This paper appears in the proceeding of 2012 IEEE Sensors Conference
http://dx.doi.org/10.1109/ICSENS.2012.6411116

Magnetic Flux Analysis on Magnetorheological Actuators Can Detect External Force Variation

Carlos Rossa, José Lozada, and Alain Micaelli
CEA, LIST, Sensorial and Ambient Interfaces Laboratory
91191 Gif-sur-Yvette, France
rossa@ualberta.ca; joselozada@uti.edu.ec; alain.micaelli@cea.fr

***Abstract*— Magnetorheological (MR) fluids consist of a suspension of ferromagnetic micron-sized particles dispersed in a carrier fluid. A magnetic field induces the magnetization of the particles which then form chain-like structures aligned in the direction of the field. The structures interact with the magnetic poles, as a consequence, the relative displacement of the poles due to the action of an external force, inclines the particle chains and alters the magnetic environment. This phenomenon can be perceived as a magnetic reluctance variation on the fluid gap. The paper focuses on a MR-based brake equipped with a magnetic flux variation measurement system, which is able to detect when the chain-like structures begin to rupture. Based on the same principle, the system is also capable of detecting a change in the direction of an external force.**

1. INTRODUCTION

Magnetorheological fluids (MR) consist of suspensions of ferromagnetic micron-sized particles (typically 1 to 10 microns) dispersed in a non-magnetic carrier fluid (mineral oils, synthetic oils or water). Their volume concentration may range typically between 20% and 40% [1]. The action of a magnetic field alters rapidly, strongly and reversibly the rheological properties of these materials by inducing the magnetization of the particles which then form chain-like structures or aggregates aligned in the direction of the magnetic field [2]. The particles magnetization is macroscopically perceived as an almost instantaneous alteration of the fluid's apparent viscosity. This change is manifested, when the fluid is sheared, by the development of a yield stress which increases with the magnitude of the applied field in a fraction of a millisecond [3].

MR-based actuators can be classified as having either a valve mode, a direct shear mode or a squeeze film compression mode [4]. On the conception of rotary MR-based brakes the fluid suspension is typically placed between two magnetic poles which can be relatively displaced by the action of an external force. The chain-like structures then create a resistive force against the pole velocity. The magnetic poles interact hydrodynamically with the particles [5] thus, if an external force induces a displacement between the magnetic poles, the fibrils are stretched according to the motion [6].

When the chains are stretched the separation between the particles by the non-magnetic liquid has a large effect on reducing the magnetic environment [7]. Thereby, it is possible to detect an external force applied along the braking direction by observing the arrangement of the chain-like structures and measuring the reluctance of the magnetic circuit. Section 2 presents a review of MR fluids behavior. Subsequently, the reluctance variation hypothesis is developed using an elementary group of ferromagnetic particles placed in a non-magnetic carrier liquid. The hypothesis has been validated using a test apparatus composed of a miniature rotary MR-based brake.

2. RHEOLOGICAL FLUID BEHAVIOR

Fig. 1 shows a schematic view of the evolution of a MR fluid gap placed between two magnetic poles submitted to an external force. Consider that the ferromagnetic particles are homogeneously placed in a carried liquid (Fig. 1a). When a magnetic field $\overrightarrow{H}$ is applied across the magnetic poles, the particles are magnetized and possess henceforth a magnetic moment aligned in the direction of the magnetic field (Fig. 1b). The magnetization of each particle depends on the applied field and on the disturbance fields emanating from the neighboring magnetized particles [8]. The particles then behave as magnetic dipoles which undergo magnetic interaction forces (Fig. 1c). Hence, this mutual interaction amongst the particles causes the formation of chain-like structures or fibrils, aligned roughly parallel to the applied field (Fig. 1d). If the magnetic poles are considered as a potential surface, the interaction between a particle and the pole can be modeled as equivalent to the interaction of the particle and the dipole images of all other particles reflected about the surface [8]. Thus, the particle, when close to the wall, has the same translational velocity. According to Bossis *et al* [6], the chains are supposed to deform with the strain, thus the distance between two neighboring particles increases according to the motion (Fig. 1d). The chains are subsequently continuously broken and immediately reconstituted due to the field across the poles and due to the pole displacement (Fig. 1e, Fig. 1f).

In the absence of a magnetic field, MR fluids exhibit a Newtonian behavior. When a field is imposed, the magnetic interaction between particles induces a magnetic force which is proportional to their relative position and orientation to the external field and the magnetic permeability of the carrier fluid [5]. As predicted by electromagnetic theory, there is a quadratic relationship between the applied field strength and the interaction force. The fluid displays a pre-yield regime characterized by an viscoelastic response [9] and a post-yield regime characterized by a viscous behavior [10]. The

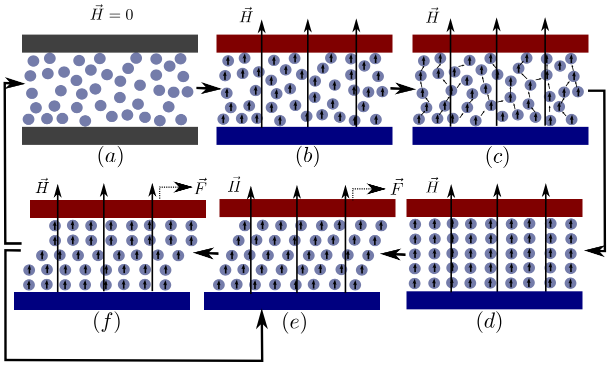

Fig. 1. Rheological effect in a magneto-rheological suspension between shearing plates: The particles are homogeneously distributed in the carrier liquid (a). A magnetic field is imposed (b), the particles are magnetized and behave as a magnetic dipole (c). They form then the chain-like structures aligned to the field (d). When the poles moves the chain structures are stretched and broken (e) and immediately reconstituted (f).

transistion point appears when the shear rate $\dot{\gamma}$ is zero; this point is called yield point $\tau_z(H)$. The Herschel-Bulkley model [11] is the plastic model commonly employed to describe the post-yield behavior as presented in Equation 1, where τ_{rz} is shear stress, and k and n are fluid index parameters.

$$\begin{cases} \tau_{rz} = \tau_z(H) + k\left|\dot{\gamma}\right|^n & |\tau_{rz}| \geqslant \tau_z(H) \\ \dot{\gamma} = 0 & |\tau_{rz}| < \tau_z(H) \end{cases} \tag{1}$$

On the pre-yield regime however, ($|\tau_{rz}| < \tau_z(H)$) the MR fluid presents a viscoelastic behavior, neglected by the previous model. The elastic portion is almost negligible compared to the plastic response. When an external force is applied on the magnetic pole, the relative displacement stretches the chain structures. Through this elastic behavior, if the external force is released, the interaction forces between the particles tend to realign them with the applied field. In both cases, a change in the reluctance occurs. This is treated in the next section.

3. RELUCTANCE VARIATION ASSUMPTION

Considering the displacement of two particles in the same chain. Fig. 2 presents a representative interaction between two ferromagnetic isolated particles situated in a non magnetic carrier fluid. The particles with diameter a are placed in a cubic volume of fluid measuring a^3 units. The center of each particle is separated by r units by a non-magnetic liquid, which possesses an absolute permeability μ_c and the absolute permeability of the particles is denoted μ_{fe}. Note that $\mu_{fe} >> \mu_c$. The chains are in the initial position an the magnetic field Φ_0 creates a magnetic flux perpendicular to the poles (Fig. 2)). The particles are then inclined from θ degrees and the magnetic flux is deviated (Fig. 2b) (Φ_1) .

The total reluctance of two particles is approximately calculated as follows:

$$\Re_t = \frac{2}{a}\xi + \frac{(r-a)}{\mu_c a^2}\cos(\theta) \tag{2}$$

Where ξ is a constant parameter depending only on the magnetic permeabilities given by:

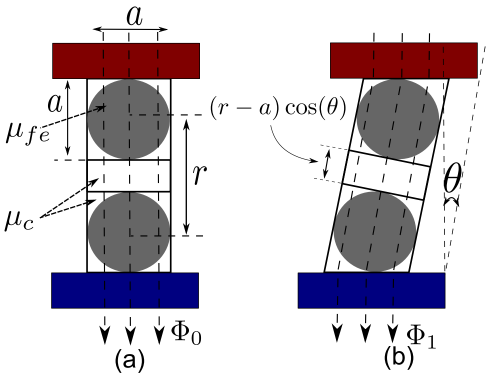

Fig. 2. Magnetic interaction between two isolated particles in a stretched chain structure

$$\xi = \frac{4}{\pi}\frac{1}{\sqrt{\mu_{fe}^2 + 2\mu_{fe}\mu_c - 3\mu_c}}\arctan\left(\frac{1}{\sqrt{\mu_{fe} + 3\mu_c}}\right) \tag{3}$$

The effective variation of the total reluctance in function of the inclination angle θ is computed as:

$$\delta\Re = \frac{(r-a)}{\mu_c a^2}\left(1 - \cos(\theta)\right) \tag{4}$$

Note that this amount of reluctance variation is given only between two isolated particles. Vicente et al. [12] developed a micro-rheological model of a magnetorheological fluid at low magnetic field strengths by equalizing the torque exerted on a pair of particles by the external field and the hydrodynamic force by using the Stokesian friction approximation. Considering only the interaction between neighboring particles, they obtained a critical rupture angle $tan(\theta) \approx \sqrt{1/2}$. This critical angle represents almost 22% of augmentation in the total reluctance when the single structure of Fig. 2 is stretched. Nonetheless, for a representative volume of fluid, the particles can interact with their neighbors particles and the variation of the total reluctance is considerably inferior.

4. TEST APPARATUS

Fig. 3 shows a cross view of a miniature cylindrical MR-based brake equipped with a measuring coil and an excitation coil supplied by a constant voltage in order to generate the magnetic flux $\Phi(t)$. The reluctance variation modifies the magnetic flux across the magnetic circuit, this change will induce a current on the coils proportional to $d\Phi(t)/dt$. The MR fluid is a commercial Lord Corp. MRF-122EG situated between two ferromagnetic cylinders separated by a gap of 1 mm. The inner cylinder possess a radius of 8 mm.

The excitation coil has $N_1 = 1000$ turns of wire corresponding to a measured inductance $L_1 = 9,39mH$. For the measuring coil, the inductance is $L_2 = 132,7\mu H$ corresponding to $N_1 = 180$ turns of wire. If we call R_1, i_1 and R_2, i_2 the electric resistance and the current of the excitation coil and the measuring coil respectively, and $\Re(t)$ the magnetic reluctance, the constitutive equation of the excitation coil is $v_1(t) = i_1(t)R_1 + N_1 d\Phi(t)/dt$. And the voltage induced on

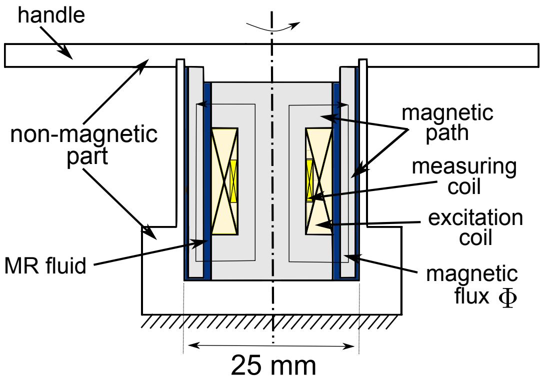

Fig. 3. Schematic representation of the miniature MRF brake developed to measure the reluctance variation on the fluid gap

the measuring coil is $v_2(t) = i_2(t)R_2 + N_2 d\Phi(t)/dt$, where the magnetic flux is given by $\Phi(t) = (N_1 i_1 - N_2 i_2)/\Re(t)$. In fact, both currents are influenced by the variation of the magnetic flux and the same result could be reached with only the excitation coil. However, for high current values, high noise affects the precision.

The induced current in the measuring coil is observed as a voltage across a shunt resistance. This voltage is amplified by means of an instrumentation amplifier. Despite the maximum differential gain, the measured voltage remains around the microvolts. Another gain is then implemented using a differentiator and an integrator circuit. The measuring circuit was first validated using an U-shaped variable reluctance magnetic core.

The miniature MR brake was placed on the test bench shown in Fig. 4. It is composed of an incremental encoder and a torque transducer in order to allow the measurement of the braking torque, and consequently to correlate the change of the reluctance with the applied torque at the handle. Two different tests were conducted. In both cases, a torque is manually imposed to the handle and the evolution of the measured torque and the output voltage are simultaneously monitored. A constant voltage is sent to the excitation coil in order to activate the brake. Experimental results are presented in the next section.

5. EXPERIMENTAL RESULTS

Fig. 5 presents the experimental results in a dynamic case (the velocity of the rotor is not negligible). A torque is manually imposed at the handle and the chains are inclined: a negative voltage appears in the measurement circuit ($t = 0,7s$) which characterizes a reluctance augmentation (1). The torque is maintained until $t = 2,3s$ and then inverted: The reluctance decreases until the chains are aligned with the field and then raises again while the chains are inclined in the other direction by the displacement of the pole. This behavior is observed as a positive voltage (2) followed by a negative voltage (3) representing the diminution and augmentation of the reluctance respectively. When the chains do not move, the output voltage returns to zero.

The second experiment aims to observe the evolution of the output voltage as a function of the torque in a quasi-static regime (the velocity of the rotor is almost zero). Fig. 6 shows the experimental result. The torque is applied at $t = 0,5s$ and gradually reaches its maximum value at $t = 0,8s$. The chains are stretched and the reluctance of the system increases. Therefore, the output voltage of the measuring circuit has a peak at $t = 1s$. The torque is maintained until $t = 2,3s$ and the voltage becomes zero because the reluctance does not change. The observed delay is due to the transient discharge of the integrator capacitors. The torque is then released at $t = 2,6s$. The chains tend to realign themseves when the external force becomes zero, and the reluctance decreases slightly. As a consequence, a positive voltage appears in the measuring circuit informing that there is no more torque applied on the

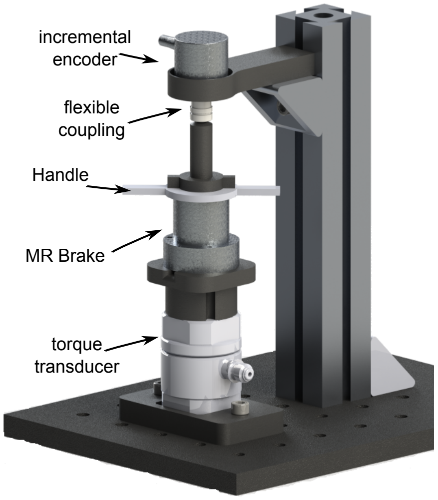

Fig. 4. Experimental validation test bench. The MR brake is placed over a torque transducer. The rotor is linked to a incremental encoder of 4096 ppr through a flexible coupling

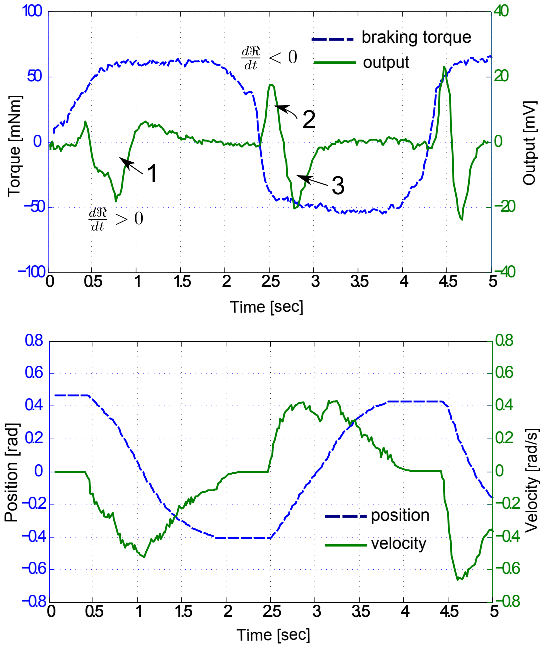

Fig. 5. External torque variation detection thought magnetic flux variation analysis

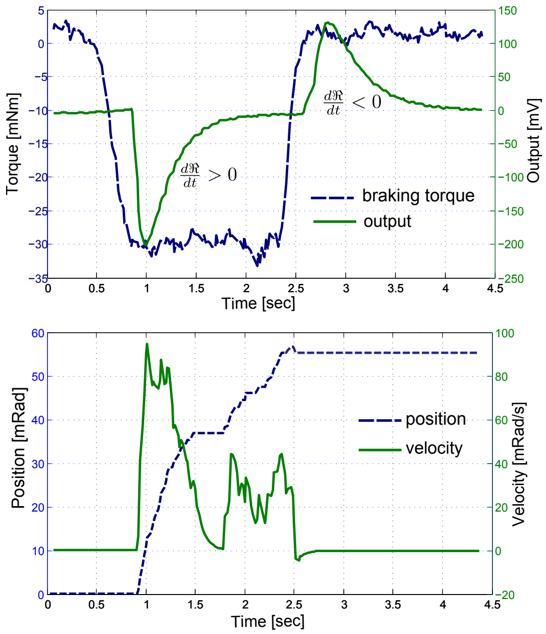

Fig. 6. Quasi-static torque detection: The position is measured using a encoder with 4096 ppr which is not able to detect the displacement of the chain when the handle is released

brake. Note that the position encoder was not able to detect the displacement of the rotor.

6. CONCLUSION AND FUTURE WORK

An analysis of the assumption that the position of the chain-like structures in a MR actuator has an effect on the magnetic reluctance has been described. We concluded that when the chains are stretched by the action of an external force, the separation between the particles by the non-magnetic liquid has a considerable effect on increasing the magnetic reluctance of the fluid gap. Considering that the chains interact with the magnetic poles, the reluctance can be associated with an external torque which induces a relative deformation of the chains.

We distinguish two different cases in the preceding experimentation. First: when a torque is applied at the handle, the displacement of the poles stretches the chains and the reluctance of the magnetic circuit increases. The relative displacement of the poles is inversely proportional to the braking torque. As a consequence the reluctance variation is even better measurable than the magnetic field is weak. Second: when the chains are stretched by an external torque and the torque is released, the interaction force between the particles, proportional to the field, tends to realign the chains to their original position and the reluctance decreases. It characterizes the elastic response of the fluid in pre-yield regime. This phenomenon is best observable when a high magnetic field strength is applied.

In order to validate this hypotheses, a rotary MR-based brake has been equipped with two coils: the first one is used to create a magnetic field across the gap and the second one is used to measure the variation of the reluctance. Two different tests have been conducted. In the first case, the system reacts satisfactorily to a change in the direction of an external force. The second one, when a static torque was released, the system was able to detect the realignment of the particles. This method holds great potential for the control of MR-based actuators in order to detect the chain rupture critical point (or pre-to-post-yield transition) and will be implemented in a haptic device in order to detect external forces.

REFERENCES

[1] C. Fang, B. Y. Zhao, L. S. Chen, Q. Wu, N. Liu, and K. A. Hu, “The effect of the green additive guar gum on the properties of magnetorheological fluid,” *Smart Materials and Structures*, vol. 14, no. 1, pp. N1–N5, 2005.

[2] M. R. Jolly, J. W. Bender, and J. D. Carlson, “Properties and applications of commercial magnetorheological fluids,” in *Smart Structures and Materials*, L. P. Davis, Ed., vol. 3327. SPIE, 1998, pp. 262–275. [Online]. Available: http://link.aip.org/link/?PSI/3327/262/1

[3] w. J. D. C. u. D. M. C. Clair, K A St, “Commercial magneto-rheological fluid devices,” in *Smart Structures and Materials*, vol. 332710. Singapore;[Teaneck, NJ]: World Scientific,[c1987-, Jully 1996, p. 28572866. [Online]. Available: http://link.aip.org/link/?PSI/3327/262/1

[4] A. Olabi and A. Grunwald, “Design and application of magneto-rheological fluid,” *Materials & Design*, vol. 28, no. 10, pp. 2658 – 2664, 2007. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0261306906002962

[5] C. Joung and H. See, “The influence of wall interaction on dynamic particle modelling of magneto-rheological suspensions between shearing plates,” *Rheologica Acta*, vol. 47, pp. 917–927, 2008, 10.1007/s00397-008-0282-3. [Online]. Available: http://dx.doi.org/10.1007/s00397-008-0282-3

[6] G. Bossis, S. Lacis, A. Meunier, and O. Volkova, “Magnetorheological fluids,” *Journal of Magnetism and Magnetic Materials*, vol. 252, no. 0, pp. 224 – 228, 2002, ¡ce:title¿Proceedings of the 9th International Conference on Magnetic Fluids¡/ce:title¿. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0304885302006807

[7] A. K. Kwan, T. H. Nam, and Y. Y. Il, “New approach to design mr brake using a small steel roller as a large size magnetic particle,” in *Control, Automation and Systems, 2008. ICCAS 2008. International Conference on*, oct. 2008, pp. 2640 –2644.

[8] D. Kittipoomwong, D. J. Klingenberg, and J. C. Ulicny, “Dynamic yield stress enhancement in bidisperse magnetorheological fluids,” *Journal of Rheology*, vol. 49, no. 6, pp. 1521–1538, 2005. [Online]. Available: http://link.aip.org/link/?JOR/49/1521/1

[9] G. M. Kamath and N. M. Wereley, “A nonlinear viscoelastic - plastic model for electrorheological fluids,” *Smart Materials and Structures*, vol. 6, no. 3, p. 351, 1997. [Online]. Available: http://stacks.iop.org/0964-1726/6/i=3/a=012

[10] M. R. Jolly, J. D. Carlson, and B. C. Muoz, “A model of the behaviour of magnetorheological materials,” *Smart Materials and Structures*, vol. 5, p. 607, 1996. [Online]. Available: http://stacks.iop.org/0964-1726/5/i=5/a=009

[11] X. Wang and F. Gordaninejad, “Flow analysis and modeling of field-controllable, electro- and magneto-rheological fluid dampers,” *Journal of Applied Mechanics*, vol. 74, no. 1, pp. 13–22, 2007. [Online]. Available: http://link.aip.org/link/?AMJ/74/13/1

[12] J. de Vicente, M. T. Lpez-Lpez, J. D. G. Durn, and F. Gonzlez-Caballero, “Shear flow behavior of confined magnetorheological fluids at low magnetic field strengths,” *Rheologica Acta*, vol. 44, pp. 94–103, 2004, 10.1007/s00397-004-0383-6. [Online]. Available: http://dx.doi.org/10.1007/s00397-004-0383-6