Effect of seven different additives on the properties of MR fluids

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Abstract. Magnetorheological (MR) fluids have been developed for application in semi-active magnetorheological fluid dampers and other magnetorheological fluid devices. In order to prepare special MR fluids to satisfy the demands of tracked vehicle, two different carrier fluids were chosen to prepare MR fluids. Preparation of MR fluids, which are based on carriers such as special shock absorption fluid and 45# transformer oil, was finished. And characteristics of these samples were tested and analyzed. Results indicate, Tween-80 and Span-80 can improve sedimentary stability. Using 45# transformer oil instead of special shock absorption fluid as a carrier, the shear yield stress remains nearly invariable but the viscosity and the sedimentary stability are reduced. MR fluids with diameter of 2.73µm show better sedimentary stability than that of the MR fluids with diameter of 2.3µm, or 4.02µm. Stearic acid obviously improves sedimentary stability and off-state viscosity, but don’t perform an obvious function on shear yield stress. In magnetic field of 237KA/m, the shear yield stress of MR fluid based on special shock absorption fluid and 45# transformer oil is 18.34KPa, 14.26KPa, respectively.

1. Introduction
Magnetorheological (MR) fluids can respond to an externally applied magnetic field with a rapid and reversible change in their apparent viscosity. They have attracted much interest in their various engineering applications such as dampers, shock absorbers, isolators and brakes [1, 2, 3, 4], especially in vehicle engineering and civil engineering structures [5, 6, 7].

MR fluids are phase-controllable magnetic suspensions, which contain the magnetizable particles, non-magnetizable suspending fluids and additives. MR fluids behave similarly to Newton fluid without an applied magnetic field; under external magnetic field, the behavior of MR fluids can be described by the Bingham plastic model. When certain magnetic field intensity is imposed, the magnetic particles form chain clusters in the direction of the external field [8].

Though MR fluids do have most of the desirable properties, they also have the following disadvantages [9]: poor sedimentary stability, high viscosity at off-state, and low shear yield stress. Two different carrier fluids are used to prepare MR fluids and use these MR fluids in dampers in semi-active suspension of tracked vehicle to improve performances of vehicle. According to numerous experiments, sedimentary stability of MR fluids was investigated by applying different additives and particle weight fractions. Based on these results, some advanced experiments were made. And off-state viscosity, shear yield stress and sedimentary stability of MR fluids were comprehensively measured and analyzed in order to analyze the effect of different additives on property of MR fluids.
2. Experimental

2.1. The first phase experiment

In order to make clear components and additives, this set of experiments was used to evaluate the sedimentary stability of MR fluid samples. Additives were dispersed uniformly in carrier, and the mixture was kept in 60° for 1 hour, and then carbonyl iron particles were dispersed in the mixture, the MR fluid samples were mixed round in a colloid milling machine for 24 hours. Carbonyl iron particles with diameter of 4.02µm were dispersed in special shock absorption fluid (shown in Table 1) to prepare three kinds of MR fluid, and they were named as MRF11, MRF12, MRF13, their concentrations of carbonyl iron were 80%, and their corresponding additives were Tween-60 and Span-60, OP emulsifier (the structure of OP is shown in Figure 1) and oleic acid, Tween-80 and Span-80 (the components of MR fluids are shown in Table 2). Then sedimentary stability of MR fluid samples was tested and the results were researched.

Table 1. Characteristics of shock absorption fluid.

| Component | Density (kg/m³) | Viscosity (Pa.s) |
|-----------|----------------|-----------------|
| 70% olefin polymer oil and 30% mineral oil | 0.857×10³ | 0.0693 | 0.00857 |

Figure 1. The structure of OP.

Table 2. Components of MR fluids.

| Diameter (µm) | Concentration (wt.%) | Carrier | Additives |
|---------------|----------------------|---------|-----------|
| MRF11         | 4.02                 | 70%     | shock absorption fluid | Tween-60 and Span-60 |
| MRF12         | 4.02                 | 70%     | shock absorption fluid | OP and oleic acid |
| MRF13         | 4.02                 | 70%     | shock absorption fluid | Tween-80 and Span-80 |

2.2. The second phase experiment

To comprehensively investigate and analyze sedimentary stability, off-state viscosity and shear yield stress, the second phase experiment was designed. Carbonyl iron particles with diameter of 2.3µm are produced by Beijing Mountain Technical Development Center for Non-Ferrous Metals and their purity is 98.5%; carbonyl iron particles with other diameters are produced by Beijing Youxinglian Non-Ferrous Metals Co., Ltd and their purity is 99.5%. The components of MR fluids are shown in Table 3.

Table 3. Components of MR fluids.

| Diameter (µm) | Concentration (wt.%) | Carrier | Additives |
|---------------|----------------------|---------|-----------|
| MRF21         | 2.3                  | 70%     | shock absorption fluid | tween-80 span-80 |
| MRF22         | 2.73                 | 70%     | shock absorption fluid | tween-80 span-80 |
| MRF23         | 4.02                 | 70%     | shock absorption fluid | tween-80 span-80 |
| MRF24         | 2.3                  | 70%     | 45# transformer oil   | tween-80 span-80 |
| MRF25         | 2.3                  | 70%     | shock absorption fluid | tween-80 span-80 Stearic acid |
3. Instrumentation

3.1. Sedimentary stability
Since density of the dispersed iron particles was much higher than that of the carrier fluid, sedimentation of the iron particles was generally observed. Placed in the lab for a long time, MR fluids settled and agglomerated so easily that parts of carbonyl iron particles lost their magnetorheological effect. Sedimentary rate \( R \) can be determined by placing MR fluid in a vertical cylindrical container at room temperature [10], \( R \) can be calculated by:

\[
R = \frac{\Delta h}{h}
\]

Where \( \Delta h \) is the length of the turbid fluid, and \( h \) is the whole length of the fluid.

3.2. Off-state viscosity
In zero magnetic field (off-state), some MR fluids behave similarly to Newton fluid, their off-state viscosities have no relationship with shear strain rate; and some MR fluids at off-state behave characteristics of non-Newton fluid, whose viscosities are inversely proportional to the shear strain rate. Off-state viscosity of MR fluids versus shear strain rate was measured by SNB-1 viscosimeter (Shanghai Exact Science Instruments Co. Ltd).

3.3. Shear yield stress
There are two different yield stress values, dynamic yield stress and static yield stress. The dynamic yield stress of MR fluid is usually described as zero-rate intercept determined through a linear regression curve fit to the measured flow data, while the static yield stress corresponds to the shear stress necessary to initiate flow.

\[
\tau_y = \frac{F_y}{\pi r^2}
\]

Where, \( \tau_y \) is shear yield stress, \( r \) is radius of the hole, \( F_y \) is the press force measured by sensor.

4. Results and discussions

4.1. Sedimentary stability
In the first phase experiment, according to figure 3, sedimentary stability of MR fluid with additives of Tween-80 and Span-80 is better than that of two other MR fluids with additives of OP and oleic acid, or Tween-60 and Span-60. This result indicates that Tween-80 and Span-80 can improve the sedimentary stability of MR fluid.
According to figure 4, the sedimentary stability of MR fluid with diameter of 2.73µm is better than that of MR fluid with diameter of 4.02µm or 2.3µm. This phenomenon can be explained by Stokes equation (3):

\[ V = (\rho - \rho_0)gd^2 / 18\eta \]  

(3)

Where \( V \) is the sedimentary velocity of particles in carrier fluid; \( \rho \) and \( d \) are the density and radius of the particles, respectively; \( \rho_0 \) and \( \eta \) are the density and viscosity of the carrier fluid, respectively; \( g \) is the gravitational constant.

According to equation (3), the sedimentary velocity of MRF21, MRF22, MRF23 are calculated in table 4, where, gravitational constant \( g=10(\text{m/s}^2) \), density of the particles \( \rho=7.8 \times 10^3(\text{kg/m}^3) \), the density of the carrier \( \rho_0=0.8 \times 10^3(\text{kg/m}^3) \), as shown in table 4.

| Diameter (m) | Viscosity (Pa.s) | Velocity (m/s) |
|-------------|-----------------|----------------|
| MRF21       | 2.3×10^{-6}     | 1.309          | 1.8072×10^{-8} |
| MRF22       | 2.73×10^{-6}    | 3.36           | 0.8625×10^{-8} |
| MRF23       | 4.02×10^{-6}    | 4.34           | 1.4480×10^{-8} |

Obviously, according to table 4, MRF22 has the slowest sedimentary velocity. This result accords well with the observed phenomenon. Thus, the sedimentary stability of MR fluid with diameter of 2.73µm is better than that of MR fluids with diameter of 4.02µm or 2.3µm.

Additionally, according to figure 4, the sedimentary stability of MRF24 is the worst, mostly because the viscosity of 45# transformer oil is much lower than that of special shock absorption fluid and the viscosity of MR fluid based on 45# transformer oil is lower than that of MR fluid based on special shock absorption fluid. Sedimentary stability of MRF25 is much better than that of MRF21, this indicates that stearic acid can increase the viscosity of MR fluids and improve sedimentary stability of MR fluids.

### 4.2. Off-state viscosity

Figure 5 represents the viscosities of MR fluids measured in 22.3°C. According to figure 5, viscosities of all MR fluids exhibit shear-thinning behavior. Viscosity of MRF24 based on 45# transformer oil is the lowest, because other MR fluids are based on special shock absorption fluid which has a bigger viscosity than 45# transformer oil. From viscosities of MRF21, MRF22, MRF23, diameter of the carbonyl iron particles has strong influence on the viscosity of MR fluid—means that diameter of the particles is almost in direct proportion to the viscosity of MR fluid. Comparing the viscosity of MRF25 with MRF21, it is easy to observe that the viscosity of MRF25 is higher than that of MRF21, because stearic acid increases the viscosity of MR fluid.
4.3. Shear yield stress

Figure 6 represents relationship of shear yield stress with different magnetic field intensity. For an increase in magnetic field intensity, a similar increase in the shear yield stress is observed. This is because the stronger magnetic field intensity makes the pull force among the soft magnetic particles bigger, and thus the shear stress becomes bigger to break the column-like structures formed by magnetic particles. According to curves of MRF21, MRF22, MRF23, for an increase in diameter, a similar increase in shear yield stress is observed. From curves of MRF21 and MRF25, the shear yield stress is similar and has not strongly difference, this indicates that stearic acid don’t change the shear yield stress of MR fluid. From curves of MRF21 and MRF24, although MR fluids are based on different carriers they have similar shear yield stress but different viscosities. In practice, 45# transformer oil can also be used instead of special shock absorption fluid to prepare MR fluid with low viscosity, to some extent. In magnetic field of 237KA/m, the shear yield stress of MRF23 is 18.34KPa and the shear yield stress of MRF24 is 14.26KPa.

5. Conclusions

Numerous MR fluids based on such carriers as special shock absorption fluid and 45# transformer oil were prepared, and their sedimentary stability, off-state viscosity and shear yield stress were tested and analyzed. The results indicate that tween-80 and Span-80 can improve the sedimentary stability; 45# transformer oil can also be used as a carrier and MR fluids based on this oil can have a low viscosity; sedimentary stability of MR fluids with particle diameter of 2.73µm is the best among the three kinds of diameters referred to this experiment; stearic acid can increase the viscosity and sedimentary stability of MR fluid, but can’t improve shear yield stress of MR fluid; in magnetic field of 237KA/m, the shear yield stress of MR fluid based on special shock absorption fluid and 45# transformer oil can reach 18.34KPa, 14.26KPa, respectively.

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