Preliminary investigation of magneto-rheological fluid durability in continuous slippage clutch

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Abstract. Magneto-rheological (MR) devices, such as dampers, engine mounts and clutches, are now appearing in the ground vehicle industry. Although important work has been directed to assess the longevity of MR dampers, few studies have targeted the aspect of magneto-rheological fluid (MRF) durability when used in continuous shear, such as in MR clutches. The objective of this research is to identify the degradation phenomena associated with MRF used in continuous shear and to understand the main causes and effects, in order to propose design improvements to enhance clutch durability. Experiments are conducted on two test benches in order to reproduce MRF aging in a controlled environment and to evaluate the proposed solutions. The effect of the operating conditions (shear rate, shear stress and temperature) on the long term degradation of the torque-current relationship is evaluated. Two degradation phenomena are identified: base oil expansion and particle oxidation. The dominant failure mode of the tested clutches is a MRF leakage resulting from the base oil expansion which occurs between 1.5 MJ/mL and 9 MJ/mL of dissipated energy depending of the operating conditions. Two solutions are proposed to extend clutch durability: 1- MRF circulation and 2- compliant elements.

1. Introduction
Magneto-rheological (MR) clutches offer highly controllable forces and rapid dynamics compared to conventional actuation approaches [1], as well as a high reliability potential due to their simplicity and absence of metal-to-metal contact. MR clutches can be categorized according to the relative slip between their input and output. Thus, when used as torque limiters, as per [2], no slippage occurs in the clutch unless the maximum transmissible torque is reached. MR clutches can also operate in continuous slippage [3, 4], where the input shaft rotates at a constant speed and the transmissible torque is constantly adjusted by the clutching action to control the output position or speed (see Figure 1) of the system.

This later clutch category has interesting advantages in terms of actuator bandwidth, since the input inertia is separated from the output [5]. However, these MR clutches must dissipate large amounts of energy through a small quantity (~10 – 100 mL) of MR fluid (MRF) that is subject to continuous shear stress. The durability of the clutches is therefore limited by the MRF operating life.

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Even though a great number of MR fluid devices have been proposed such as dampers [6], clutches [3, 7, 8] and brakes [9], MR-fluid durability has not been thoroughly addressed in literature. MR fluid durability becomes of prime concern as MR devices make their way to the market and more specifically, in economic sectors where reliability is of outmost importance such as aerospace. In damper applications, the maximum operating life of the MRF has been estimated to be 10 MJ/mL, where an increase in off-state viscosity of the MRF causes device failure [10]. For clutching applications, commercial MRF’s have been shown to undergo an increase in oil volume around 6 MJ/mL [11] that leads to a significant torque decrease of the device. However, the occurrence of the expansion phenomenon, its exact nature, and relation with MR clutch design is not clear in the literature. A study makes no mention of this phenomenon up to 70 MJ/mL [12] and that device failure is associated to iron particle oxidation, slowly reducing torque output. Up to this day, a general comprehension of MRF degradation in clutch applications has not been given and thus, clear design guidelines for durability still do not exist.

The objective of this investigation is to lay the basis of a holistic description of MR-fluid degradation in clutch applications. In this work, two test benches are specifically developed to understand the degradation phenomena that characterize the aging of MRF submitted to different operating conditions of shear stress, shear rate and temperature. An accelerated aging test bench is developed to obtain large scale degradation signature of a MR clutch containing MRF that is aged up to 100 MJ/mL. Chemical and morphological analysis of the used MRF samples, in combination with pressure measurements performed with a full-scale clutch, reveal two MRF degradation phenomena occurring at specific energy levels: base oil expansion and particle oxidation. For all tested operating conditions, the base oil expansion is recorded between 1.5 MJ/mL and 9 MJ/mL of dissipated energy. This MRF degradation phenomenon is identified as the dominant failure mode of the tested MR clutches as it causes MRF leakage which decreases torque output. A fluid circulation mechanism is shown to extend clutch durability with regards to the dominant failure mode by allowing a larger amount of MRF to participate in the energy transfer process. A mitigation measure is also proposed to extend MRF life beyond the first failure mode, thus extending the transmissible energy per volume of commercially available MRFs.

### 2. Methodology

#### 2.1. Experimental setup

An accelerated aging test bench, shown in Figure 2 (a), is designed at small scale to minimize the total testing time and rapidly obtain the degradation signature of MRFs. A full scale device, shown in Figure 2 (b), is used to identify the dominant failure mode observed in the degradation signatures and to validate proposed solutions to optimize durability.

![Figure 1. Example of a continuous slippage MR clutch.](image-url)
Figure 2. Test benches designed for (a) accelerated aging and for (b) full scale validation.

The design parameters of each test bench are summarized in Table 1. For the accelerated aging test bench, specific attention is given to the uniformity of the operating parameters. A drum type clutch is chosen to provide a uniform shear rate (<3500 s<sup>-1</sup>), while double coils are used to provide a uniform magnetic flux density (<1.2 T). Bearing seals are used to contain the MRF in the shear gap while keeping the volume of MRF not submitted to magnetic fields (dead volume) as small as possible, here < 5%.

The full scale test bench uses radial lip seals, placed away from the shear gaps, in order to replicate the typical design of a MR clutch. This results in an additional volume of MRF which does not dissipate energy. Thus, the dead volume of the full scale clutch represents 90% of its 30 mL overall volume.

Table 1. Main characteristics of the test benches.

| Characteristic                  | Test bench           |
|---------------------------------|----------------------|
| Clutch type                     | Accelerated aging    |
| MRF volume                      | Full scale           |
| Dead volume                     | Drum                 |
| Uniform magnetic field          | Drum                 |
| Shear rate                      | 1.5 mL               |
| Uniform magnetic field          | 30 mL                |
| External cooling                | 0-3500 s<sup>-1</sup>|
| Max aging rate                  | 0-3000 s<sup>-1</sup>|
| Sealing technology              | 1000 Watts           |
| Torque sensor                   | 350 W/mL             |
| Temperature sensor              | Sealed bearing       |
| Pressure sensor                 | (6908 DDU)           |
| Torque sensor                   | Lip seal             |
| Temperature sensor              | (CRx80x100x10 CRW1 V) |

The accelerated aging test bench is driven by a 2 hp motor, with variable output speed between 0 and 1500 RPM. The speed of the electric motor is controlled while the torque output of the clutch is
measured with a torque sensor (Transducer Techniques model TRT-200). The test bench is equipped with a temperature sensor (Omega thermocouple No. TJ36-CASS-116G-6-SB-SMPW-M) while a Copper Core radiator (HX-360HL) is used to control the temperature of the clutch. The measurement and control are done with a National Instruments USB card 6211.

The full scale test bench is also driven by a 2 hp motor with variable output speed between 0 and 250 RPM. The torque output of the clutch is measured with a load cell (Tedea Huntleigh 1042) fixed on the clutch output lever. The test bench is equipped with two temperature sensors (Omega thermocouple No. TJ36-CASS-116G-6-SB-SMPW-M). The first one is located at the shear interface and the other one measures the MRF temperature in the dead zone. Two pressure sensors (SSI Technologies Inc. No. P51-50-G-B-I36-4.5v-R) are located on each side of the shear interface. A Copper Core radiator (HX-360HL) coupled with three fans is used to regulate the temperature of the clutch. The full scale test bench is equipped with a National Instruments Compact RIO-9022 embedded control and acquisition system for control and data logging.

2.2. Test sequence

Unless otherwise noted, each test described in this research is submitted to a two parts sequence (see Figure 3), and is performed with BASF Basonic 5030 MRF. In the first one hour portion of the test sequence, a steady torque reference is set while the current command is adjusted automatically by a closed-loop controller, operating at the rate of 100 Hz. As this steady-state portion of the test sequence is used to gather a general degradation signature for the MRF, the torque output, acquisitioned at the rate of 100 Hz, is averaged and recorded at a rate of 20 Hz. After each hour, the steady-state test is stopped and the open-loop portion of the test sequence is performed. In this portion, deterministic current steps of specific amplitudes are imposed and the torque response is recorded at the acquisition rate of 1000 Hz. This test portion is used to qualitatively evaluate the current-torque relationship of the MRF aging from the off-state (no current) to the on-state (maximum current).

![Test sequence diagram]

**Figure 3.** Test sequence used to age and to characterize the MRF (a) steady-state closed-loop control and (b) transient open-loop current steps.
2.3. MRF chemical and morphological analysis

Several analyses are performed with new and aged MRF in order to correlate the MRF degradation signature and behavioral changes with acute physiological variations in the MRF composition. Thermo gravimetric evaporation of volatile constituents is performed by temperature ramping up to 500 °C under a non-reactive environment (argon gas) to precisely determine the quantity of oil present in each MRF sample submitted to accelerate aging. Scanning electron microscopy (SEM) is used to observe the dry constituents (e.g.: iron) present in the MRF. Combined with X-ray fluorescence and X-ray diffraction, the SEM images are also used to evaluate the presence of oxygen (oxide) in the MRF samples. Finally, granulometry measurements are performed to quantify the particle size distribution.

3. Large scale degradation of the torque-current relationship

3.1. Typical degradation signature

Several tests are performed under the typical operating conditions, listed in Table 2 to identify the degradation signature of a MR clutch containing BASF Basonetic 5030 MRF.

| Parameter       | Value          |
|-----------------|----------------|
| Shear stress    | 30 - 60 kPa    |
| Shear rate      | 1000 - 2500 s$^{-1}$ |
| Temperature     | 40 – 80 °C     |
| MRF             | BASF 5030      |
| Gap             | 0.5 mm         |

A typical closed-loop torque-current relationship measured from the steady-state test described in section 2.1 is shown in Figure 4, for operating conditions of 40 kPa, 2350 s$^{-1}$ and 60°C. For each open-loop current step, the resulting mean torque is normalized by its initial value (unused MRF torque output at given current) and presented in Figure 5. The calculations are done over a one second period, starting when the torque reaches its stabilized value.

![Figure 4](image-url)
Altogether, this particular test last up to 20 MJ/mL and two distinct parts are identified. Before 2.3 MJ/mL, both the closed-loop and open-loop current-torque relationship are found fairly steady (see Figure 4 and Figure 5). For this test, at 2.3 MJ/mL, the first sign of degradation is noted through a sharp increase (0.5A to 1A) in closed-loop current, which is correlated with a ~18% decrease of the maximum open-loop torque.

3.2. Effect of operating parameters and MRF composition

The accelerated aging bench test is used to determine the occurrence of the first degradation sign as a function of the clutch operating conditions (shear stress, shear rate and temperature). As seen in Figure 6, maximum measured life dissipated energy is observed when the shear stress, shear rate, and temperature are set at minimum values (40 kPa, 1000 s⁻¹, 40°C). The life dissipated energy is always found to decrease when aging tests are performed with one parameter increased at a time. Although these results do not show the influence of combined operating parameter modification, the results qualitatively demonstrate the relative influence of each parameter. Temperature is found to be the most influential parameter of MRF’s life, while shear rate is the least influence. Note that these results are intended to represent the general tendency of an operating parameter and thus, must be used with care due to the limited number of operating points investigated.

Aging tests are also performed on Lord MRF-140CG. As seen in Figure 7, the degradation signature of this MRF is found similar to that obtained with the BASF 5030 and for a similar level of dissipated energy (4.5 MJ/mL).
Altogether, a first sign of degradation is observed between 1.5 MJ/mL and 9 MJ/mL for all test conditions and for both MRF fluid formulation (BASF 5030 and Lord MRF 140CG) tested with the accelerated aging bench test.

4. Detailed study of MRF degradation phenomena and resulting failure modes

4.1. Base oil expansion

The first sign of MRF degradation is characterized by a sharp increase in closed-loop current and a sharp decrease in open-loop torque between 1.5 MJ/mL and 9 MJ/mL. To confirm that this behavior is caused by base oil expansion as reported by [11], a test is performed on the full-scale test bench, which is equipped with pressure sensor. In this test, the current in the coil is set at a constant 1.5 A, and the operating conditions are set at typical values (25 kPa, 2700 s⁻¹, 70°C). As shown in Figure 8, the pressure inside the MR clutch as well as the open-loop torque output are both found stable up to 1.4 MJ/mL. After this energy input, a rapid increase in pressure (between t = 6 min and t = 20 min) is recorded, suggesting that the oil undergoes a transformation. However, since the torque output remains fairly steady (95% of its initial value) during the pressure rise, it is believed that the overall performance is not directly affected by this degradation phenomenon.
As the pressure approaches the maximum rated pressure of the seals (70 kPa), the torque output of the clutch starts to slowly decrease, and is accompanied by a decreasing pressure. The simultaneous decrease in pressure and torque is attributed to seal failure, followed by particle leakage. Loss of particle caused by oil expansion is therefore identified as the main clutch failure mode, which causes the observed degradation in the torque-current relationship expressed in Figure 4 and Figure 5.

As shown in Figure 9, thermogravimetric analyses of the remaining MRF showed a lower volume percentage of base oil than in original MRF, suggesting that seal failure also caused severe base oil leakage. This could, in part, explain the erratic torque-current, measured in the accelerated aging tests.

![Figure 9. Thermogravimetry analysis of new and aged MRF.](image)

4.2. Iron particle oxidation

Samples from the accelerated aging tests are submitted to x-ray diffraction (XRD) tests and scanning electron microscopy (SEM). As shown in Figure 10, MRF samples aged up to 10MJ/mL did not show any presence of oxide. However, at 100 MJ/mL, distinctive peaks corresponding to magnetite crystalline structure are observed on the XRD measurements.

![Figure 10. X-ray diffraction showing peaks corresponding to magnetite in MRF 10 MJ/mL and 100 MJ/mL aged sample.](image)
The SEM images of new and aged MRF presented in Figure 11, show morphological changes of the particles. Compared to new MRF (see Figure 11(a)), Figure 11(b) and (c), show the evidence of oxide formation around the micron size particles when MRF is aged at 100 MJ/mL. Similar results were presented by Smith et al. (2007), who showed that an oxide layer surrounding the iron particles aged at a dissipated energy level of 70 MJ/mL, is responsible for a decrease in maximum output torque. In the current study however, the same conclusion cannot be drawn since oil expansion caused particle leakage before significant amounts of oxide can be identified in the MRF.

In Figure 11 (b) and (c), smaller particles can also be seen, mixed with the micron sized particles. A granulometry test, presented in Figure 12, shows that the used MRF sample (100 MJ/mL) contains a much larger percentage of small particles (sub-micron) than new MRF sample. The presence of small oxide particles has been reported by [10], where the authors suggested that the brittle oxide shells are broken from micron sized particles, increasing off-state viscosity of MRF, eventually leading to MR damper failure. In this study, no significant increase in off-state torque is measured. However, note that oil and particle leakage could have mitigated the effect of an increase in off-state MRF viscosity or yield stress.

5. Potential solutions to extend MRF life
For all tests performed in this study, particle and oil leakage, caused by oil expansion, is observed between 1.5 MJ/mL and 9 MJ/mL. Combined with the very small quantities of MRF required in typical MR clutches shear interfaces, these levels of dissipated energy limit the overall life of continuous slippage clutches to a few hours of operation. The following section proposes solutions to extend the life of MR clutches, by either increasing the total MR fluid present in such device or by mitigating the effect of base oil expansion on the failure mode.
5.1. Circulation of MRF
The first proposed solution is to add a circulation mechanism that pumps MRF from a reservoir into the shear zone of the MR clutch (Figure 13). This aims to increase the total amount of MRF in the clutch to extend clutch durability. To validate this hypothesis, two tests are performed with similar operating parameters (40 kPa, 2350 s\(^{-1}\) and 70°C). From the accelerated aging test bench, where the total amount of MRF is confined in the shear interface, the dissipated energy limit of the MRF corresponding to the specified operating conditions is measured at 1.5 MJ/mL. From the full-scale test bench, where only 10% of the MRF is present in the shear interface, a recirculation mechanism is used to circulate the MRF.

![Figure 13. 30 mL of MRF circulate in a 4 mL shear zone of a MR clutch.](image)

As seen from Figure 14, the total energy input to the full-scale test bench is measured to be 42 MJ, before a pressure increase is recorded and loss of torque is measured. This corresponds to a 1.4 MJ/mL of the total fluid present in the clutch, thus validating the feasibility of using recirculation to extend the life of a MR clutch. While this strategy delays the occurrence of base oil expansion, other phenomena could also lead to MRF leakage such as seal failure due to extended exposure to MRF abrasive particles.

![Figure 14. Energy per mL dissipated in the MRF using recirculation.](image)

5.2. Compliant element
For applications where MR clutch costs and weight must be minimized, the addition of a MRF reservoir could not be a suitable option. To overcome this issue, compliant elements or voids could be used inside the MR clutch in order to mitigate the effects of base oil expansion, thus increasing the life of the MRF without the weight disadvantage.
The percentage of volume expansion undergone by the MRF must be determined in order to design an appropriate compliant element. Hence, a method to approximate the expansion volume of MRF is presented by drawing an analogy with the coefficient of thermal expansion of the MRF. First, the full-scale prototype (containing no expansion chamber) is run at different temperatures and the corresponding pressures are recorded. As seen on Figure 15, the relationship between pressure and temperature is found to be linear in the range of interest (35 kPa to 45 kPa).

Knowing the coefficient of thermal expansion $\alpha$ of the MRF, here 0.00007 K$^{-1}$ [13], it is possible to determine an equivalent bulk modulus ($K$) for the studied clutch with Equation 1, where $V_0$ is the initial MRF volume, $\Delta P$ is the recorded pressure variation and $\Delta V$ is the MRF volume variation.

$$K = -V_0 \frac{\Delta P}{\Delta V}$$ (1)

Assuming the equivalent bulk modulus value determined from equation 1 is valid up to the maximum recorded pressure (65 kPa), it is possible to correlate pressure variations to changes in MRF volume. Hence, the volume expansion caused by oil degradation, which corresponds to the pressure increase shown in Figure 8, is found to be 8%.

In order for the clutch to remain functional despite base oil expansion, this supplementary expansion volume must be taken into account in the design of expansion chambers, supplementary to the amount required for thermal expansion.

6. Conclusion
Results from this work lead to a quantitative description of MR fluid durability when used in shear clutch mode. The effects of operating conditions such as shear rate, shear stress and temperature on the large-scale degradation signature of the torque-current relationship were analyzed on two MR-clutch designs. Two MRF degradation phenomena are identified: base oil expansion and particle oxidation. Solutions to extend the life of MR clutches were also proposed: recirculation and expansion volume.

For all tests conditions, clutch failure is dominated by oil expansion and occurs at energy input levels comprised between 1.5 MJ/mL and 9 MJ/mL. Post-oil expansion behavior is characterized by a loss of transmitted torque for a given current due to MRF leakage and by a slightly erratic behavior in
the torque vs current relationship. This is attributed to seal failure, caused by the oil expansion of ~10%. The exact nature of oil expansion is not known and remains to be investigated. When pushed beyond the oil expansion limit, oxidation appears at energy input levels of 10 MJ/mL or more. In this study, it is not possible to conclude on the effect of oxidation on clutch performance since the effects of oxidation cannot be isolated from the effects of oil expansion.

It was confirmed experimentally that adding a supplementary volume of MRF and circulating it through the shear interface allows to increase the maximal energy dissipated by the clutch in direct proportion with the supplementary volume. The introduction of an additional volume that can withstand both expansion due to temperature change and MRF aging could also be used to prevent excessive pressure on the seal. Experimental evidence of the impact of additional volume on durability remains to be provided.

Future work will include testing of clutches equipped with compliant elements in order to validate the extent to which the MRF life can be lengthened after the base oil expansion. Also, investigation of the base oil degradation causes and impacts on MR fluid properties will be conducted.

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