Rheological behavior of a magnetorheological shear-thickening fluid (MRSTF) and dynamic characteristics of an MRSTF damper

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Rheological behavior of a magnetorheological shear-thickening fluid (MRSTF) and dynamic characteristics of an MRSTF damper

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Abstract

In this study, a magnetorheological shear-thickening fluid (MRSTF) containing nano-grade fumed silica and polyethylene glycol mixed with different iron powder mass fractions was first evaluated, and the rheological behavior of the MRSTF was analyzed. The viscosity amplitude of thickening with the MRSTF decreased with increasing magnetic field strength. When the magnetic field strength of the MRSTF reached 197 mT, the thickening effect was eventually eliminated. An increasing content of carbonyl iron powder effectively increased the viscosity of the fluid under a weak magnetic field environment. And then magnetorheological shear-thickening damper (MRSTD) was designed and its dynamic characteristics were studied using an MTS809 fatigue testing machine. The results indicated that the damping force of the MRSTD changed with the vibration frequency, amplitude, and magnetic field strength. Finally, according to the mechanical characteristics of the MRSTD, linear and nonlinear damping models were established based on the energy storage stiffness and energy dissipation stiffness, respectively. And the results of the two fitting functions were compared with those of the experiments. The nonlinear damping model was found to better replicate the nonlinear stiffness, nonlinear damping, and shear rate-related characteristics of the MRSTD. The results of this study provide guidance for future theoretical and applied research into MRSTDs.

Keywords: Magnetorheological shear-thickening fluid. Rheological characteristics. Damper. Dynamic characteristic. Nonlinear model

1. Introduction

Research on energy absorption and vibration reduction is of great significance in many fields, such as industry, biomedicine, and military. Some researchers have used a Newtonian fluid with higher viscosity as a damping fluid to fabricate viscous dampers [1-2] and apply them in building anti-vibration devices or suspensions in the automotive industry [3-4]. A limitation is that once the structure of such dampers is
determined, its damping effect is no longer effective. This significantly reduces the vibration reduction performance of the damper in relatively complex vibration conditions. Therefore, many scholars have developed variable orifice viscosity dampers [5] and semi-active friction devices [6] by changing the damper structure. By adjusting the orifice size or the cam rotation position, different damping characteristics can be provided. However, these methods complicate the structure of the damper for engineering applications. In engineering fields, some researchers have applied smart fluid materials to achieve damping under complex vibration conditions, as in the case of the magnetorheological damper (MRD). The MRD can provide different damping characteristics to be adapted to complex vibrations by changing the magnetic field strength [7]. However, the use of a magnetorheological fluid (MRF) also has some shortcomings. First, the density of magnetic particles in the MRF material is relatively high, facilitating sedimentation and agglomeration in the fluid [8]. Second, MRF is a low-viscosity shear-thinning material, and in the absence of a magnetic field, the damper will lose most of its shock absorption capacity, potentially resulting in safety hazards or accidents [9-10]. Third, at the microscopic level, there are a large number of microcavities in the magnetic chain formed in the MRF material under a magnetic field environment. Therefore, a high strain shear will cause a break in the old magnetic chain and form a new chain, which will manifest as a fluctuation of the shear stress in the MRF [11].

Some researchers have attempted to use a relatively stable shear-thickening fluid (STF) for damping in a shear-thickening damper. This approach has not the problem of the settlement stability, and the shear-thickening damper does not require an external current source, resulting in a simpler structure [12-15]. Zhou et al. [16] produced a prototype of double output rod damper, evaluated its dynamic performance through experiments, and established an equivalent linear model of effective elastic stiffness and viscous damping. Zhang et al. [17] prepared a new prototype shear-thickening fluid (STF) damper and proposed a nonlinear model of the equivalent linear stiffness and power law viscous damping terms consistent with the nonlinear performance of the STF damper. However, the STF damper can only realize variable damping control by passive excitation of the shear rate, and its damping characteristics cannot be actively adjusted during application.

Magnetorheological shear-thickening fluid (MRSTF) exhibits a synergistic effect created by the addition of magnetic particles to a nano-silica-based STF [18-19]. The MRSTF exhibits excellent thickening characteristics in a weak magnetic field. With increasing magnetic field strength, the rheological properties of the fluid begin to resemble those of an MRF. However, different from the sedimentation characteristics of MRF, the settlement rarely occurs in an MRSTF within a span of two weeks, and the shear stress fluctuation of MRSTF is prevented by the addition of the nano-silica
thickening particles [10]. Peng et al. explored the viscoelastic properties of MRSTF through oscillating shear rheological experiments, reporting that the fluid exhibited excellent energy dissipation characteristics and proposing a four-parameter viscoelastic model to accurately determine its viscoelastic properties [20]. Furthermore, Tian et al. developed a single-rod type damper to examine the aging characteristics of MRSTF [21]. Snyder et al. studied the damping characteristics of a magnetorheological shear thickening damper (MRSTD) containing 20 % and 80 % iron powder, thus finding that the damping characteristics of an MRSTD with high iron content are similar to those of an MRD [22]. However, relevant research on an advanced intelligent damper using MRSTF to synergistically combine the rheological effects of MRF and STF is non-existent. This study addresses this gap.

The remainder of this paper is organized as follows. Section 2 describes the manufacturing process, rheological properties, and the main factors influencing the behavior of an MRSTF. Section 3 summarizes the structural design and working principle of the proposed MRSTD and an evaluation of its controllable damping performance using an MTS809 fatigue testing machine. In Section 4, theoretical models are established and compared to describe the frequency shift performance of an MRSTD. Section 5 presents the conclusions.

2. Experimental details

2.1 Materials

The MRSTF suspension used in this study was based on fumed silica with an average particle size of 14 nm (Aladdin Industries, USA), a polyethylene glycol (H(OCH2 CH2)n OH) carrier liquid with an average molecular weight of 200 g·mol\(^{-1}\) (Sinopharm Chemical Reagent Co., Ltd.), and 3μm carbonyl iron powder (CI) (Yuhuan CNC Group Co., Ltd.) as magnetic particles. During the preparation process, the carrier liquid was added to the fumed silica powder multiple times to avoid particle agglomeration. A mixer was used to mechanically mix the three components for 1 h. And then the resulting suspension was placed in a vacuum chamber for 2-3 h to eliminate air bubbles.

To determine the effect of CI content on the rheological properties of the MRSTF, three samples containing 5 %, 10%, and 15 % mass fraction of CI added to the STF (MRSTF5, MRSTF10, and MRSTF15, respectively), shown in Figure 1, were subjected to rheological testing. Furthermore, the MRSTF sample with 15 % CI was dried in a magnetic field environment to fix the chain distribution morphology and prepared. The MRSTF15 sample was observed at 1000× magnification using a scanning electron microscope (SEM).
2.2 Rheological testing

Using a parallel plate rheometer (MCR 301, Anton Paar, Germany), time–shear rate scanning measurements were conducted under static load conditions to measure the relationship between the fluid viscosity and shear rate, and thus the rheological properties of the MRSTF specimens were obtained. The diameter of the parallel plate was 20 mm and the thickness of the test sample was set to 1 mm under the room temperature 25°C. All tests were repeated three times at the same condition, and the mean value of the viscosity were used for discussion.

3. Rheological testing results and analysis

3.1 Rheological behavior of MRSTF

Figure 2 shows an SEM of MRSTF15 in a magnetic field environment (98mT). It can be observed that the magnetic particles in the specimen were arranged into short magnetic chains under the action of the magnetic field. When this fluid is sheared as shown Figure 3, the presence of these magnetic chains will increase the fluid viscosity of the fluid. In the initial shear phase, the stable structure inside the fluid is disturbed by the input shear rate, and the fluid begin to undergo shear thinning (Zone I). When the fluid shear rate exceeds the critical value $\dot{\gamma}$, the short chains are torn apart under the disturbance of the shear force to form single particles or even shorter chains. However, polyethylene glycol particles produce hydrogen bonds with SiO$_2$ particles and larger particles clusters wrapping iron powder particles produce due to shear disturbance. These thickening particle clusters rapidly increases the fluid viscosity (Zone II). When the shear rate exceeds the maximum shear rate ($\dot{\gamma}_{\text{max}}$), the particle clusters are destroyed again, and the fluid viscosity exhibits a thinning trend (Zone III). Therefore, as the shear rate of the MRSTF increases, the viscosity characteristic curve will show the three distinct regions: shear thinning (Zone I), shear thickening (Zone II), and secondary shear thinning (Zone III).
1 Effect of CI content on MRSTF

The prepared samples of MRSTF5, MRSTF10, and MRSTF15 were placed under 0 mT and 98 mT magnetic field strengths for rheological testing. The relationship between the viscosity and shear rate in the MRSTF specimens under a shear rate change of 1–3000 s\(^{-1}\) are shown in Figure 4 and 6. In the 0 mT magnetic field, the fluid viscosity increased slightly when the CI content increased from 5 to 10 % and then decreased when the CI content increased from 10 to 15 %. In general SiO\(_2\) particles produce hydrogen bonds with SiO\(_2\) particles and particles clusters wrapping iron powder particles produce due to shear disturbance. When the CI content increased from 10 to 15 %, iron powder particles could hinder particles clusters formation. At the same time, the critical shear viscosity increased from 3.12 Pa\cdot s for MRSTF5 to 4.59 Pa\cdot s for MRSTF10, then decreased to 3.01 Pa\cdot s for MRSTF15.
In the 98 mT magnetic field, the viscosity of the MRSTF increased significantly when the CI content increased from 5 to 15 %, as shown in Figure 5. Particles clusters wrapping iron powder particles produce due to shear disturbance. The higher iron fraction leads more iron particle chains under the magnetic field. Larger particles clusters wrapping iron particle chains increase the viscosity of the MRSTF. Moreover, with the increasingly high shear rate, iron particle chains are tilted and elongated, and the short chains increases. The effect of thickening gradually decreases and the MRSTFs exhibits a thinning trend (Zone III). Furthermore, the critical shear viscosity increased from 6.74 Pa.s for MRSTF5 to 49.5 Pa.s for MRSTF15. Comparing Figure 4 with Figure 5, it can be observed that increasing the CI content effectively improved the viscosity of the MRSTF in a magnetic field. Therefore, it can be concluded that the higher the CI content, the viscosity of MRSTFs can be more effectively regulated by the magnetic field.

3.3 Effect of magnetic field strength on MRSTF

Four magnetic field strengths were experimentally evaluated to explore the influence of the magnetic field on the rheological characteristics of MRSTF15 in terms of the relationship between the
viscosity and shear rate, as shown in Figure 6. The relative shear thickening intensities (defined as $(\eta_{\text{max}}-\eta_{\text{min}})/\eta_{\text{min}} \times 100\%$) of the fluid under magnetic field strengths of 0, 48, 98, and 197 mT were determined to be 1287%, 306%, 129%, and 12%, respectively. In a low magnetic field, the MRSTF readily exhibited stronger shear thickening characteristics, as indicated by the slope of the curve in Figure 6. Furthermore, the initial shear stresses of MRSTF15 were 8, 228, 764, and 2400 Pa, with increasing magnetic field strength the rheological characteristics of the MRSTF gradually change to resemble those of a Bingham fluid. Under high magnetic field strength, iron particle chains are tilted and elongated, and finally produce some short chains. And then particles clusters in the MRSTFs become small. Therefore the effect of thickening gradually decreases. The MRSTF under magnetic field strengths of 197 mT even presents MR fluid characteristics. The rheological characteristics of the MRSTF tend to become more similar to those of an MRF than an STF under high magnetic field strength. The results of this experimental analysis indicated that MRSTF can exhibit rheological properties of both MRF and STF depending on the magnetic field environment. Therefore, in vibration reduction applications, MRSTFs achieve dual coordinated and controllable characteristics by controlling the magnetic field and shear rate.

![Figure 6 Effect of magnetic field strength on viscosity and shear stress of MRSTF15](image)

**4. Design, testing, and modeling of an MRSTD**

**4.1 Design and analysis of an MRSTD**

The MRSTD is designed and evaluated in this study as shown in Figure 7(b), which is similar to a conventional single-tube damper consisting of a piston with a built-in coil and a gas chamber filled with MRSTF inside the damper. Maximum stroke=10 mm, cylinder diameter $(D=2r=48 \text{ mm})$, and piston rod diameter $(d1=10 \text{ mm})$. In the absence of a magnetic field, the output force of the damper is changed by controlling the vibration amplitude and frequency of the piston as shown in Figure 7(a). Under a
magnetic field (Figure 7(c)), the damper could change the damping force by piston vibration signal and by controlling the coil current. Thus the output damping force and energy consumption capacity can be adjusted.

4.2 Relationship between piston velocity and shear rate

The relationship between the viscosity of the MRSTF and shear rate was obtained as described in Section 2. However, the shear rate of the fluid in the damper gap was mainly affected by the amplitude and frequency of the piston vibration. Therefore, the relationship between the shear rate in the piston gap and the piston vibration amplitudes (frequencies) could be obtained.

According to the continuity equation in fluid mechanics, the instantaneous flow rate of the fluid in the piston gap is equal to the volume of fluid swept by the piston in that time, and is thus given by:

$$Q = \frac{\pi}{4} D^2 \cdot v_0 = v' \cdot S,$$

(1)

where $S$ is the piston clearance area in the radial direction of the piston, and $v_0$ is the piston movement speed. Thus, the flow velocity of the fluid in the clearance can be determined as $v'$:

$$v' = \frac{Q}{S} = \frac{\pi r^2 \cdot v_0}{S},$$

(2)

$$S = \pi \left( r^2 - \frac{d_1^2}{4} \right),$$

(3)

$$= \pi \delta(2r + \delta)$$

Where, $\delta$ is the piston clearance, and $d_1$ is the piston rod diameter.

Combining Equations (2) and (3) to obtain the fluid velocity $v'$ yields:

$$v' = \frac{r^2 \cdot v_0}{\delta(2r + \delta)}.$$
Then, from the definition of shear rate ($\dot{\gamma}$):

$$\dot{\gamma} = \frac{d\nu'}{dr} = \frac{r^2 \cdot \nu_0}{\delta(2r + \delta)} \left( \frac{1}{2r + \delta} + \frac{1}{\delta} \right).$$  

(5)

Once the shock absorber has been designed, its structural parameters are constants ($r$ and $\delta$). Thus, $\nu_0 = 2\pi f A \sin(2\pi f)$; therefore, Equation (5) can be re-written as:

$$\dot{\gamma} = 12\nu_0 = 24\pi f A \sin(2\pi f).$$  

(6)

Where $A$ is the amplitude of the piston vibration and $f$ is the frequency of the piston vibration.

According to Equation (6), once the damper structure has been determined, the fluid shear rate is mainly affected by the amplitude and frequency of the piston motion. In practical applications, the viscosity and damping can be controlled using the loading frequency or amplitude. Based on the rheological characteristic curve of MRSTF at a magnetic field intensity of 197 mT, it can be determined that the critical frequency of an MRSTD vibrating in an environment with an amplitude of 6 mm is about 1 Hz by Equation (6).

4.3 Mechanical characteristics Testing of the MRSTD

MTS809 fatigue testing machine (MTS Systems Corporation, USA) was used to evaluate the mechanical characteristics of the MRSTD. The MTS809 uses a fully digital control system (Testar IIIs digital control system) for subjecting specimens to loading three independent closed-loop control methods—load, strain, and displacement—and conduct compression, bending, shear tension, and torsion combination tests (dynamic frequency range: 0.01–100 Hz, maximum load: ±50 kN), as shown in Figure 8. In these tests, the fixed chuck B remained stationary, and chuck A was hydraulically pushed and pulled to apply a sinusoidal displacement load to the shock absorber piston rod to examine the relationship between the damping force and displacement of the shock absorber. The following parameters were evaluated to determine their influence on the damping characteristics of the proposed MRSTD: magnetic field strengths of 0, 98, and 197 mT; piston vibration frequencies of 0.2, 0.5, 1.0, and 2.0 Hz; and excitation amplitudes of 3, 6, and 9 mm.
4.3.1 Dynamic performance test with different magnetic fields.

As the key control parameter, the magnetic field strength can change the value of the MRSTD damping force by controlling the flux linkage strength. Therefore, the MRSTF15 sample was selected in this experiment to study the influence of magnetic field strength on the dynamic performance of the MRSTD. These experiments were accordingly conducted using different magnetic field strengths (\( \phi = 0, 55, \) and 100 mT) at a fixed scanning frequency (\( f = 1 \) Hz), as shown in Figure 9.

Figure 9(a) shows that the maximum MRSTD output damping force was 0.317, 0.48, and 0.553 kN for magnetic field strengths \( \phi \) of 0, 55, and 100 mT with the displacement of the piston, respectively. Thus, as the magnetic field strength increased, the damping force of the MRSTD was considerably risen. Therefore the energy consumption capacity of the damper was improved. It was observed in the hysteresis characteristic curve under the 0 mT magnetic field that the MRSTD damping force increased rapidly at a displacement of 0.71 mm owing to fluid shear thickening as shown in Figure 9(a). As the intensity of the magnetic field increased, the increasing rate of the damping force slowed. Combined with the rheological characteristics of the MRSTF, these results indicate that the thickening effect of the MRSTF was limited by the magnetic field.
4.3.2 Dynamic performance test with different frequencies.

To explore the influence of the piston vibration frequency on the damping force of the MRSTD (MRSTF15), the output damping characteristic curves were determined using a signal generator to apply a sine signal loading with frequencies of 0.2, 0.5, 1.0, and 2.0 Hz at an excitation amplitude of 6 mm under a magnetic field of 55 mT. The resulting force–displacement and force–velocity hysteresis curves are shown in Figure 10. The results indicate that when the frequency was lower than the critical shear frequency of 1 Hz, the damping force does not change significantly. When the frequency exceeded the critical value, the MRSTF in the piston gap exhibited thickening, and the output damping force increased significantly from 0.315 kN to 0.713 kN. In the MRSTD force–velocity curve, the increasing frequency of the piston raised the damping force.

![Hysteresis Curves](image)

(a) Force vs. displacement  
(b) Force vs. velocity

Figure 10 MRSTD hysteresis curves under different frequencies

4.3.3 Dynamic performance test with different amplitudes.

Both the amplitude and frequency of the piston vibration cause changes in the fluid shear stress by influencing the shear rate in the piston gap, as shown in Equation (6), and then it affects the damping force. In these tests, the vibration frequency and magnetic field strength were set to 1.0 Hz and 100 mT, respectively, and the vibration amplitudes were set to 3, 6, and 9 mm to obtain the MRSTD hysteresis characteristic curves shown in Figures 11(a) and (b). As shown in Figure 11(a), under a 3-mm-vibration amplitude, the damping force remained unchanged with displacement. When the vibration amplitude was 6 or 9 mm, the damping force of the shock absorber changed significantly with the change in displacement. Due to the second shear thinning of the MRSTF between vibration amplitudes of 6 and 9 mm, the results show that the curve corresponding to the 9 mm vibration amplitude was smoother, and a constant damping force was basically maintained within a displacement range of 0–2 mm. Therefore, the
results demonstrate that the damping force of the MRSTD maintains a constant value at a higher shear rate, providing an excellent self-protection effect.

(a) Force vs. displacement                     (b) Force vs. velocity
Figure 11 MRSTD hysteresis curves under different amplitudes

5. Mechanical model analysis of the MRSTD

Under the dual action of the velocity and magnetic field, the MRSTD damping force increased with the shear rate. The MRSTD exhibited the characteristics of an MRF damper or an STF damper depending on the magnetic field strength. To accurately evaluate the vibration control strategy and simulate the output of the MRSTD damping force, it is necessary to establish an accurate mathematical model of the MRSTD. According to the experimental data by the performance tests in Section 3, the damping force and displacement characteristics of an MRSTD were described using energy storage stiffness and energy dissipation stiffness. The linear damping model and nonlinear damping model are introduced in this paper, and the Levenberg–Marquardt (LM) algorithm was used to conduct nonlinear fitting and comparative analysis of the experimental results under the three test conditions shown in Table 1.

<table>
<thead>
<tr>
<th>Test condition</th>
<th>Amplitude (mm)</th>
<th>Magnetic field (mT)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>6</td>
<td>55</td>
<td>2</td>
</tr>
<tr>
<td>Test 2</td>
<td>6</td>
<td>98</td>
<td>0.5</td>
</tr>
<tr>
<td>Test 3</td>
<td>6</td>
<td>98</td>
<td>2</td>
</tr>
</tbody>
</table>

5.1 Linear damping and Nonlinear damping model

The linear damping model is composed of a viscous element and an elastic element in parallel and can be expressed as:
\[ F = Kx + C\dot{x} \]  

(7)

where \( K \) is the storage stiffness coefficient, defined by:

\[
K = \frac{F^+ - F^-}{A^+ - A^-}
\]

(8)

in which \( F^+ \) and \( F^- \) are the forces at the active displacement \( (A^+) \) and negative displacement \( (A^-) \), respectively, and \( C \) is the loss stiffness coefficient, defined by:

\[
C = \frac{W_d}{\pi f A^2}
\]

(9)

where \( W_d \) is the energy expended by the damper in one cycle.

Based on the nonlinear characteristics of the MRSTF, the nonlinear damping model adds a power law model to the linear model for expressing the MRSTD damping force as:

\[ F = Kx + C|\dot{x}|^\alpha \text{sign}(\dot{x}) \]  

(10)

where \( \alpha \) is the damping index.

5.2 Fitting results and discussion

The equivalent linear model and nonlinear damping model were analyzed as fitting functions. A nonlinear fitting was performed based on the experimental data obtained under the various magnetic field strengths and frequencies listed in Table 1. The initial values and fitting parameters of both the linear and nonlinear models are listed in Tables 2 and 3, respectively.

The fitting results of the two different models are shown in Figures 12(a), (b), and (c). To accurately describe the fitting results of the mechanical model, the error between the theoretical and experimental values of the linear and nonlinear damping models was calculated and plotted in Figure 13. Under the three evaluated testing conditions, the average error of the nonlinear damping model was less than that of the linear damping model. With the change in testing conditions, the average error of the nonlinear model was maintained at about 15%. On the contrary, that of the linear damping model varied with the magnetic field strength and frequency within the interval [23, 122]. It is worth noting that under the Test 3 conditions, the error value of the nonlinear model was only 5% less than that of the linear model. Referring to the rheological characteristics of the MRSTF reported in Section 2, as the magnetic field increased, the fluid characteristics tended to reflect those of an MRF, which behaved similarly to a linear fluid [22]. Furthermore, the vibration frequency of the MRSTD was only 0.5 HZ, so the fluid viscosity
in the damping gap exhibited only linear change during movement. Comparing to the experimental results, the errors of the models indicate that the nonlinear fitting method to describe the dynamic performance of MRSTF dampers was accurate and effective. The prediction error of the nonlinear model was controlled within an interval of (11%, 18%).

Table 2. Fitting results of the linear damping model.

<table>
<thead>
<tr>
<th>Fitting data</th>
<th>$K$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial value</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Test 1</td>
<td>0.01582</td>
<td>0.01042</td>
</tr>
<tr>
<td>Test 2</td>
<td>0.0144</td>
<td>0.01597</td>
</tr>
<tr>
<td>Test 3</td>
<td>0.01306</td>
<td>0.02879</td>
</tr>
</tbody>
</table>

Table 3. Fitting results of the nonlinear damping model.

<table>
<thead>
<tr>
<th>Fitting data</th>
<th>$K$</th>
<th>$C$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial value</td>
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<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>Test 1</td>
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<td>0.0234</td>
<td>0.8888</td>
</tr>
<tr>
<td>Test 2</td>
<td>0.01438</td>
<td>0.05229</td>
<td>0.5686</td>
</tr>
<tr>
<td>Test 3</td>
<td>0.02881</td>
<td>0.01022</td>
<td>1.071</td>
</tr>
</tbody>
</table>

(a) Test 1  
(b) Test 2
Figure 12 Linear and nonlinear MRSTD model fitting curves for the three tests defined in Table 1

Figure 13 Fitting errors under different test conditions

6. Conclusion

In this study, nano-grade fumed silica, carbonyl iron powder, and polyethylene glycol were mixed to prepare MRSTF samples, and their rheological properties was analyzed. The results indicated that the viscosity of MRSTF increased significantly when the shear rate exceeded the critical value. And the increasing amplitude of thickening decreased with increasing magnetic field strength. When the magnetic field strength of the MRSTF reached 197 mT, the thickening effect was eventually eliminated from MRSTF. It was also found that an increasing content of carbonyl iron powder effectively increased the viscosity of the fluid under a weak magnetic field environment.

An MRSTD was designed and tested to determine the influence of vibration frequency, amplitude, and magnetic field strength on its dynamic characteristics. It was found that the vibration frequency and amplitude of the MRSTD, as passive input excitation, changed the MRSTF viscosity and damping force by controlling its shear rate in the piston gap. The active control of the MRSTD output damping force was achieved by adjusting the magnetic field by the damping coil. The damper can provide vibration
reduction under dual coordinated active and passive control.

To evaluate the hysteresis characteristics of the MRSTD, a linear damping model and nonlinear damping model using the energy storage stiffness and energy dissipation stiffness were fitted, respectively. The average error between their predictions and the experimental results were analyzed. The comparison indicated that the nonlinear damping model was reliant upon the displacement and velocity, and which more accurately described the mechanical behavior of the MRSTD. Therefore, the results of this study demonstrated that the proposed MRSTD can provide both active and passive controllable damping performance, indicating good application prospects in the field of energy consumption and vibration control.

Acknowledgements

Declarations

Availability of data and materials
The authors confirm that the data supporting the findings of this study are available within the paper.

Competing interests
We declare that we do not have any financial and personal relationships with other people or organizations that can inappropriately influence reported in this article. All the authors have no conflict in interest about this work.

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Authors' contributions
Professor Huang interpreted the experimental results and wrote the manuscript. Mr. Sanfeng Yang designed the damper and contributed to the experiments. Mr Ming Yang contributed to the analysis and rheological test. Dr. Wei Li checked the manuscript. Ms Qing Zeng also participated in rheological test. All authors commented on the manuscript draft and approved the submission.

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References


