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An investigation into the effect of temperature on the performance of magnetorheological fluid dampers

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ABSTRACT

Magnetorheological (MR) dampers are semi-actively controlled smart damping devices. MR dampers have been the focus of intense research for the past few decades and have been used in various practical applications. Many studies have been conducted on control applications of MR dampers along with dynamic, numerical, and analytical models for predicting the force response. Nevertheless, many problems still limit the widespread use of MR dampers. One of these challenges is the performance loss due to the elevated temperatures inside the MR damper body, which is induced by viscous heating and electrical resistance. This is a common problem for many types of MR dampers, reducing the performance of the control algorithms. Thus, it is important to predict the effect of the temperature on the force response under different conditions. In this study, an experimental test setup was used to monitor the effect of the temperature on the performance of a commercial LORD RD-8041-1MR damper. Experiments were conducted under different current and frequency settings. The results showed that the force loss due to the temperature difference could reach up to 50% at the highest frequency and lowest current condition. According to the results, both current and frequency play a critical role in predicting the force loss, as they significantly influence the damper's sensitivity to temperature changes.

1. Introduction

Magnetorheological (MR) fluid and MR dampers have recently become an attractive research area in engineering. The invention of MR fluid goes back to the 1940s [20]. After the 1980s, studies started to gain pace. Many theoretical models [10, 13, 18] are presented, and different MR devices have been proposed until now, such as clutches [14], bearings [4], brakes [15] and dampers. However, with the widespread usage of MR dampers, different problems are encountered, such as sedimentation [27], agglomeration [24], leakage, and viscosity drop of the MR fluid by temperature [29]. These problems restrict the performance of MR dampers. While sedimentation, agglomeration, and leakage affect the performance of the MR damper over the long term, the performance loss due to the temperature increase is present as long as the MR damper is in operation [9]. Temperature also plays a role in increasing these problems, particularly by promoting sedimentation [11]. Another issue is that the presence of such defects makes the damper's performance more sensitive to temperature increases [28].

In practical use, MR dampers need an appropriate controller for practical applications. However, the response generated by the controller cannot predict the correct signal due to the performance loss of the MR damper caused by the temperature increase [1]. Therefore, it is a critical issue to be considered in the design and control of MR dampers.

The structure of an MR damper is shown in Figure 1. Two heat sources are present in MR dampers; the viscous dissipation during the damping of the vibration and the electrical resistance in the coil inside the MR damper [9]. The heat generated by the viscous dissipation is distributed within the MR fluid by the motion of the piston. However, the removal of this heat from the damper body to the surrounding air is limited, as it primarily relies on natural convection.

On the other hand, the heat generated by the coil also contributes significantly to the temperature rise. Unlike viscous heating, this heat cannot be effectively distributed throughout the MR fluid. Since the coil is typically embedded within the piston head, it further limits heat

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dissipation from the outer cylinder of the MR damper to the surrounding air. Besides, as the required resistance force increases, the required current increases, accompanied by a larger viscous dissipation, eventually leading to cumulative heat generation. A substantial temperature rise can occur within a few minutes of operation under elevated current levels [9]. As a result of the rise in temperature, the viscosity decreases, which can dramatically affect the performance of the MR damper.

In early studies, the effect of temperature on the viscosity of the MR fluid has been clearly demonstrated [30]. Batterbee and Sims reported a viscosity drop of 34% with a yield stress drop down to 22% with a range between 15°C to 75°C [1]. Conversely, the operation of MR fluid at low temperatures also changes the damping force of MR damper. For instance, at -40°C and 3 A of applied current, the damping force was observed to increase by 219.2% [16]. That said, the influence of temperature remains an active topic of discussion as it is used across various applications [22]. The effects of temperature on MR damper performance are well presented in McKee's work [17], and these effects are also evident across different operational modes of MR fluids [8]. Different studies have also investigated transient heat transfer in the MR damper [9]. It has been shown that within 5 minutes of operation, the viscosity of MR fluid decreases, resulting in a reduction of the damper's resistance force. This change in the resistance force significantly affects the controller's efficiency [1]. To address this issue, a temperature compensation method for controlling the damping force of MR dampers is proposed as a patent [23]. Additional control strategies are offered to better assess the temperature-induced performance variations [1, 16, 26]. Some studies also suggest adapting existing models such as the Bouc-Wen model or developing new dynamic models that explicitly account for temperature effects [21, 25].

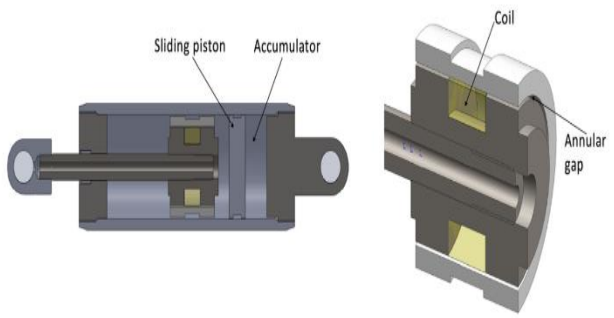

Figure 1. Schematic view of the MR damper [19]

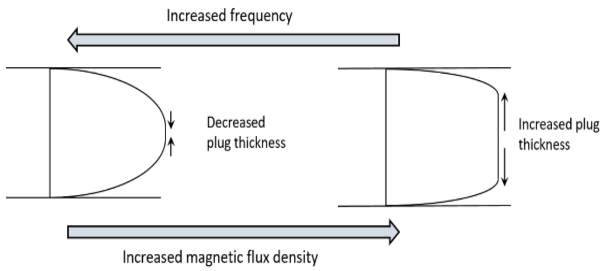

Figure 2. The plug formation inside the annular gap of the MR damper

In a recent study by Delijani et. al. [5], a force loss of up to 14% was calculated at 1 A current within a frequency range of 2–4 Hz. Another study reported a 22% reduction in maximum force and a corresponding 26% decrease in energy dissipation at 1 A and 3 Hz, caused by a temperature difference of just 10°C [2]. Similarly, it was found that even a 7°C increase could lead to a 20% reduction in energy dissipation [3]. Between 20°C and 40°C, a 20% decrease in maximum force was also observed in another study [7]. At elevated temperatures as high as 125°C from the ambient temperature, force losses were reported to reach up to 66.32% [12]. These results vary significantly depending on factors such as excitation frequency, MR damper type, and applied current. Therefore, each study must be evaluated independently, and only a general assessment can be made across literature.

The frequency is another parameter that affects the performance of the MR damper, and the effect of frequency on the temperature increase is pointed out in later studies [2]. However, to the authors' knowledge, no study directly focused on the frequency and current effect on the force loss due to the temperature increase. These effects are of paramount importance when designing a control algorithm to deal with these shortcomings.

In this study, the MR damper's force loss regarding the applied current and frequency is investigated, and the underlying reasons are discussed. It is shown that these two parameters have a key role in prediction of the force loss due to the temperature rise.

2. Problem Definition and the Experimental Setup

MR fluid flow in MR dampers is mainly considered the valve mode of the MR fluid flow [24]. Valve mode expresses that the MR fluid flows through a channel driven by a pressure gradient, which is created by the motion of the MR damper. The apparent viscosity of the MR fluid is generally expressed by the Bingham plastic fluid model in valve mode. Regarding the Bingham plastic fluid model, the shear stress can be expressed in Eq. (1) as:

$$\tau = \tau_y + \mu\dot{\gamma} \tag{1}$$

where τ is the shear stress, τ_y is the yield stress, μ is the viscosity, and $\dot{\gamma}$ is the shear rate of the flow. In order to directly obtain the apparent viscosity, all terms of the equation can be divided with shear rate, $\dot{\gamma}$, as shown in Eq. (2) below:

$$\mu_{app} = \frac{\tau_y}{\dot{\gamma}} + \mu \tag{2}$$

In the Bingham fluid flow, plug flow region is observed, which is shown in Figure 2, and the plug thickness, δ can be expressed in Eq. (3) as follows [18]:

$$\delta = -\frac{2\tau_y}{\Delta P/L} \tag{3}$$

It is well known that as the applied magnetic flux increases, yield stress τ_y increases and leads to an increased plug thickness. On the other hand, as the frequency increases, the pressure drop per length increases and leads to a decreased plug thickness. At high frequencies and under low magnetic flux conditions (e.g., at 0 A), the plug thickness approaches zero, and the velocity profile does not change further with the increase in frequency.

To investigate the effect of temperature on the resistance force of the MR damper, an experimental analysis was conducted in Sakarya University Mechanical Engineering Fracture Mechanics Laboratory, as shown in Figure 3. A commercial LORD RD-8041-1 MR damper was tested using an MTS 890 axial-torsional test system. The uncertainty of the load cell in axial load is measured as 3.15% between 0 and 2kN [6]. The tests were conducted at 4 different frequencies, 8 different current and 7 different temperatures which make 224 individual tests in total. The operating temperature ranged from 10 °C to 70 °C, with an increment of 10 °C. The current varied from 0 A to 1 A with an increment of 0.1 A and from 1 A to 2 A with an increment of 0.5 A. A temperature-controlled bath and a surrounding water jacket were used to maintain a constant temperature during testing. Water temperature was regulated with a precision of ±0.1 °C. To eliminate transient thermal effects, each test began after the damper temperature stabilized for at least one minute. Each test consisted of 10 loading cycles, and the average of 4th, 5th and 6th cycle was considered as the test data.

A sinusoidal motion was applied to the MR damper, and the displacement of the MR damper d is shown below:

$$d = A \cdot sin(\omega t) \tag{3}$$

Where ω is the frequency, A is the maximum displacement, and t is the time. The frequency values were set to 0.4 Hz, 0.8 Hz, 1.2 Hz and 1.6 Hz. The amplitude was chosen as 20 mm, corresponding to a total stroke of 40 mm.

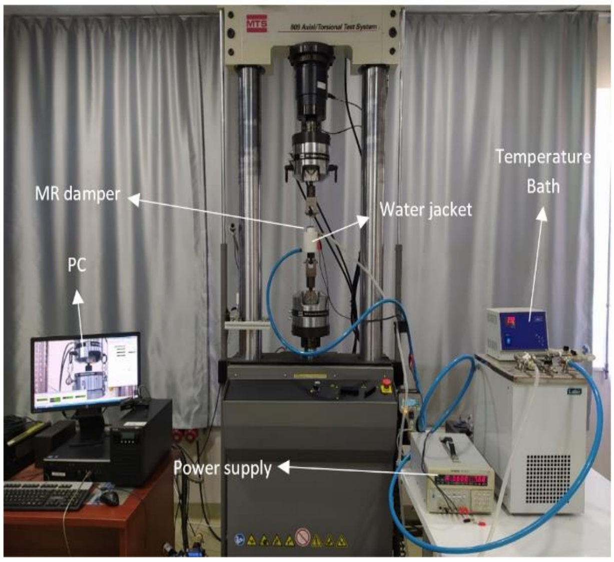

Figure 3. General view of the test setup.

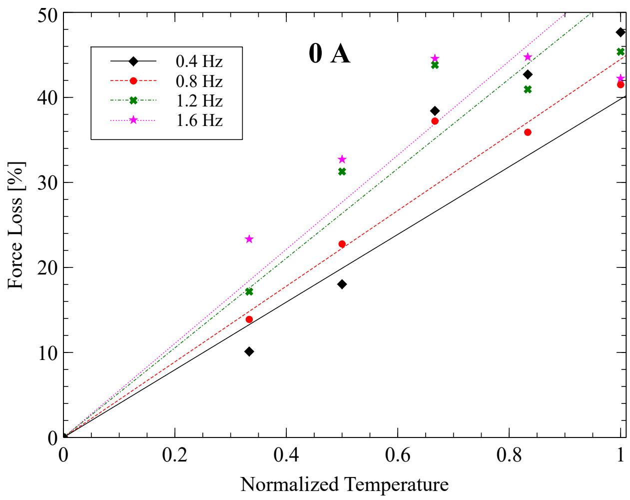

Figure 4. The variation of force loss ratio at 0 A with the normalized temperature.

3. Results and Discussion

In order to evaluate the experimental results, the minimum temperature was taken as the reference, and the percentage of force loss was calculated regarding the reference temperature. The normalized temperature θ was calculated using Eq. (4) below:

$$\theta = \frac{T - T_0}{T_h - T_0} \tag{4}$$

where T is the MR damper operating temperature, T_0 is the minimum temperature and T_h is the maximum temperature. T_0 was selected as 10°C and T_h was selected as 70°C. The force loss ratio was calculated from the Eq. (5) below:

$$Force\ loss\ [\%] = \frac{F}{F_a} \times 100 \tag{5}$$

Where F is the maximum force at the operating temperature and F_a is the maximum force at the minimum temperature, 10°C, during the sinusoidal motion cycles.

In Figure 4, the variation of the force loss ratio with the normalized temperature is illustrated at 0 A, which corresponds to the conventional viscous damping. A force loss of approximately 50% was observed when the operating temperature increased from 10°C to 70°C at a frequency of 0.4 Hz. This dramatic decrease at 0 A is also supported with the experiments in the literature where the force loss was reported to be 2.5 times greater at 0 A to that of observed at 3 A [16]. Considering the frequency, similar trends were observed. With the increasing frequency, the temperature effect tends to be slightly more significant. As the shear rate increases with the increasing frequency, the velocity profile does not change considerably at 0 A, as stated before, and the change in the apparent viscosity becomes marginal. Thus, the insignificant change in the force loss ratio with frequency can be attributed to the trivial difference in the apparent viscosity.

The variation of the force loss ratio at 1 A with the normalized temperature is shown in Figure 5. It can be seen that as the MR fluid is exposed to a magnetic field, the force loss becomes one-third of the value observed at 0 A. This indicates that the resistance force is less sensitive to the temperature variations when a magnetic field is applied (on-state). On the other hand, with increasing frequency, the force loss shows a significant change, unlike in the case without a magnetic field (off-state). This observation is consistent with findings in the literature, which report a 22% reduction in force loss at a frequency of 3 Hz and a current of 1 A [2]. This aligns with the 17.5% reduction observed in the present study at 1.6 Hz.

The variation of the force loss ratio at 2 A with the normalized temperature is shown in Figure 6. The difference in force loss ratios across various frequencies becomes more pronounced at elevated temperatures. This behavior can be attributed to the larger plug thickness under high magnetic fields, tending to shrink further with increasing frequency. As a result, varying velocity profiles are observed at different frequencies, leading to more significant variations in force loss.

A summary of the three plots is presented in Figure 7, illustrating the variation of force loss with frequency for different current levels. As previously discussed, force loss is largely independent of frequency at 0 A, corresponding to the off-state of the MR damper. In contrast, when the MR damper is in the on-state, the force loss is clearly influenced by frequency.

The variation of the force loss ratio with the current is shown for different frequencies in Figure 8. The curves were obtained using the moving average method. The force loss ratio was calculated based on the minimum and maximum temperature conditions for each current and frequency.

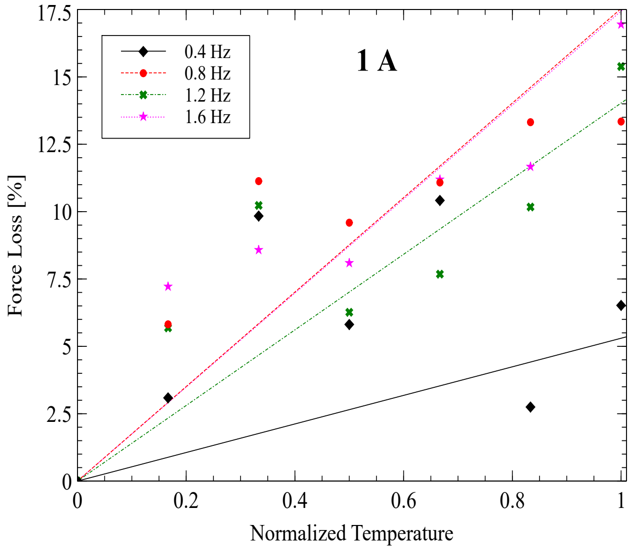

Figure 5. The variation of force loss ratio at 1 A with the normalized temperature.

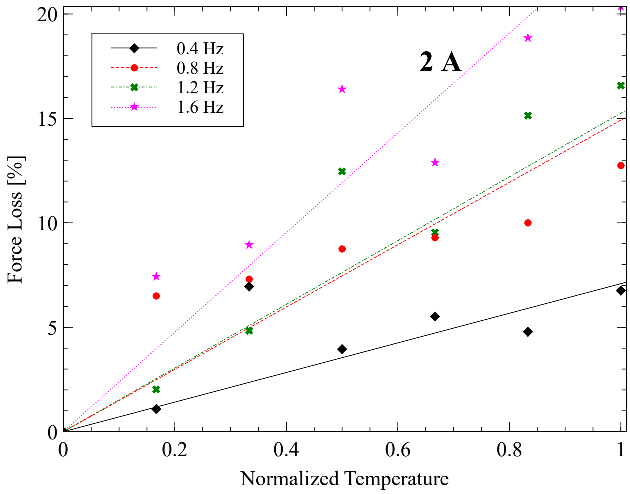

Figure 6. The variation of force loss ratio at 2 A with the normalized temperature.

The force loss ratio decreases with increasing current, indicating that the MR damper becomes less sensitive to temperature variations under the magnetic effect, as expected. Eventually, when the MR fluid saturates at the magnetic field around 1 A, the force loss ratio becomes nearly constant and independent of the current. The results also highlight frequency as a significant parameter in predicting force loss at higher current values. This is primarily due to the increase in plug thickness under strong magnetic fields. Consequently, higher frequencies are required to reduce or eliminate the plug region, as illustrated in Figure 2.

The variation of the force loss ratio with frequency at different current values is presented in Figure 8. The force loss ratio was calculated considering the minimum and maximum operating temperatures. It can be inferred that, in the absence of the magnetic field, the force loss ratio remains nearly constant with increasing frequency. On the contrary, at higher current levels, the force loss ratio varies significantly with frequency, indicating that the influence of temperature becomes more frequency-dependent when a magnetic field is applied. As discussed before, this dependency of the temperature effect might be associated with the changes in the velocity profile. The plug starts to grow proportional to the applied field, and increasing frequencies become capable of reducing the thickness of the plug further, leading the force loss ratio increase continuously. On the other hand, under zero applied field, the flow is nearly Newtonian, and the plug region becomes minimal. In such cases, increasing the frequency has little to no further effect on plug thickness, resulting in a relatively stable force loss ratio. The slight decrease observed in Figure 8 at higher frequencies may be attributed to experimental uncertainty.

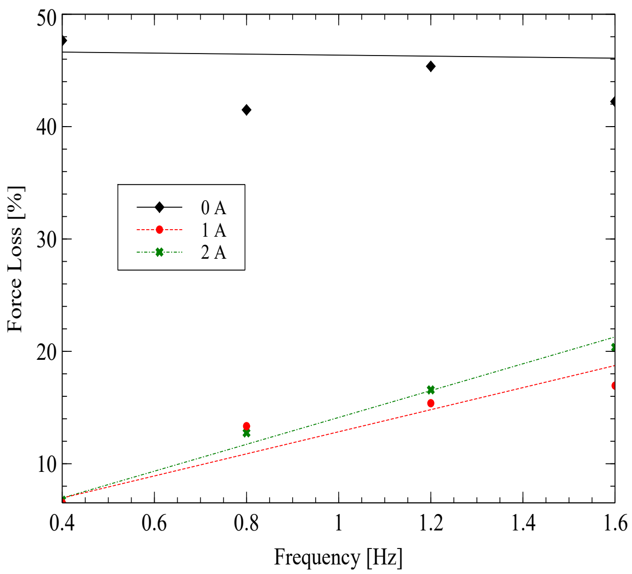

Figure 7. The variation of force loss ration with the frequency for different current levels.

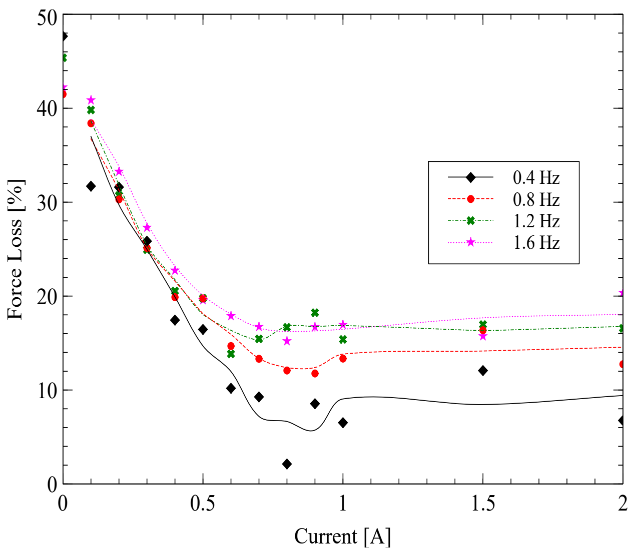

Figure 8. The variation of the force loss ratio with the current for different frequencies.

4. Conclusion

In this study, the effect of the temperature on the force loss of an MR damper was investigated under varying current and frequency conditions. Based on the findings, the following concluding remarks can be drawn.

- The results demonstrated that the temperature effect is most prominent in the absence of magnetic field, with up to 50% reduction in force observed across the experimental temperature range. Furthermore, the effect has still remained with a force loss of around 12% even when the magnetic field is applied.
- The study revealed a clear dependency of the force loss ratio on frequency, highlighting its critical role in the design of MR damper control algorithms.
- It was observed that the influence of frequency on the force loss becomes more significant under higher magnetic flux densities. This behavior is strongly associated with the variation in plug thickness of the velocity profile.

In conclusion, force loss must be considered in the design of the control algorithm under all operating conditions. While the results offer valuable insights, several limitations remain. Most notably, the temperature effect should be explored further at higher operating temperatures. Additionally, uncertainties in the experimental data limited deeper analytical interpretation such as generating an analytical correlation between viscosity and force loss. As future work, a comprehensive analytical framework can be developed to examine these interdependencies more rigorously and incorporate them into dynamic models of MR dampers.

Declaration

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author also declared that this article is original and was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

The author solely conducted all aspects of the study, including conceptualization, methodology, visualization, analysis, and manuscript preparation.

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Nomenclature

τ	: Shear stress
τ_y	: Yield stress
μ	: Viscosity
μ_{app}	: Apparent viscosity
ΔP	: Pressure loss
L	: Length
d	: Displacement
A	: Maximum displacement
ω	: Frequency
t	: time
θ	: Normalized temperature
T	: Temperature
T_0	: Minimum temperature
T_h	: Maximum temperature
F	: Force
F_a	: Maximum force

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