Non-dimensional Modeling and Experimental Evaluation of a MR Squeeze Mode Rheometer

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Abstract. Squeeze mode flow in MR fluids has recently become an interest to many researchers. In squeeze mode, MR fluids can generate a wide range of force associated with a small displacement. The generated force is controllable by means of a variable magnetic field. This is promising for applications that require variable forces along short strokes. There are not many published data on the behavior of MR fluids in squeeze mode. Many of the basic properties of MR fluids in squeeze mode are still unknown. The presented research here focuses on modeling and testing MR fluids in squeeze mode. A novel squeeze mode rheometer was designed and built. The results show that MR fluid can deliver a force that is comparable in magnitude to the force in shear mode. A non-dimensional mathematical model was developed and validated experimentally.

1. Introduction

Shear and valve mode flow of MR fluids are the most extensively explored modes in MR research and many commercial products are available based on shear or valve mode. The basic properties of MR fluids in shear and valve mode are completely understood and there are numerous literature available on modeling and simulation of MR fluids in these modes. On the other hand, there is very little literature concerning the squeeze mode flow of MR fluids and their basic properties in compression [1]. However, the number of publications on squeeze mode flow is increased recently [2, 3]. In this paper, the authors present basic research on MR fluids in squeeze mode. MR fluid is squeezed and its behavior and performance are evaluated. Having the knowledge of the basic properties of MR fluids in squeeze mode is essential for the design of devices based on this mode.

In squeeze mode, the MR fluid is placed between two plates (commonly referred to as poles). In the presence of a magnetic field, the poles move toward each other and squeeze the MR fluid as shown in Figure 1. As the magnetic field is turned on, iron particles line up in the direction of the magnetic field and form chains. These chains increase the resistance of MR fluid to flow.

2. Non-dimensional mathematical model

The pressure in the MR fluid when squeezed is known to be due to three factors [4]:

- Pressure due to the viscosity of the MR fluid.
- The pressure due to formation of chains and their resistance to flow (MR effect).
• The pressure due to the inertia of the MR fluid. If the amount of MR fluid is small and the relative velocity of the poles is low, the inertial effect can be neglected.

![Figure 1 MR fluid in squeeze mode](image1)

![Figure 2 Schematics of the squeeze mode rheometer configuration](image2)

The rheometer designed and built at CVeSS has the schematics shown in Figure 2 to squeeze the MR fluid. A piston with a hole in the center is pushed down in a cylinder filled with MR fluid, squeezing the MR fluid. The excess of the MR fluid escapes from the center hole to compensate the volume decrease caused by movement of the piston.

Neglecting the inertial effects, the total force, \( F \), can be calculated as [5]:

\[
F = \frac{3\pi \eta \dot{x}}{2(x_0 - x)} \left[ R^4 - R_1^4 - 4R_1^2 R^2 \ln \left( \frac{R}{R_1} \right) \right] + \frac{2\pi \tau_y}{3(x_0 - x)} \left( R_1^3 + 2R^3 - 3R^2 R_1 \right)
\]

(1)

Where, \( \tau \) is the yield stress of MR fluid, \( \eta \) is the viscosity of the MR fluid, \( R \) is the radius of the piston, \( R_1 \) is the radius of the center hole, \( x_0 \) is the initial gap size, and \( \dot{x} \) is the relative velocity of the piston.

Equation (1) can be used to obtain the squeeze force as a function of the gap size \( (h = x_0 - x) \). The first term on the right hand side is the force generated by the viscosity of the MR fluid and the second term is the force caused by the magnetic effect of the MR fluid.

Transforming equation (1) to the non-dimensional form gives the ability to better understand the behavior of the MR fluid and make some means to compare its performance in squeeze mode with other flow modes. Rearranging equation (1) into its non-dimensional form results:

\[
\psi = \frac{A}{Bn \zeta^3} + \frac{B}{\zeta^2}
\]

(2)

where, \( \zeta = \frac{h}{R} \) is the non-dimensional gap size. The Bingham number, \( Bn = \frac{R \tau_y}{\eta \dot{x}} \), can be considered as the ratio of the MR effect to the viscous effect. The non-dimensional force, \( \psi = \frac{F}{\pi R^2 \tau_y} \), is the ratio of the squeeze force to the yield stress multiplied by the area of the pole. It can be used as a measure for comparison between the squeeze mode force and direct shear mode. The denominator of \( \psi \) can be interpreted as the force acting on the same area and the same MR fluid to yield the MR fluid in direct shear mode. \( A \) and \( B \) are geometric constants which depend on the geometry of the rheometer.

3. Test results
A large number of tests have been done on MRF-120RD from LORD, with the squeeze mode rheometer. Tests have been carried out for different initial gap sizes and different magnetic field densities. The velocity of the piston has been chosen to be very small assuring a quasi-static condition. The results show that MR fluid is capable of delivering a wide range of force in squeeze mode. Figure 3 shows the force versus displacement plot. The initial gap is 0.1 in (2.5 mm) and the MR fluid is squeezed to a gap size of 0.05 in (1.3 mm). The coil current is increased from 1 Amp to 3 Amps (corresponding to 0.3 T to 0.7 Tesla in the MR fluid gap). As can be seen, MR fluid could deliver a maximum force of approximately 700 lb (3100 N) at 3 Amp. A further increase in current did not considerably increase the maximum force. The yield stress of the MR fluid does not increase significantly as the magnetic field density is increased beyond 0.7 Tesla in the gap.

One of the behaviors seen was the clumping effect. At high currents the iron particles are trapped in the magnetic field forming chains, but the carrier fluid is free to flow. Therefore, as the piston moves, the iron particles stay in the gap and the carrier fluid leaves the gap leaving iron particles behind. After a few repetitions of tests, the amount of iron particles is considerably high in the gap and a large percentage of the carrier fluid has left the gap. This makes the volumetric percentage of the MR fluid increase and consequently, increases the force. Similar behavior is also seen by other researchers [2].

Another important property of MR fluids in squeeze mode, shown in Figure 3, is the inability to withstand tensile forces. After the minimum gap is reached, the piston contracts at the same rate of approach but the force rapidly decreases from its maximum value to zero.

Test results shown in Figure 3 are based on displacement control tests of the rheometer. If the force is used as the input to the rheometer (force controlled mode), the MR fluid will flow based on the force that is exerted. With the force controlled mode the yielding behavior of MR fluid is more obvious in the beginning of the tests. As the force is increased, the MR fluid is resisting the movement of the piston without yield. This can be identified as a high slope region in the force-displacement curves. Once the MR fluid is yielded, the slope is decreased and the MR fluid flows. shows the results of the forced controlled tests on MRF-120RD. For the force controlled tests, the initial gap was 0.2 in (5 mm) and the final gap depends on the current and the amount of force exerted. The force was increased from 0 lb to approximately 200 lb (890 N) with a constant rate. At higher currents the MR fluid is more resistive and the piston moves a shorter distance.

The mathematical model introduced in the previous section agrees with the test results, especially the force controlled tests because they better illustrate the pre-yield phase of the MR fluid in squeeze. At 1 Amp the average magnetic field density is 0.3 Tesla. At this magnetic field density, the properties of MR fluid can be approximated as: \[ \eta = 6.09 \times 10^{-6} \text{ Reyn (0.042 Pa.s), } \tau_y = 1.9 \text{ Psi (13 kPa)} \].

The average velocity of the piston is 0.0135 in/sec (0.3 mm/sec). Using these parameters along with the non-dimensional model, a comparison between the test data and the mathematical model is obtained as shown in Figure 5.
As shown in Figure 5, the magnitude of the non-dimensional force at the yield point of MR fluid in squeeze mode is approximately 7. This shows that the amount of force required to yield the fluid in squeeze mode is almost 7 times larger than the force needed to yield the same MR fluid in direct shear mode when $\zeta = 0.16$. As the non-dimensional gap size decreases, the magnitude of the non-dimensional force increases.

4. Conclusion
It is shown that the tested MR fluid is capable of carrying a wide range of force in squeeze mode. This force range is achievable along a short stroke. The amount of the force achieved depends on the magnetic field density and gap size. The clumping effect was observed in squeeze mode testing. The design of MR devices which work on squeeze mode requires a solution to reduce the clumping effect. Clumping causes the carrying liquid to separate from iron particles reducing the repeatability. The clumping behavior is currently being studied at CVeSS.

The mathematical model presented is able to illustrate the basic behavior of MR fluids in squeeze mode and can be used for design purposes. The mathematical model is in agreement with the test results. However, the force controlled test results have a better match with the mathematical model. At force controlled tests, MR fluid can resist movement of the piston before yielding. While in displacement controlled tests, the piston starts to move right after the test is started and MR fluid has to flow.

References
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