An alternate operation mode for MR fluids—Magnetic Gradient Pinch

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Abstract. MR fluids have been employed in a wide variety of applications, providing viable solutions to many engineering challenges. Controllability in MR fluid devices is achieved through one of three commonly recognized operating modes—valve mode, direct-shear mode, and squeeze mode. This paper presents evidence of an alternative valve configuration for controlling MR fluids. This valve design represents a considerable departure from the commonly recognized modes. Specifically, this novel valve design replaces the conventional narrow gap with a relatively large circular orifice, and it changes the way in which the magnetic field interacts with the fluid. With these changes, we present evidence that this novel valve design may offer functionality not currently available in conventional MR fluid valves.

1. Introduction
Today’s MR fluid devices achieve controllability through proper valving of the fluid using one of the three commonly recognized operating modes—valve mode, direct-shear mode, and squeeze mode. Regardless of the operating mode, all current MR fluid devices rely on creating a more or less uniform magnetic field across the thin layer of fluid in the channel and perpendicular to the flow direction. This has profound practical implications on the geometry and size of the flow channel. Specifically, the narrow dimension of the flow channel or gap must be kept small to minimize the power required for generating the magnetic field and to allow a large on-state force. Yet the gap must not be too small so as to make the off-state viscous force too large. Moreover, the size of the particles in the MR fluid must be carefully chosen to avoid jamming in the narrow gap.

This study presents evidence of an alternative valve configuration for controlling MR fluids, namely, Magnetic Gradient Pinch or MGP [1]. Initial motivation for the MGP valve was to find a way to enable the use of low-cost iron powder in MR fluid devices. The carbonyl iron powder that is used today is quite expensive and the goal was to design a valve that could allow the use of larger, coarser particles that are significantly less expensive than carbonyl iron.

The idea is to radically change the way in which one attempts to valve MR fluid such that the normally accepted MR fluid design paradigms and constraints are significantly altered to allow the use of coarser, low-cost particles. Rather than the very narrow rectangular flow channel of a normal MR fluid valve, the MGP valve is a relatively large circular aperture through which large particles can easily pass. The MGP valve also changes the way in which the magnetic field interacts with the fluid.

2. Magnetic Gradient Pinch valve

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Conventional MR fluid valves rely on the ability to generate a field-dependent yield stress throughout the entire active fluid volume. The fluid essentially becomes a solid and no flow occurs until the pressure becomes sufficiently large to yield the fluid near the walls at which point the entire body of fluid moves as a plug. The greater the magnetic field, the larger the yield strength and the more pressure required to move the plug, as shown in figure 1.

![Figure 1. MR fluid valve showing key geometric features and resulting pressure.](image)

The fundamental difference between a conventional MR fluid valve and the Magnetic Gradient Pinch (MGP) valve is in the design of the magnetic circuit. The MGP valve replaces the rectangular flow channel by a simple orifice and arranges the poles axially, as shown in figure 2. Arranging the poles axially along the flow path and separating the poles by a non-magnetic spacer generates a highly non-uniform magnetic field.

![Figure 2. The Magnetic Gradient Pinch valve has poles arranged axially along the flow channel (left) which generates a highly non-uniform magnetic field (right).](image)

The basic premise for the MGP valve is that the flow of MR fluid through a circular orifice can be controlled with a strong magnetic field gradient. Rather than solidifying the fluid throughout the valve, the non-uniform field only solidifies MR fluid near the wall. The overall magnetic field strength will control the inward distance that such solidification occurs, thus effectively controlling the orifice diameter. This type of control has been identified as the MGP pinch mode.

A second, more extreme, mode of control was discovered while exploiting another benefit of the MGP valve. The MGP valve replaces the rather narrow rectangular flow channel by a relatively large (2 mm) orifice. Such a large orifice enables the use of much coarser iron in the fluid formulation. Without the fear of spontaneous jamming, a fluid with iron particles on the order of 100 µm can be used in the MGP valve. While testing with these coarse-iron fluids, it was observed that a strong enough magnetic field could initiate controllable, and reversible, jamming in the valve. This type of controlled jamming was identified as the MGP jamming mode.

Preliminary studies with an MGP valve identified two modes of control—the pinch mode, and the reversible jamming mode. The details of each mode will be highlighted below, along with supporting experimental data.

3. Experimental investigation

An MGP valve was built to evaluate the controllability of this novel valve design. A piston driven rheometer was used to drive fluid through the valve. Several fluids of varying concentrations and particle size distributions were tested. Experimental testing identified two modes of control for the MGP valve—pinch mode, and jamming mode.

3.1. Pinch Mode

The MGP pinch mode is a continuously variable control mode in which the application of a magnetic field changes the effective diameter of the MGP orifice. As indicated in figure 3, a magnetic field mediated change in effective orifice diameter will change the slope of the pressure/velocity relationship. This relationship can be approximated by the Wuest equation for flow through a sharp
edged orifice [2]. This type of control is unique to MGP valves and is very different from the normal MR fluid case where the slope remains constant.

\[ P = \frac{50.4\eta Q}{\pi D_{eff}^3} (H) \]

Figure 3. Magnetic Gradient Pinch valve illustrating the MGP pinch mode (left) and the resulting pressure profile (right). \( P \) is pressure, \( \eta \) is viscosity, \( Q \) is flow rate, \( D \) is diameter, \( H \) is field strength.

Preliminary experiments conducted on an MGP valve and have validated the MGP pinch effect. As shown in figure 4, the slope of the pressure versus flow rate curve increases as applied field increases, indicative of a change in the effective diameter of the flow orifice. To quantify the pinch effect, the data is curve fit and the slope is extracted from each curve. From the slope of each curve, and the nominal valve geometry, an effective diameter can be found. As shown in figure 4 (right), the increase in slope corresponds to a reduction in effective diameter of greater than 50% from the off-state to the 3000 mA test.

Figure 4. MGP pinch effect showing slope increase (left) and reduction in effective diameter (right).

3.2. Jamming Mode
Another MGP operating mode was discovered while testing with a coarse-particle MR fluid. It appeared that a strong enough magnetic field could initiate jamming in the valve. At a critical field strength, the granular nature of the coarse-particle fluid would set up a jam in the valve causing the pressure to climb quite suddenly as illustrated in figure 5. We normally make every effort to avoid jamming in conventional MR fluid devices because it is normally irreversible. An exciting feature of the MGP valve is that jamming is indeed reversible. Once the magnetic field is removed, fluid flow resumes and the pressure drops. This reversible jamming concept appears to be a completely new operating regime for MR fluids and devices.

Figure 5. MGP reversible jamming mode.
The MGP reversible jamming mode has been studied with fluids which contain relatively large iron particles. Unlike the very narrow rectangular flow channel of a normal MR fluid valve, the MGP valve is a relatively large circular aperture through which large particles can easily pass. Particle sizes ranged from 45–150 microns. Fluid was passed through the valve at various operating currents while the pressure was monitored. At some critical field strength, the measured pressure climbed suddenly indicating that the valve had jammed. Figure 6 shows the peak pressure measured during the experiment versus the applied current. For low currents (i.e. less than 700 mA) the pressure remains relatively low; once the current reaches 700 mA, the pressure peaks to 20 MPa (nearly 3000 psi). The pressures observed in the MGP valve operating in the jamming mode are an order of magnitude higher than pressures normally observed in ordinary MR valves.

Figure 6. Sudden onset of jamming at critical field strength.

4. Discussion

The Magnetic Gradient Pinch valve is a novel MR fluid valve that may expand the solution space for MR technology. This study has presented evidence of new functionality through the two identified modes—pinch mode and reversible jamming mode. A particularly advantageous feature of the circular MGP valve compared to a normal MR fluid valve is the potential to have a much lower viscous off-state. The viscous flow loss of a single 2 mm MGP orifice is considerably smaller than the flow loss experienced with the narrow gap (~0.5 mm) found in many MR fluid valves. This may be paradigm shifting with regard to desirable or necessary fluid properties.

The MGP jamming mode represents a significant leap in functionality for MR technology. Jamming has historically been considered a significant problem in ordinary MR valves because jamming in such valves is often irreversible and leads to poor device performance. However, with the MGP valve, jamming reversibility has been validated and this mode of control may provide solutions to challenges unmet by conventional MR technology. Many applications may benefit from the truly enormous pressures achievable with the MGP jamming mode. Such applications may include small, high-force devices or controllable locking devices. Another key benefit of the MGP jamming mode is that it may enable the use of extremely low cost iron powder in MR fluids. Coarse, water-atomized iron particles have been shown to perform well in the MGP jamming mode.

References
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