Static and dynamic behaviours of helical spring in MR fluid

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Abstract. MR fluid has been used in automobile industry for vibration suppression device. However its dynamic interaction between structural spring and electro-magnetised MR fluid has not been thoroughly investigated. As a result, this paper highlights static and dynamic behaviours of helical spring interacting with MR fluid magnetised at various levels. Static hysteresis behaviours have been evaluated altogether with the dynamic modal properties of the system. Modal impact hammer testing technique was used to investigate the modal parameters. It is found that MR fluid improves the hysteresis capacity and dynamic properties of the systems when it is electro-magnetised. The outcome of this study will lead to a new development of new spring-dashpot system using MR fluid for better control in adaptive tuneable vibration damping and stiffness suppressing real-time dynamic motions such as the train body, passenger seats, train door, etc.

1. Introduction
MR fluid is a smart material that has been recently developed for automobile industry. It has also been used as brace-frame dampers in steel structures subjected to winds and earthquakes. The concept proposed in this study is a novel, original and innovative combination between MR fluid and spring-dashpot. The initial aim of the study is to evaluate the static and dynamic performance of integrated MR fluid with spring-dashpot for shock absorption dampers for railway applications. MR fluids are one kind of controllable fluids that respond to a magnetic field with dramatic changes in rheological behaviours. The essential feature of the MR fluid is its ability for reversible change from free flowing liquid to solid with controllable yield strength. They can respond instantly to varying levels of a...
magnetic field precisely and proportionally for controllable energy-dissipating applications, such as brakes, shocks and dampers [1-4]. Although the formulation depends on the needs of the application, MR fluid typically contains three basic components:

- Liquid carrier - mineral oil, synthetic hydrocarbon oil, silicone oil, water, glycol, etc.
- Magnetic particles - carbonyl iron, iron/cobalt alloys, nickel alloys (see Figure 1)
- Other additives - suspending agents, thixotropes, anti-wear and anti-corrosion additives, friction modifiers.

Figure 1. Nano magnetic particles (after LiquidsResearch, 2016).

![Nano magnetic particles](image1.png)

Figure 2. Yield stress vs. magnetic field strength.

![Yield stress vs. magnetic field strength](image2.png)

The upper limit on force that can be created in an MR fluid is directly related to the amount of iron in the fluid. The more iron there is, the higher the attainable force. Depending on the volume fraction of
iron particles, MR fluids can have maximum yield strengths ranging from 30 to 80 kPa for applied magnetic field of 150-250 kA/m. Figure 2 shows the Yield Stress data obtained for 80% hydrocarbon oil and 64% silicone oil fluids. It proves that the higher field yields provide higher yield stress.

In the absence of an applied field magnetic field, MR fluids are generally well modelled as Newtonian liquids characterized by their viscosity [5-6]. Time response for MR fluids in order to reach their maximum shear strength is only milliseconds. Figure 3 shows the time response graph of the purchased MR fluid at the room temperature. This MR Fluid is used for engineering property tests and spring-MR fluid interaction test.

![Time response graph at room temperature](image)

**Figure 3.** Time response graph at room temperature.

2. Experiments on spring-MR fluid interaction

The literature review shows that there is currently no information on the interaction between MR fluid and spring support (to provide load bearing) [5-6]. As a result, there is a need to understand this interactive behaviour. The experiments (using the mechanism in Figure 4) were carried out using 2 different springs travelling up and down in a metallic tube. Table 1 shows the properties of the spring used in the experiment. Model 121-236 is stiffer and has almost half of the maximum load capacity compared to 121-270 model.

| RS component spring number | 121-270 | 121-236 |
|---------------------------|---------|---------|
| Free Length (mm)          | 98      | 110     |
| Load at Minimum Working Length (N) | 198 | 105.9 |
| Material                  | Steel alloy | Steel alloy |
| Minimum Working Length (mm) | 35.9 | 31.2 |
| Outside Diameter (mm)     | 18      | 17.6    |
| Spring rate (N/mm)        | 3.19    | 1.3     |
| Wire Diameter (mm)        | 2       | 1.6     |
Weights from 7 to 15 lb (3.2 to 6.8) were applied on a steel bolt used as a piston to compress the spring inside the tube. The tube was filled with MR fluid 80% hydrocarbon oil formulation up to 100mm. A coil with 450 turns and wire gauge of AWG 20 was used in order to make 45 A/mm magnetic field density. Figure 3 illustrates the experimental setup.

\[ N = \frac{L}{2\pi r} = \frac{100}{2\pi \times 3.5 \times 0.01} = 450 \]  

(1)

Where \( N \) = number of the coil turns  
\( L \) = length of the wire  
\( r \) = the radius of the coil

\[ H = \frac{I \times N}{L} = \frac{5 \times 450}{0.05} = 45000 \]  

(2)

Where \( H \) = Magnetic field density  
\( A/m = 45 \) A/mm  
\( L \) = length of the coil  
\( N \) = Number of the coil turns

According to the MR fluid data sheet provided by the supplier (Liquid Research Ltd) 45 A/mm changes the liquid yield stress up to 6 kPa. This amount can be changed by changing the magnetic field density around the MR fluid.

Figure 5 shows the dynamic testing setup. The modal impact hammer has been used to generate impact excitation to the single degree of freedom (SDOF) system. The damping property can be defined as phenomena which causes loss of vibration energy in material. In this study, the damping ratio of each concrete mix was measured according to vibration theory. As shown in Figure 4, the steel base was clamped to the stable rod support over the spring submerged in MR fluid. Then, the accelerometer was mounted at end of the top surface of the plate. After that the PCB impact hammer was used to excite vibrations in the sample over the frequency range 0 to 1,600 Hz, and the 5-time
average vibration responses represented by the FRFs and natural frequency were obtained using the PROSIG system.

At the next stage of the experiment, the vibration signal obtained from the experiment was analysed. Then amplitudes of the signal was plotted, and the amplitude response will be followed Equation 3 below.

\[ A = A_0 e^{-\zeta \omega t} \]  

where \( A \) is an amplitude which can be displacement, velocity or acceleration, \( A_0 \) is peak amplitude, \( \zeta \) is damping ratio, \( \omega \) is natural frequency (rad/s) which is equal to \( 2\pi f_n \) (\( f_n \) is natural frequency, Hz), and \( t \) is time (second).

![Dynamic experiment setup](image)

**Figure 5.** Dynamic experiment setup.

### 3. Static performance

Spring displacement using MR fluid without applied current hence no magnetic field has no effect on the spring piston displacement however by applying the current, displacement is gradually decreases. This can prove that MR fluid along with the spring can improve the damping force of the tube. It can also show that the MR fluid with the higher viscosity caused by a higher magnetic field has better damping properties.

As illustrated in Figure 5, in order to increase the magnetic field, number of the coil turn, length of the coil and current need to be increased. However due to the size of the MR fluid damper and size of the wires, increasing these parameters can be limited. Extended experiment was carried out by BE project students. The spring was inserted in the tube with 150 mm of length. MR fluid was installed at the same height as the spring, which is 110 mm. A bolt was then inserted to compress the spring. A steel recipient was fixed to the bolt, so all of the weights could be applied without falling. The first 500g consisted on the weight of the steel recipient plus a few crushed stones, weighted on a scale. The other
loads consisted of 500g weights, applied one by one until the sum of them totalized 5 kg. Then, one by one, the loads were removed. The displacement on each load application was taken.

Tests were realised with four different coil lengths, of 37.5 mm, 75 mm, 112.5 mm and 150 mm. For each coil length, three different currents were applied: 1, 2 and 3 Amp. Figure 6 shows the test results. It is found that MR fluid can dissipate energy through the hysteretic capacity (area between load and un-load path). This significantly benefits the damping mechanism of the demonstration and prototype MR fluid damper to suppress dynamic loading conditions.

4. Dynamic performance
The instrumented modal impact hammer has been used to apply impulse loading and the vibration of lumped steel plate has been recorded by an accelerometer. Figures 7 and 8 show the vibration responses from modal testing. Using the vibration concept of SDOF system, modal parameters can be extracted from the vibration frequency response functions. Table 2 shows the dynamic behaviours of the spring – MR fluid integration considering the change of applied magnetic fields.
**Figure 7.** Summary of hysteretic capacity of spring embraced by MR fluid.

**Figure 8.** Summary of hysteretic capacity of spring embraced by MR fluid.
Table 2. Dynamic behaviour of spring-MR fluid interaction*. 

| No magnetic field | Damping ratio | Resonant frequency (Hz) |
|-------------------|--------------|-------------------------|
| Magnetic field of 2.08 A/mm | 0.475 | 40 |
| Magnetic field of 4.16 A/mm | 1.017 | 42 |
| Magnetic field of 6.42 A/mm | 0.717 | 44.1 |
| Magnetic field of 6.42 A/mm | 0.604 | 50.3 |

*based on the lumped mass (steel plate and bolt) of 1151 g.

5. Conclusions
This research has established the novel integration between MR fluid and spring-dashpot, aimed to enhance a smart shock absorber in the future. The static and dynamic abilities of the integration can improve the dynamic impact load transfer mechanism. This project, kindly sponsored by the Department of Transport (DfT), has investigated such the feasibility, aimed at building the prototype for vibration dampers on trains and tracks [6-8]. The static and dynamic investigations have shown promising results proven that this concept is practically viable and realistic. The understanding will improve technology in MR damper, piston damper mechanics, and effect of magnetic flux.

The spring tests confirmed with dynamic testing results show that MR fluid can improve load bearing of spring system as rail fastener for more than 30%. It is important to note that our experiments show that MR fluids still have poor shear strength, and they cannot provide sufficient resistance and generate enough damping to impact load. Based on the dynamic behaviour of the MR fluid, it is found that the magnetic flux has a key role in improving dynamic stiffness (via increases of resonant frequency, $\omega = (k/m)^{1/2}$). It can also be observed that the damping of the systems increases with the use of magnetic fields but it decreases inversely with the increment of stiffness.

Acknowledgments
The authors are deeply grateful to the Department of Transport for T-TRIG Grant Project No RCS15/0233 and the BRIDGE Grant (provided by University of Birmingham and the University of Illinois at Urbana Champaign). Industry support from Network Rail, CEMEX, Liquids Research Laboratory, STRAND7, Zimmer Group, Prosig and Mid Atlantic Rubber Co. is gratefully acknowledged. The authors would also like to thank Erosha Gamage, Ratthaphong Meesit, Arash Amini, Kaio Jara Faria and Renan Santos Maia for their assistance during the course of this project. Financial support from European Commission for H2020-MSCA-RISE ‘RISEN’ Project (No 691135) is gratefully acknowledged.

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