic or electric) excitation that the particles within the respective fluids join to form columns aligned with the field lines (see Fig. 1-a) and 1b). Due to this characteristic change, MR and ER fluids become viscoelastic solid and the yield stress of fluid is increased dramatically. It is quite remarkable that this kind of process is fast and fully reversible, which means that MR and ER fluids can turn from liquid to solid and back within milliseconds. This is why, by modulating the strength of the corresponding fields, the viscosity of the MR and ER fluids can be accurately controlled. It is due to these unique features of the fluids that MR and ER fluids have increasingly been considered and used in various applications in recent years.

As history has it, the ER fluids were first reported in 1940s [1, 2]. They did not attract much attention for commercial purposes for the first few decades after their discovery. In the 1990s, the use of silicon oil as carrier fluid in ER fluids [3] improved the tolerance of the fluid to high temperature [4], enabling its commercial applications, of which ER dampers and clutches are the most well-known applications.

Similar to ER fluids, the initial discovery of MR fluids can be traced back to the late 1940s. The initial discovery and development of Magneto-rheological (MR) fluids can be credited to Jacob Rabinow (1948, 1951) at the US National Bureau of Standards. Jacob Rabinow published a paper [15] about MR fluids and patented the initial MR fluids devices [16]. Not unlike ER fluids, MR fluids did not receive much attention until the early 1990s. In 1993, a mathematic model that described the MR effect was proposed by Kordonsky [17]. In the same year, a high-strength MR fluid was proposed [18].

While ER and MR fluids can both offer advantages, each fluid may best suit a particular application given their differences in their characteristics [20, 32, 33, 34, 35]. MR fluids feature much higher maximum yield stress than ER fluids. MR fluid has a shear strength about 10 times stronger. Therefore, in a similar configuration, MR fluids can generate larger output torque than ER fluids. Moreover MR fluids are less sensitive to thermal variations and have better overall stability. In ER's favour, its excitation using external electric fields are mechanically less heavy and less complex and the particles are less prone to settling, although these particles require longer time to relax than the time for aligning themselves with the direction of external electric field [36].

Basically, MR fluids can be used in three different ways: shear control, valve control and squeeze mode control. Shear control applications control relative movement of adjacent parts, such as in torque converters, clutches and brakes. In valve control mode, it can be used in place of any kind of flow control valve, the most common application being the automotive shock absorbers. In squeeze mode, low amplitude, high energy vibrations may be controlled, finding applications mainly in shaft vibration damping.



a) *b)*

a) Microphotography of MR fluid where particles are randomly dispersed
b) MR fluid with an applied magnetic field with parallel chains of carbonyl iron

Fig. 1: Microphotography of a MR fluid

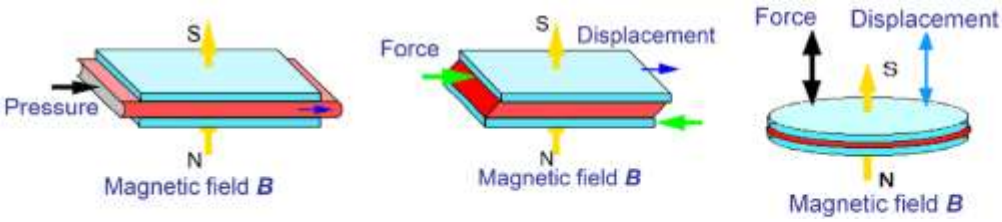
MR fluids have an overall aspect that is like a greasy quite heavy mud. The ferromagnetic particles feel the induction field and acquire a magnetic dipole, and then they move and redesign their arrangement, start to flow and to form chains and linear structures. These microscopic chains have the macroscopic effect to change the apparent viscosity of the fluid. The size of the particles lie at a micron size for the so called MR fluids (Fig. 2a) mainly produced by Lord Corp., while the nanosized particles produce a similar substance called ferrofluid (Fig. 2b), produced by Apexmagnets LLC. While the applications of MR fluids are relevant for engineers and can be used in many damping devices, the ferrofluids are mainly a fancy stuff to play with for artists and kids. The reason for this distinction is simple: there is a huge difference in the yield shear stress of the MR and ferrofluids, which affects the maximum force the fluid can provide.

a) **b)**

Fig. 2: Magneto rheological fluid (a) from Lord Corp. and ferrofluid (b), produced by Apexmagnets LLC.

In order to exploit MR fluids properties, as already mentioned, there are three main ways envisioned in current engineering applications:

a) Flow mode, shown in Fig. 3a;
b) Shear mode, shown in Fig. 3b;
c) Squeeze mode, shown in Fig. 3c.



a) b) c)

Fig. 3: Typical utilisation modes for MR fluids, flow (a), shear (b) and squeeze (c) mode.

The flow mode, also called valve mode, exploits the fluid between two fixed walls, the magnetic field is normal to the flow directions and is typical for linear damper applications. The shear mode is mainly used in rotary applications such as brakes and clutches and the fluid is constrained between two walls which are in relative motion with the magnetic field normal to the wall direction. The squeeze mode is used mainly for bearing applications, is able to provide high forces and low displacements having the magnetic field normal to walls directions. In all the above mentioned cases the working principle is the same: the applied magnetic field regulates the yield stress of the fluid and changes its apparent viscosity. So the amount of dissipated energy of the system is simply controllable by acting on the coil current and the system can provide semi-active behaviour.

2. Applications of Magnetorheological Fluids

The fast change in the MR behaviour (order of milliseconds) due to the magnetic field generation makes the material attractive for damping and dissipative devices. The MR fluids can be used to build integral, silent, quick mechanical systems controlled by electronic microprocessors and adequate electric drives.

In 1992, Petek build a shock absorber that featured an ER fluid [5] and experimentally proved that the use of ER dampers may bring advantages over classic dampers. Three years later, he used ER dampers in a car suspension system [6]. In 1995, a small-size, high-voltage ER damper was developed, again as car suspension system [7]. ER fluids have also been widely used to viscously couple components as in ER clutches and brakes. The experimental results in [8] demonstrate that the output torque of an ER clutch is dependent on the strength of the electric field, the temperature, and the input velocity. By using these characteristics, a 2 degrees-of-freedom (DOF) passive force display using ER brakes was developed in [9]. One main advantage of ER clutches within the class of devices with similar functionality is the ability of ER clutches to control the impedance as reported in [10]. Another interesting study on ER fluids was conducted by Kenaley [11] in which ER fluids were used in order to simulate the behaviour of a human’s finger. In this study ER fluids were placed between two components: “skin” and “bone”. The stiffness of ER fluids was changed by controlling the magnitude of the electrical field applied between ”skin” and ”bone” allowing for the grippers that were built using such fingers to lift lightweight objects with small grasping force. ER dampers have also been used in the field of civil engineering [12, 13, 14].

In 1994, MR fluid dampers with magnetic valves for controlling the flow parameters of the MR fluids were developed [19]. With further enhancement of the MR fluids, MR fluids devices became commercial successes in the late 1990s [20]. A controllable MR damper was applied to a track suspension [21]. In another example, an MR clutch was used to control the fan speed of an engine in a cooling system [22]. The use of MR fluid dampers for building earthquake-proof structure with millisecond response time was explored by mechanical and civil engineers [23]. More recently, MR fluids devices were applied to different fields and achieved a huge success. MR fluids also offer advantages as actuators. A simple MR actuator was developed in [24]. The experimental results proved that the MR actuators featured high torque to mass and torque to inertia ratios, simple interfaces and safe actuation. The response time of this actuator was later improved by replacing the aluminium connections in the actuators with plastic connections and applying a closed-loop torque control scheme [25]. MR actuators were employed in exoskeleton legs [26] as well as assistive knee braces [27]. In these applications, the MR actuator acts as an MR clutch to augment the human's motions while acting as an MR brake when the motion requires limiting. The characteristics of MR actuators also make them an ideal candidate for applications involving human-robot interactions. To this end, Shafer and Kermani proposed a new actuation concept called Distributed Active Semi-Active (DASA) actuation and experimentally validated it [28].

Using this concept, the same research group developed a 1-DOF, 2-DOF, and 3-DOF antagonistically actuated manipulators [29], [30], and [31]. It was shown that these manipulators were not only capable of enhancing the safety of the robots towards their human counterparts but also of maintaining the desired performance of operations in demanding tasks.

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

One of the most interesting engineering applications of MR fluid is the construction of smart and controllable MR linear dampers. The main asset of a MR based damper is the controllability of the system, which can be adjusted in order to provide the desired level of damping by simply changing the supply current. The main idea is to obtain the desired level of damping by varying the magnetic induction in an orifice between two separated MR fluid chambers. The orifice acts like a magnetic valve for the fluid, regulated by the current and thus exploits the MR fluid in flow mode. Two architectures are envisioned for this purpose: the single ended damper (Fig. 5a) and the double ended damper (Fig. 5b).

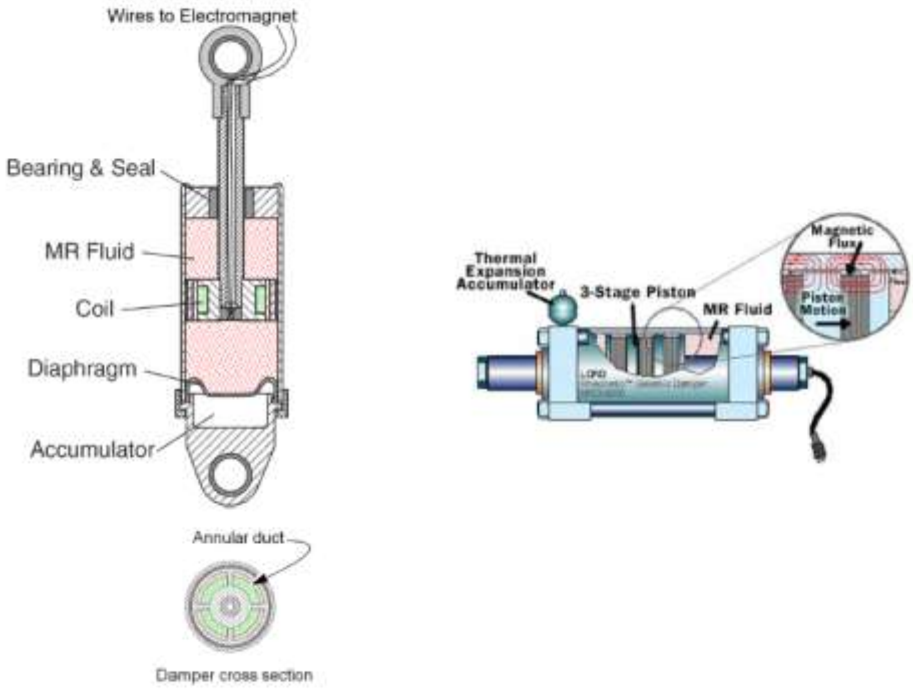


Fig. 4: Schematic of single ended MR damper and double ended MR damper, both produced by Lord Corp.

The single ended damper has only one reservoir for the MR fluid which is transferred through an orifice from one chamber to another. Since the rod volume is just on one side the system accounts for the change in volume that results from piston rod movement. In order to accommodate this change in reservoir volume, an accumulator is usually used. The accumulator provides a barrier between the MR fluid and a compressed gas (usually nitrogen) that is used to accommodate the necessary volume changes. Moreover the accumulator pressure can be used to enhance the performance of the MR system. The double-ended MR damper has piston rods of the same diameter that protrude through both ends of the damper. In this case there is no change in volume as the piston rod moves, the double ended damper does not require an accumulator or other similar device. The applications of the single ended damper are mainly in the vibration suppression of mechanical components like seat suspension, car suspensions, and industrial vibration suppression, while the double ended damper is mainly used for bicycle applications, gun recoil applications, and for stabilizing buildings and bridges during earthquakes. The output forces of such a device can range from quite low forces (hundreds of Newtons) in the case of light suspension system up to 20 tons in the case of civil applications, in which they must compensate the incredibly large forces caused by the shaking of entire buildings.

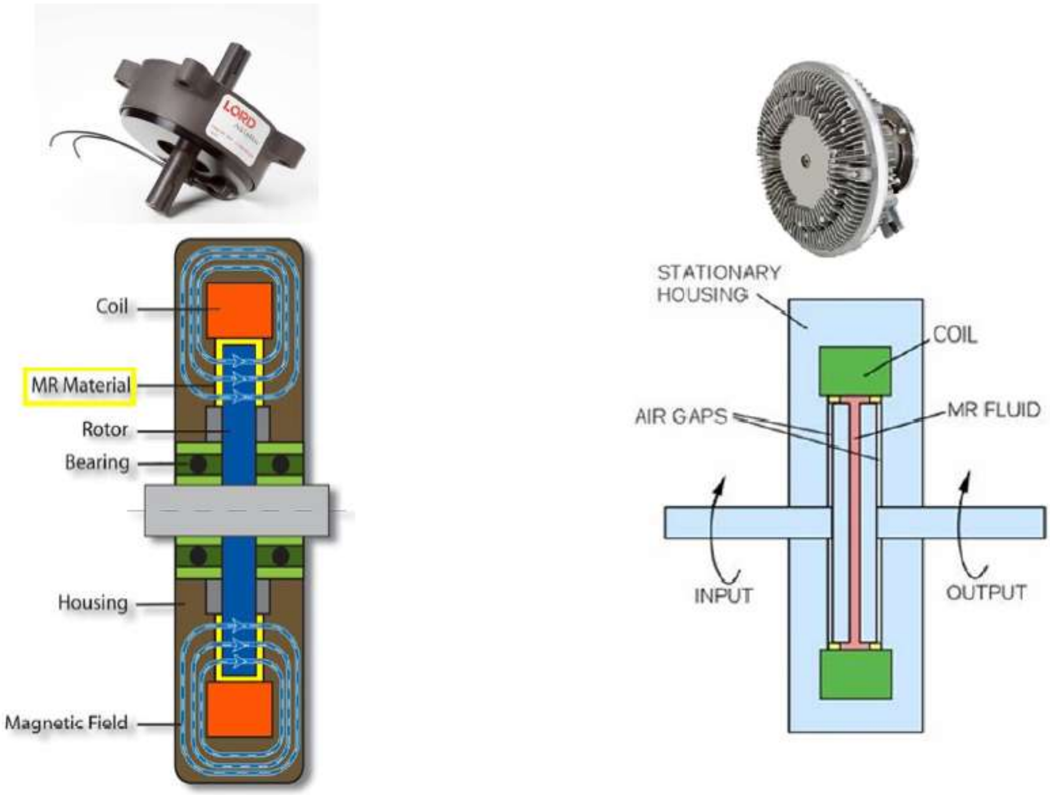


Fig. 5: Picture and schematic of MR based brake and clutch, both produced by Lord Corp.

The other main application exploits the MR fluid in shear mode to realize a sort of hydraulic brakes and clutches with MR fluids. The aim is to obtain a precise control of the braking torque (in the case of brakes) or transmitted torque (in the case of clutches) with no moving parts by simply varying the current in the coils. The typical architecture for a MR based brake is shown in Fig. 6a, where the basic idea is clearly depicted. The magnetic flux path passes through the chassis and the rotating disk and the fluid is sheared between these elements. The braking force depends on the yield stress of the fluid making the system controllable. The MR based clutch is ideally described by Fig. 6b, the fluid is between the input disk and the output disk and the amount of transmitted torque is proportional to the yield stress of the fluid. No moving parts are used to change the transmitted torque and the torque value can be smoothly controlled through the coil current. Even though multidisc applications can be used to increase the output torque, the typical application of rotary MR fluid devices is in the high precision and low power range. For example the Rheoknee, developed by Ossur Company, is the first prosthetic knee which allows the amputee to have a normal leg motion even in the case of stairs. The MR knee exhibits a very low torque when it is not active enabling the leg to move forward freely and in a few milliseconds the MR is able to carry all the human weight to complete the step. The overall performance is outstanding and shows how the smartness of MR fluid can improve human condition.

3. MR Fluid Models

A simple Bingham visco-plasticity model (Phillips 1969), as shown in Fig. 6, is effective at describing the essential field-dependent fluid characteristics. In this model, the total shear stress is given by

$$\tau = \tau_0(H)\operatorname{sgn}(\dot{\gamma}) + \eta\dot{\gamma} \tag{1}$$

where τ0= yield stress caused by the applied field; H= magnitude of the applied magnetic field; γ ·= shear strain rate; and η= field-independent plastic viscosity, defined as the slope of the measured post-yield shear stress versus shear strain rate.

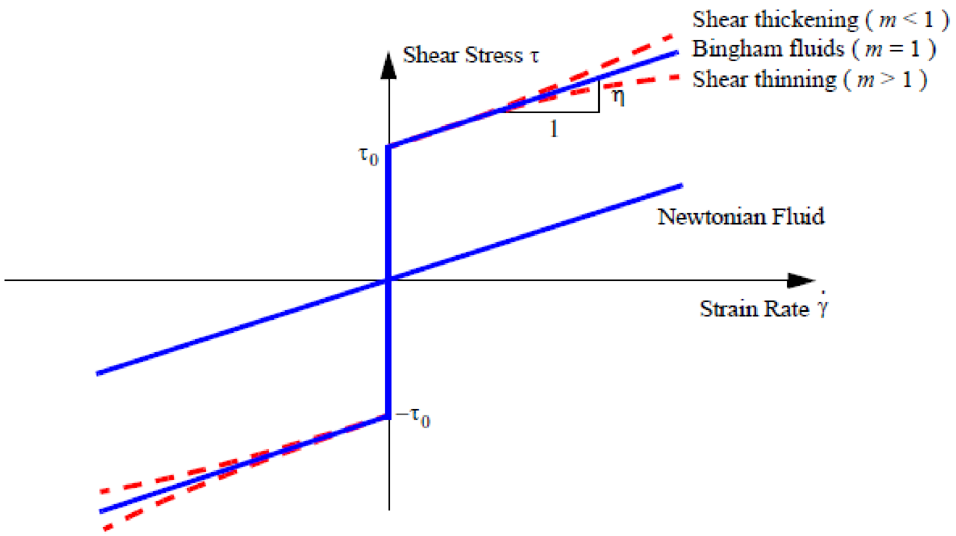


Fig. 6: Visco-plasticity models of MR fluids

Note that the fluid post-yield viscosity is assumed to be a constant in the Bingham model. Because MR fluids exhibit the shearing thinning effect which is shown in F,

$$\tau = \left(\tau_0(H) + K|\dot{\gamma}|^{\frac{1}{m}}\right)\operatorname{sgn}(\dot{\gamma})$$

(2)

the Herschel-Bulkley visco-plasticity model (Herschel and Bulkley 1926) can be employed to accommodate this effect. In this model, the constant post-yield plastic viscosity in the Bingham model is replaced with a power law model dependent on shear strain rate.
Therefore,

$$\eta_e = K|\dot{\gamma}|^{\frac{1}{m}-1} \tag{3}$$

where m, K= fluid parameters and m, K > 0. Comparing Eq. (2) with Eq. (1), the equivalent plastic viscosity of the Herschel-Bulkley model is Eq. (3) indicates that the equivalent plastic viscosity ηe decreases as the shear strain rate γ increases when m > 1 (shear thinning). Furthermore, this model can also be used to describe the fluid shear thickening effect when m < 1. The Herschel-Bulkley model reduces to the Bingham model when m = 1, therefore $\eta = K$.

4. Conclusions

The world of dissipative and damping devices is full of potential MR fluid applications, especially when it is desirable to control motion. Traditional viscosity based system with moving parts can be easily replaced by a MR fluid with changing viscosity as function of current, obtaining an improvement in functionality and a cost reduction. The MR fluid main features are: fast response, simple interface between electrical power input and the mechanical power output, controllability and integration in complex system. Nowadays MR fluids are a reliable technology for many engineering applications. Flow mode (used in dampers) and shear mode (used in brakes and clutches) have been studied thoroughly and several products are already present on the market.

R E F E R E N C E S

[1] W. M. Winslow, "*Method and Means for Translating Electrical Impulses into Mechanical Force*," Mar. 25 1947. US Patent 2, 417, 850.

[2] W. M. Winslow, "*Induced Fibration of Suspensions*," Journal of Applied Physics, vol. 20, no. 12, pp. 1137–1140, 2004.

[3] J. D. Carlson, "*Electrorheological Fluids*," Sept. 20 1988. US Patent 4,772, 407.

[4] W. E. Armstrong and F. E. Filisko, "*Electric Field Dependent Fluids*," May 17 1988. US Patent 4, 744, 914.

[5] N. K. Petek, "*An Electronically Controlled Shock Absorber Using Electrorheological Fluid,*" tech. rep., SAE Technical Paper, 1992.

[6] N. K. Petek, a.o. *Demonstration of an Automotive Semi-active Suspension Using Electrorheological Fluid*, SAE publication SP 1074, technical paper 950586), 1995.

[7] M. Sturk, X.Wu, and J.Wong, "*Development and Evaluation of a High Voltage Supply Unit for Electrorheological Fluid Dampers,*" Vehicle System Dynamics, vol. 24, no. 2, 1995.

[8] C. A. Papadopoulos, "*Brakes and Clutches Using Er Fluids*," Mechatronics, vol. 8, no. 7, pp. 719–726, 1998.

[9] M. Sakaguchi, J. Furusho, and N. Takesue, "*Passive Force Display Using Er Brakes and Its Control Experiments*," in Virtual Reality, 2001. Proceedings. IEEE, pp. 7–12, IEEE, 2001.

[10] T. Nakamura, N. Saga, and M. Nakazawa, "*Impedance Control of a Single Shaft-type Clutch Using Homogeneous Electrorheological Fluid*," Journal of intelligent material systems and structures, vol. 13, no. 7-8, pp. 465–469, 2002.

[11] G. L. Kenaley and M. R. Cutkosky, "*Electrorheological Fluid-based Robotic Fingers with Tactile Sensing*," in Robotics and Automation, 1989. Proceedings, 1989 IEEE International Conference on, pp. 132–136, IEEE, 1989.

[12] R. Ehrgott and S. Masri, "*Modeling the Oscillatory Dynamic Behaviour of Electrorheological*

Materials in Shear," Smart Materials and Structures, vol. 1, no. 4, p. 275, 1992.

[13] H. P. Gavin and R. D. Hanson, "*Characterization of an Er Active Member*," in Structures Congress XII, pp. 863–868, ASCE, 1994.

[14] H. P. Gavin, *Electrorheological Dampers for Structural Vibration Suppression*. No. 35, University of Michigan, 1994.

[15] J. Rabinow, "*The Magnetic Fluid Clutch*," Electrical Engineering, vol. 67, no. 12, pp. 1167–1167, 1948.

[16] J. Rabinow, "Rabinow," Nov. 20 1951. US Patent 2,575, 360.

[17] W. Kordonsky, "*Magnetorheological Effect as a Base of New Devices and Technologies,*" Journal of Magnetism and Magnetic Materials, vol. 122, no. 1, pp. 395–398, 1993.

[18] K. D. Weiss, T. G. Duclos, J. D. Carlson, M. J. Chrzan, and A. J. Margida, "*High Strength Magneto-and Electro-rheological Fluids*," tech. rep., SAE Technical Paper, 1993.

[19] J. D. Carlson and M. J. Chrzan, "*Magnetorheological Fluid Dampers*," Jan. 11 1994. US Patent 5,277, 281.

[20] M. R. Jolly, J. W. Bender, and J. D. Carlson, "*Properties and Applications of Commercial Magnetorheological Fluids*," in 5th Annual International Symposium on Smart Structures and Materials, pp. 262–275, International Society for Optics and Photonics, 1998.

[21] J. Carlson and B. Spencer Jr, "*Magneto-rheological Fluid Dampers for Semi-active Seismic Control*," in Proc. of the 3rd Int. Conf. on Motion and Vibr. Control, pp. 35–40, 1996.

[22] X. Xu and C. Zeng, "*Design of a Magneto-rheological Fluid Clutch Based on Electromagnetic Finite Element Analysis*," in Computer Engineering and Technology (ICCET), 2010 2nd International Conference on, vol. 5, pp. V5–182, IEEE, 2010.

[23] https://science.howstuffworks.com/engineering/structural/smart-structure.htm Acc.05.2018.

[24] N. Takesue, H. Asaoka, J. Lin, M. Sakaguchi, G. Zhang, and J. Furusho, "*Development and Experiments of Actuator Using Mr Fluid*," in Ind. Electronics Society, 2000. pp. 1838–1843.

[25] N. Takesue, J. Furusho, and Y. Kiyota, "*Fast Response mr-fluid Actuator*," JSME International Journal Series C, vol. 47, pp. 783–791, 2004.

[26] J. Chen andW.-H. Liao, "*Design and Control of a Magnetorheological Actuator for Leg Exoskeleton,*" in Robotics and Biomimetics, 2007. pp. 1388–1393.

[27] J. Chen and W. Liao, "*Design, Testing and Control of a Magnetorheological Actuator for Assistive Knee Braces*," Smart Materials and Structures, vol. 19, no. 3, p. 035029, 2010.

[28] A. S. Shafer and M. R. Kermani, "*On the Feasibility and Suitability of Mr Fluid Clutches in Human-friendly Manipulators*," Mechatronics, ASME Transactions, vol. 16, pp. 1073, 2011.

[29] A. S. Shafer and M. R. Kermani, "*Design and Validation of a Magneto-rheological Clutch for Practical Control Applications in Human-friendly Manipulation*," in Robotics and Automation (ICRA), 2011 IEEE International Conference on, pp. 4266–4271, IEEE, 2011.

[30] P. Yadmellat, A. S. Shafer, and M. R. Kermani, "*Design and Development of a Single Motor, Two-dof, Safe Manipulator*," 2015.

[31] A. S. Shafer and M. R. Kermani, "*Development of High Performance Intrinsically Safe 3-dof Robot*," in Robotics and Automation (ICRA), 2014 IEEE International Conference on, IEEE.

[32] A.-G. Olabi and A. Grunwald, "*Design and Application of Magneto-rheological Fluid*," Materials & design, vol. 28, no. 10, pp. 2658–2664, 2007.

[33] R. W. Phillips, *Engineering Applications of Fluids with a Variable Yield Stress*. PhD thesis, University of California, Berkeley, 1969.

[34] J. Carlson, D. Catanzarite, and K. St. Clair, "*Commercial Magneto-rheological Fluid Devices,*" International Journal of Modern Physics B, vol. 10, no. 23n24, pp. 2857– 2865, 1996.

[35] J. D. Carlson, "*What Makes a Good Mr Fluid?,*" Journal of Intelligent Material Systems and Structures, vol. 13, no. 7-8, pp. 431–435, 2002.

[36] T. C. Halsey and W. Toor, "*Structure of Electrorheological Fluids*," Physical review letters, vol. 65, no. 22, p. 2820, 1990.

[37] Wenjun Li, "*Design and Development of Magneto-Rheological Actuators with Application in Mobile Robotics*", Electronic Thesis and Dissertation Repository. 2073, 2014.

[38] A. Spaggiari, "*Properties and Applications of Magnetorheological Fluids*", The Italian research on smart materials and MEMS, Scilla, 2012.

[39] Guangqiang Yang, B.S., M.S., "*Large Scale Magnetorheological Fluid Damper for Vibration Mitigation: Modeling, Testing and Control*", Department of Civil Engineering and Geological Sciences Notre Dame, Indiana, December 2001.