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Development of a linear damper working with magnetorheological shear thickening fluids

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Abstract

Magnetorheological shear thickening fluid is a smart material that exhibits both magnetorheological and shear thickening effects. This study focuses on the design and development of a novel magnetorheological shear thickening fluid-based linear damper. First, micron-sized carbonyl iron particles, at a 20% and 80% weight fraction, were immersed among the shear thickening fluid base and thoroughly mixed under a high shear condition to produce the magnetorheological shear thickening fluid. Then, a monotube damper with a bypass was designed and fabricated. The testing results using an MTS machine show that the influence of incorporating shear thickening fluid allows the 20% magnetorheological shear thickening fluid-filled damper to work in different dynamic loading velocities with the stiffness and damping changed, while, simultaneously, the dynamics of the damper depend on the variations in the magnetic field. The measured responses of the 20% magnetorheological shear thickening fluid-filled damper prove that the dampers have both the MR effect and shear thickening effect. In contrast, the 80% magnetorheological shear thickening fluid-filled damper behaves more like a conventional magnetorheological fluid-filled damper because its shear thickening effect is restrained and the MR effect becomes more obvious with higher iron volume.

Keywords

development, working, magnetorheological, fluids, damper, shear, linear, thickening

Disciplines

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Development of a linear damper working with MR Shear Thickening Fluids

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ABSTRACT

Magnetorheological shear thickening fluid (MRSTF) is a smart material that exhibits both magnetorheological and shear thickening effects. This study focus on the design and development of a novel MRSTF based linear damper. Firstly, micron sized carbonyl iron particles, at a 20% and 80% weight fraction, were immersed amongst the shear thickening fluid base and thoroughly mixed under a high shear condition to produce the MRSTF. Then a monotube damper with a bypass was designed and fabricated. The testing results using a MTS machine show that the influence of incorporating STF allows the 20% MRSTF filled damper to work in different dynamic loading velocities with the stiffness and damping changed while, simultaneously, the dynamics of the damper depend on the variations of the magnetic field. The measured responses of the 20% MRSTF filled damper proves that the damper have both the MR effect and shear thickening effect. In contrast, the 80% MRSTF filled damper behaves more like a conventional MRF filled damper because its shear thickening effect is restrained and the MR effect becomes more obvious with higher iron volume.

Keywords: magnetorheological shear thickening fluid, linear damper, shear thickening effect, magnetorheological effect.

1. Introduction

Vibration control, a field devoted purely to the absorption of impact energy, has seen ubiquitous in industrial, biomedical, and military applications. Approaches abound committed to diverting or isolating the unwanted energy. One of the most popular approaches is the use of fluid-filled dampers and vast advancements over time with the implementation and application of the dampers have been achieved (Carlson and Spencer Jr, 1996; Stanway et al., 1987; Wang and Liao, 2009). Applications of these dampers include seismic protectors for buildings and shock absorbers for the automotive industry (Yoshioka et al., 2002; Jung et

al., 2004; Du et al., 2013). More recently, these semi-active devices operating with media possessing varying fluidity properties have been studied (Li and Du, 2003; Han and Choi, 2006; John et al., 2008) as their working modes can be adjusted. These semi-active dampers become promising choices because of their superiority of offering the versatility of fully active control and reliability of passive control. They are both cost and energy efficient compared to the active dampers whilst providing the comparable performances. A more convincing truth is that their flexibility, real-time, and versatility make the semi-active devices far more advantageous than the passive dampers or the active dampers. The media used to fill the dampers can be field dependent fluids, such as the electroheological fluids (ERF) and the magnetorheological fluids (MRF), which will undergo obvious changes in their rheological properties in response to the variations of the electric and magnetic and all of the alterations is completely reversible (Popp et al., 2010; Bonnecaze and Brady, 1992). Many applications use their varying fluidity in either damping or torque transfer scenarios (Wereley et al., 2004; Liu et al., 2006). ERF damper and MRF damper, for example, change their damping and force characteristics under the action of electric and magnetic fields, respectively.

Besides the electric or magnetic field powered fluids, there are some other smart materials which are activated by loading conditions without any power consumption. Such materials include shear thickening fluids (STFs) and magnetorheological shear thickening fluids (MRSTFs). STFs are typically colloidal suspensions composed of non-aggregating solid particles suspended in fluids, which possess a low viscosity until the transition of the critical shear rate where it increases dramatically. A great deal of studies have been focused on the rheological properties and impact properties of STFs (Lee and Wagner, 2003; Franks et al., 2000; Hasanzadeh and Mottaghitalab, 2014; Soutrenon and Michaud, 2014). And STFs have been used for different applications. (Fischer et al. (2006)) incorporated STFs into a composite sandwich structure for the purpose of changing the dynamic properties under specific condition. Zhang et al. (2008a) reported a STF filled damper demonstrating that the influence of shear thickening allowed the damper working in high dynamic loading velocity to absorb much more energy. However, the applications of STFs are still limited because appropriate control strategies are hard to implement.

MRSTF is a relatively new smart material which is generally fabricated by adding magnetic particles to STF. MRSTF is proposed as an effort to combine the advantages of MRF and STF (Zhang et al., 2008b), being sensitive to both shear rate and magnetic field. And its thixotropy was further studied by Zhang et al. (2010). However, its applications are not perfectly explored. In this study, a linear bypass damper was designed and fabricated attempting to investigate the energy absorption mechanism of MRSTF-based devices. For this reason, MRSTF was firstly fabricated upon the preparation of STF and tested using a rheometer. Then the MRSTF filled damper was assembled and experimentally tested by using a MTS machine. Its dependence on the magnetic field and shear rate were investigated and evaluated, respectively.

2. Fabrication and property test of MRSTF and STF

In order to fabricate the MRSTF, STF is prepared in advance because it will be serving as the fluid medium of the ferromagnetic particles. The materials used to fabricate the STF were fumed silica (S5505, from Sigma Aldrich) which has a primary particle size of 14 nm and a specific surface area of approximately 200 $\mathrm{m^2g^{-1}}$ and the carrier fluid, ethylene glycol $[\mathrm{HOCH_2CH_2OH}]$, with a density of $1.113 \times 10^3 \mathrm{kg\,m^{-3}}$ (102466, ReagentPlus®, from Sigma-Aldrich). The silica powder was added to the carrier fluid in several times to make sure of the successful mixing. In each case, a blender was used to mechanically mix the two components

entirely at room temperature. The final finished sample, which contains 25 wt% of fumed silica, was then placed into a vacuum chamber for 2 hours to eliminate any bubbles.

Upon the preparation of STF, ferromagnetic particles (Carbonyl iron, C3518, Sigma-Aldrich Pty Ltd) were immersed amongst the STF to fabricate different MRSTF samples, where the weight fractions of the iron particles were 20% and 80%, respectively. To make the MRSTF with high weight fraction of carbonyl iron, it was suggested that the particles be divided into several fractions to be added to the carrier phase. The mixtures were mixed thoroughly before placed into a vacuum chamber for bubble elimination. Then the MRSTF samples were ready for use.

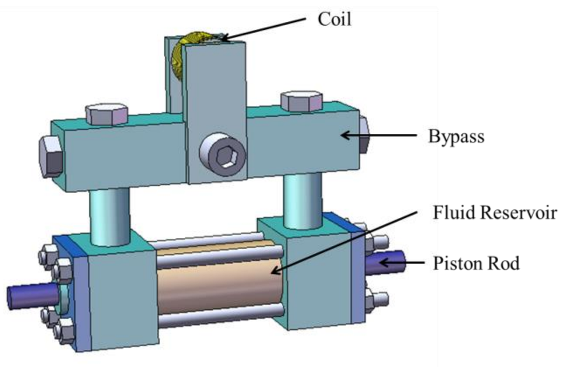
The rheological properties of STF and MRSTF can be referenced to Zhang et al. (2010) for a brevity purpose. The rheogram of the STF showed slight shear thinning first but exhibits a sharp increase in viscosity at a critical shear rate. The rheological behavior of MRSTF with low weight fraction of iron particles showed both obvious MR effect and ST effect, however, the MRSTF with high concentration of iron particles showed obvious MR effect like the conventional MR fluids with the shear thickening effect hardly observed. The MRSTF with low and high weight fraction of iron particles will be filled into a bypass linear damper in the following sections to see how the MRSTF-filled damper behaves in response to different concentrations of iron particles.

3. Design of the linear damper.

The schematic view and the prototype of the linear damper are shown in Figure 1. This damper has a double-ended structure with a long piston rod through both ends of the tube. There are two reservoirs where the fluid is stored. A bypass is used to let the fluid flow through when the piston head is moving inside the tube. By drawing out or pushing in the piston head, the filled fluids are infused from one reservoir to the other reservoir through the bypass channel. The hydraulic resistance of the damper can be changed through changing the viscosity of the filled fluids, which is energized by the magnetic field generated by the coil above the bypass. As for the velocity activated fluids, its mechanical properties can be changed by adjusting the velocity of the piston rod.

4. Test of STF and MRSTF damper

Figure 2 shows the experimental system where the prototype damper was clamped within an MTS Landmark test system, between two coaxially mounted Linear-variable Displacement Transducer (LVDT) load cells. The MTS Landmark was excited by the servo hydraulic system capable of exerting large axial loads on the test specimen and operated by a remote control system in the computer. The predetermined program package provided harmonic excitation to the damper and recorded signals taken through the load cells. The signals were saved to the computer via a data acquisition (DAQ) board measuring various feedback data series including axial displacement, axial force, and the velocity being obtained via the derivation of the displacement. All the experiments were carried out at the room temperature of 23 ◦C.



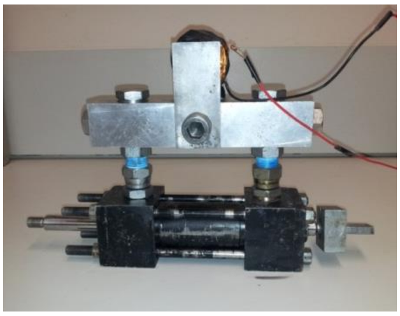


Fig. 1. The schematic view and prototype of the linear damper.

Prior to starting the testing, an extended position must be accurately determined by unloading the linear damper. The extended position is regarded as the initial position for all dynamic tests. For each test, the MTS test machine was programmed to move in a sinusoidal wave at certain displacement amplitude and frequency. In this experimental study, the linear damper filled by STF, 20% MRSTF, and 80% MRSTF was tested, respectively. The results are displayed and discussed in the following sections.

4.1 The dynamic performances of STF filled damper

Figure 3 shows the performances of the linear STF damper, which was tested under the simple harmonic motion (sine function) having its frequency varied. In this testing, the excitation frequencies of 0.2Hz, 0.6Hz, 1Hz, 1.4Hz, 1.6Hz, and 2Hz were used. It is clearly noticed that the shape of the hysteretic loops are strongly dependent on excitation frequencies. When the excitation frequencies are relatively small such as 0.2Hz, 0.6Hz, and 1Hz, the hysteresis shape is more like a parallelogram which is similar to the traditional MR damper performances, however, the hysteresis loops tend to be irregular with some bending or pinching when

Fig. 2. MTS system for damper testing.

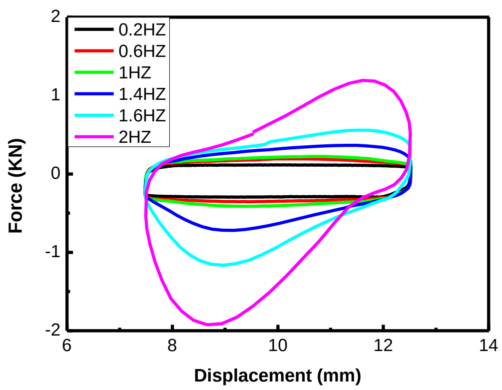


Fig. 3. ST effect of STF filled damper.

the frequency grows gradually. Also, the increase of the excitation frequency increases obviously the peak force and the effective stiffness which is indicated by the effective slope of the main-axis loop. Similarly, the area enclosed by the hysteresis loops grows with the increasing excitation frequency, which means that the energy dissipation capability increases with the increment on the frequency. It can be concluded that the linear STF damper has inherited the mechanical property of STF that it can be thickened by increasing the frequency, which is reflected by the damper as the growth in both the effective stiffness and the damping constant.

4.2 The performances of 20% MRSTF filled damper

In this part, the linear MRSTF damper with 20% weight fraction of iron particle was tested. The damper performance was tested under different testing conditions; the simple harmonic motion (sine function) used had its frequency being constant (0.5Hz), whilst altering the applied magnetic field to measure its MR effect. The current from an external power supply was adjusted from 0A to 2A with 1A step. To measure its ST effect, the excitation frequency fluctuates from 0.1Hz to 0.9Hz with 0.2Hz step while the current was maintained as 0A.

Figure 4 shows the force-displacement and force-velocity responses of the linear MRSTF damper. As can be seen from this figure, the shape of the hysteresis loop is not the parallelogram at all but the bended or pinched loops. The damping force is sensitive to the variations of the applied magnetic field, moreover, the effective stiffness and the energy dissipation capability increase obviously when the applied current increases, showing that the 20% MRSTF has an obviously MR effect. It is also observed that the peak force, the effective stiffness, and the damping constant tend to be saturated when the current tends to be bigger. For example, the effective stiffness as a function of the current is presented in Figure 5. It can be seen that the relationship shows generally a climbing trajectory. Figure 6 presents the axial force versus displacement and velocity for five different frequency sets. It is clear that shear thickening is happening when the frequency is increased. The peak force, the effective stiffness, and the damping constant all show obvious dependence on the varied frequency. The MRSTF was kept in neutral state, that is to say, no current was applied, which means that the representation is reliant completely on the frequency activation.

Compared to the linear STF damper, the force-displacement relationships all show pinching and bending phenomena, however, one obvious advantage of the linear MRSTF damper over the linear STF damper is that the dynamic properties of the linear MRSTF damper is dependent on both the applied magnetic field and the excitation frequency instead of being only sensitive to the varied frequency.

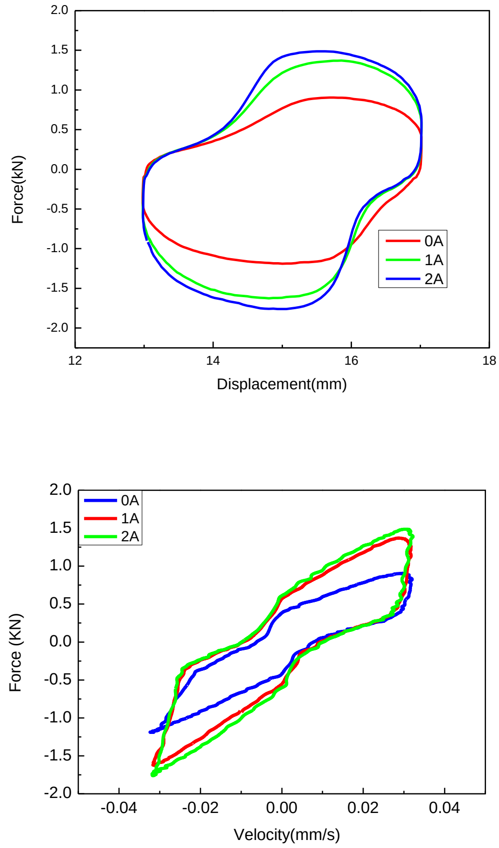


Fig. 4. MR effect of the 20% MRSTF filled damper.

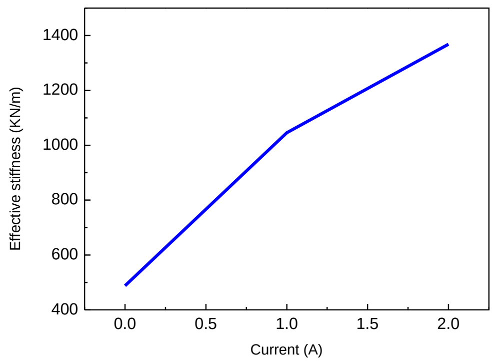


Fig. 5. Effective stiffness versus current

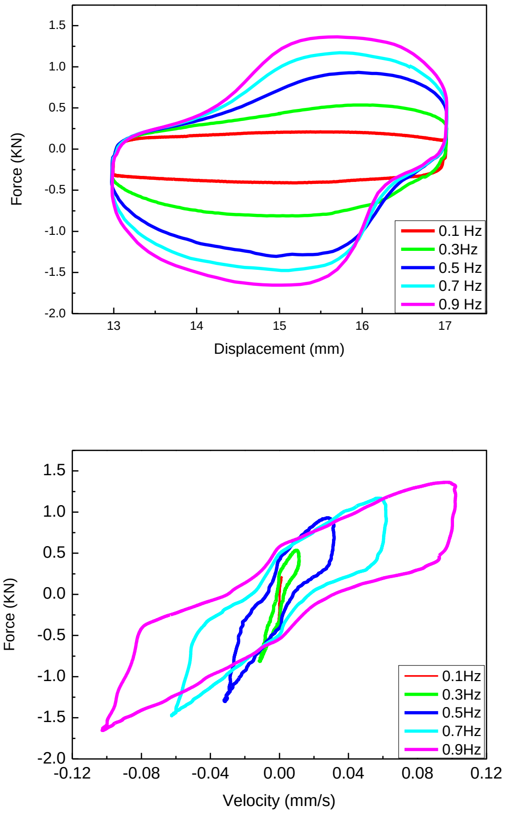


Fig. 6. ST effect of the 20% MRSTF filled damper.

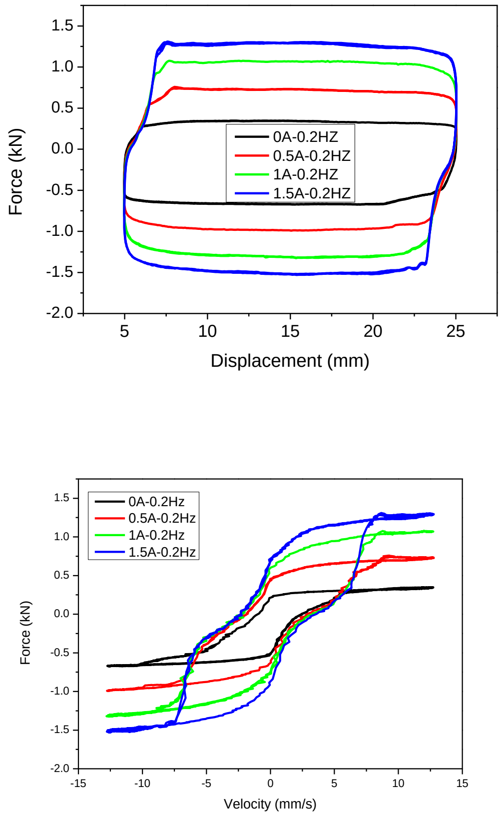


Fig. 7. MR effect of the 80% MRSTF filled damper.

4.3. The performances of 80%MRSTF filled damper

The process of testing the linear MRSTF damper with 80% iron particles is similar to that described in section 4.2, where the MR effect and ST effect were measured, respectively. The experiments were performed by various magnetic fields from 0 A to 1.5 A with an increment of 0.5 A. The frequencies applied to the damper were 0.2, 0.5, 1.0, 1.5, and 2.0 Hz, respectively. The following figures show the curves of axial force versus displacement and velocity of this MRSTF filled damper under different currents.

Figure 7 shows the force versus displacement and velocity at a constant frequency of 0.2 Hz while stepping the current in 0.5 A intervals. It is noted that the force displacement curves are perfect parallelograms and this damper shows similar properties of the traditional MRF dampers. What is meant by this is that as increasing the applied current to the damper coil, the measured damping force increases obviously. Additionally, compared to Figure 4, the damping force changes more quickly in response to the changing current, as shown in Figure 8, to which a reasonable explanation is that the higher the fraction of the iron particle the more obvious the MR effect. In the meantime, it is noticed that the damping force of 80% MRSTF filled damper is smaller than that of the 20% MRSTF filled damper under the given current, which can be explained by the dilution of the fluid by adding more iron particles.

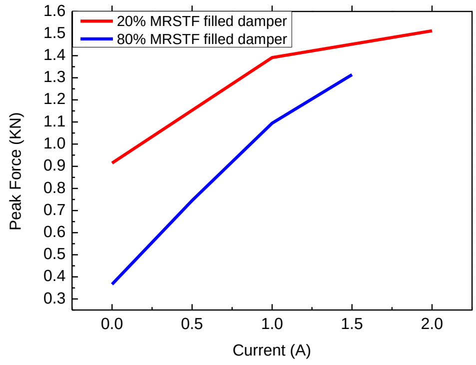


Fig. 8. Peak force versus current.

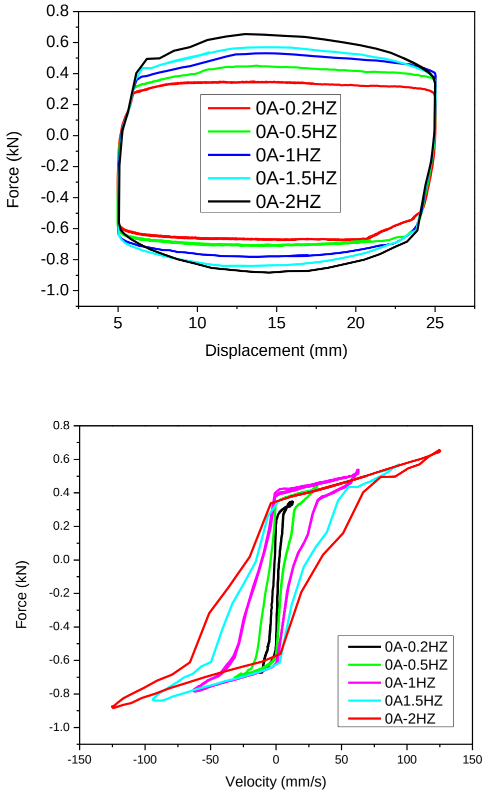


Fig. 9. Dynamic responses of the 80% MRSTF filled damper under different frequencies.

Figure 9 shows the performance of the damper under five frequency sets. It is seen that the damping force increases slightly as the frequency increases and that the effective stiffness is almost independent of the varied frequency. The shape of the loops differ greatly from that in Figure 6, however, it is similar to that of the ordinary MRF damper, which means that the developed linear MRSTF damper with 80% iron particles are almost immune to the excitation frequency.

It is concluded from the above results that with the increase of the iron particle concentration, the shear thickening of the MRSTRF damper is restrained and the magnetorheological effect becomes more obvious. With high iron particle concentrations, the MRSTF damper can be used as an equivalent MRF damper.

5. Conclusions

In this study, MRSTFs consisting of nano sized silica particles suspended in an ethylene glycol solvent, mixed with 20 wt% and 80 wt% carbonyl iron particles were fabricated and characterised, respectively. A prototype internal electromagnet semi-active damper was designed and fabricated based on research made into similarly performing devices. The MTS test procedure produced a series of outputs measuring the response of the damper under various loading conditions. Analysis of the data series displays that the MRSTF damper has the ability to vary its damping constant and effective stiffness by controlling magnetic flux density. This work also shows that integrating MRSTF into a damper can lead simultaneously to changes in stiffness and damping as the frequency is varied. One special point needed to be noted is that the MR effect of the MRSTF filled damper becomes more obvious, however, the shear thickening effect is restrained, with the increasing concentration of iron particles.

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