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DESIGN AND PERFORMANCE OF A MR TORQUE TRANSFER DEVICE

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Abstract

Magnetorheological (MR) fluids possess the unique ability to undergo dramatic and nearly completely reversible changes in their rheological properties under the application of a magnetic field. These controllable fluids can serve as quiet, rapid interfaces between electronic controls and mechanical systems. One area of application is to use these fluids in torque transfer devices, such as clutches and brakes. After determining MR fluid properties and behavior using a rheometer, a parallel disk type MR clutch was successfully developed, which utilized a stationary electromagnetic coil. Finite element analysis was used to design the coil and clutch assembly in order to maximize the magnetic field generated within the MR fluid. The resulting magnetic field was uniform over the active portion of the clutch, easily controllable by adjusting the current passing through the coil, and provided a large range of field strength values. The experimentally measured output torque was generally in good agreement with predicted values. This work details the design considerations and methodology used to develop this clutch, which can be extended to the design of other MR devices.

Keywords: magnetorheological (MR) fluid, clutch, torque prediction.

1 Introduction

Magnetorheological (MR) fluids typically consist of micron-sized polarizable particles such as iron dispersed in a polar or nonpolar liquid along with surfactants to prevent sedimentation. Applying a magnetic field to these fluids causes reversible changes in their rheological properties within milliseconds. These changes are related to the increase in their strength by developing a yield stress. In this way, these fluids are said to behave as a Bingham solid; that is, they behave like a solid until the applied shear stress becomes equal to the yield stress, which marks the onset of flow. The electric analogs of MR fluids are electrorheological (ER) fluids, which are qualitatively similar.

Because of their rapid response, these controllable fluids can serve as quiet, rapid interfaces between electronic controls and mechanical systems. Some areas of applications include shock absorbers, clutches, brakes, engine mounts and active vibration control. Progress in developing such applications has been hampered due to a limited understanding of the fluid behavior under dynamic operating conditions. A good MR device simulation should be able to describe changes in the properties of the MR fluid as a function of time, shear rate, magnetic field strength and geometry.

Many researchers have studied ER and MR fluids under dynamic conditions. Henley and Filisko (1999) studied the structure of an ER fluid with an applied electric field while simultaneously undergoing shear. They investigated the three configurations of fluid being sheared between parallel plates, parallel disks, and concentric cylinders. The particles organized into tight packed lamellar formations resembling walls between parallel plates, cylinders between parallel disks, and disks between concentric cylinders. Tang et al. (1998) also reported a field-induced structure of layered rings for ER fluids being sheared between two parallel plate disks. The higher the applied field and the lower the rotating speed, the more rings there were. Vieira et al. (2000) studied the transient behavior of the shear stress and of the structure of ER fluids under both shear and electric fields. The ER fluids were sheared at constant shear rates for up to three and a half hours, and changes in the lamellar ring formations were considered to be responsible for the changes in the shear stress. Pompeo Neto et al. (2001) demonstrated experimentally how the apparent viscosity of an ER fluid

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changed with time and proposed a governing equation to predict this time variation. Cutillas and Bossis (1997) compared structures induced by an oscillating shear flow in ER and MR fluids. Under large enough strains, parallel structures of stripes in the velocity direction were observed in both types of fluids. Volkova et al. (1999) studied structures obtained in MR suspensions. Under a constant field and steady shear flow, no structure was observed until the critical strain rate of 60 s^{-1}, when there was the onset of a layered structure and a sudden jump in shear stress. Martin (2000) conducted extensive dynamic simulations of electrorheology and magnetorheology to predict the evolution of 10,000 particle systems over short times. In steady shear a striped phase readily formed under an applied field for large strain rates.

Several authors have discussed the performance of various ER clutches, such as Whittle et al. (1995), Johnson et al. (1999), Tan et al. (2002) and Nakamura et al. (2002). Choi et al. (2000) designed and built ER and MR disk type clutches to compare their performance. They derived a nondimensional model to predict the torque developed assuming each fluid behaved as a Bingham plastic. They also demonstrated the long term torque controllability of the clutches using a PID controller. Lampe et al. (1998) used the Bingham plastic model to derive equations for the transmitted torque in MR clutches of two different geometries, i.e. parallel disks and concentric cylinders. They also designed and tested a MR clutch using a dihedral disk shape. Lee et al. (2000) studied a concentric cylinders MR clutch by taking into consideration nonuniform magnetic fields and complicated fluid flows.

This paper discusses MR fluid behavior under high shear rates and high magnetic fields over long time periods. Rheological tests were performed to measure MR fluid properties and to gain a better understanding of the fluid behavior under the conditions listed above. These results were then used to better predict the output torque of a parallel disk type MR torque transfer device.

2 Rheometer Testing

Although rheometers equipped to test MR fluids can presently be purchased, it was more cost effective to modify one that was readily available to the researchers. Also, the knowledge and experience thus gained aided in the later design of the torque transfer device. The rheometer model RDA III from Rheometric Scientific, was modified in order to be able to apply a magnetic field within the MR fluid. A test fixture was designed using a parallel plates configuration. The lower shaft and plate consisted of a steel shell surrounding an electromagnetic coil. The upper plate was also made of steel and attached to the existing upper shaft. A steel lid completed the enclosure, which directed the magnetic field to the MR fluid placed in between the plate and the flat surface at the center of the steel shell. A wall around the lower plate prevented fluid leakage. Since the test fixture rotated, current was supplied to the coil through blades rubbing against copper contact rings placed around the lower shaft. Finally, a support fixture was made identical to the fixture of the existing lower shaft so that the new test fixture could be properly clamped into the base of the rheometer. A photograph of the assembled MR test fixture is shown in Fig. 1. All steel parts were made of low carbon AISI 1018 steel. The low carbon content makes it a soft magnetic material, which is desirable to minimize the residual magnetism in the steel when the applied field is removed.

A finite element package, Maxwell 2D Field Simulator from Ansoft Corp., was used to simulate the magnetic field strength. The electromagnetic coil generated a magnetic field up to 0.4 T, which was nearly uniform from the center of the plate to the outer edge. The power consumed to generate this magnetic field was calculated to be 13 W for a current level of 2.23 A. The resistance in the coil wire was measured to be 2.6 Ω. The magnetic field inside the test fixture was measured (with the upper plate removed to allow probe access) using a F.W. Bell model 5070 gauss/tesla meter, and the values were found to be in good agreement with the results of a corresponding finite element model.

Fig. 1: *Rheometer retrofitted with new MR test fixture.*

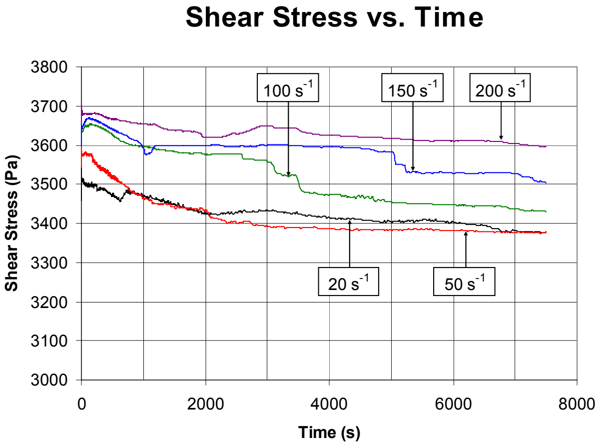

Fig. 2: *Shear stress vs. time for B = 0.1 T.*

An oil-based MR fluid, MRF-132LD from Lord Corp., was tested in the rheometer for about two hours duration at constant shear rates up to 200 s^{-1}, as measured at the outer radius, and for magnetic fields between 0.1-0.4 T. The gap between the disks was set at

0.8 mm (0.03 in.). After the fluid was placed in the test fixture, a magnetic field of 0.4 *T* was applied for two minutes at the beginning of each experiment, then the current was adjusted to provide the level of magnetic field at which the test would be run. This was done to ensure the same initial condition for each test. Figures 2-5 show the shear stress versus time for various shear rates and magnetic fields.

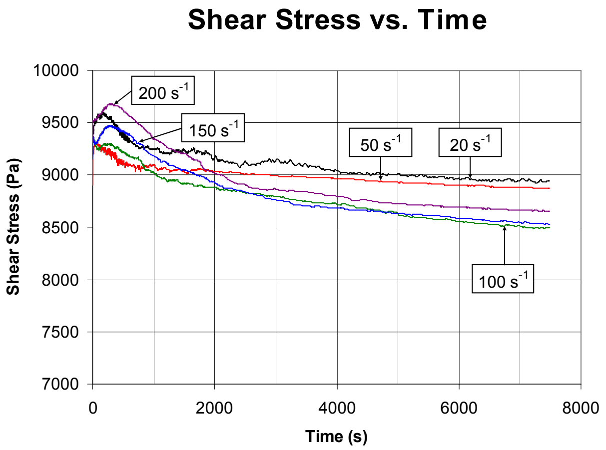

Fig. 3: *Shear stress vs. time for* $B = 0.2$ *T.*

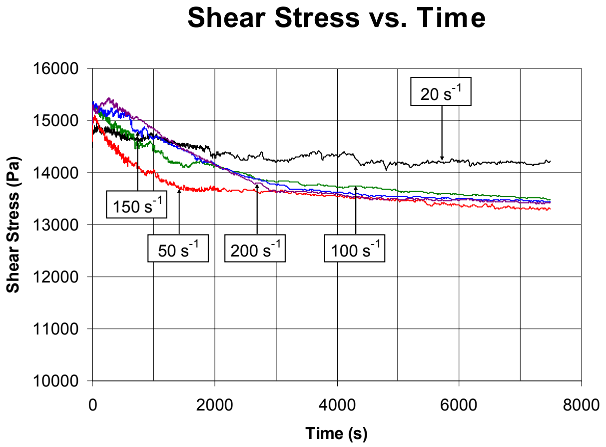

Fig. 4: *Shear stress vs. time for* $B = 0.3$ *T.*

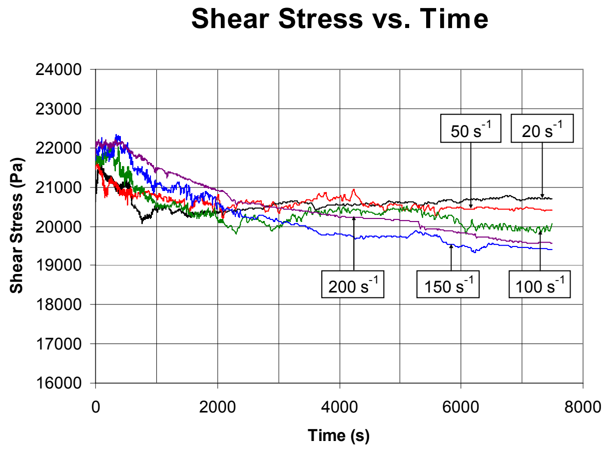

Fig. 5: *Shear stress vs. time for* $B = 0.4$ *T.*

Although the shear stress showed an initial increase for higher shear rates at magnetic fields of 0.2 *T* and 0.3 T, it appears to display an overall decrease with time for all magnetic fields and shear rates at which the MR fluid was tested. One of the possible reasons for this may be seen in Figs. 6 and 7, which are pictures of the lower and upper plates of the test fixture, respectively, after the completion of a test at a magnetic field of 0.1 *T* and a shear rate of 150 s^{-1}. There is a clear ring around the outside edges of the plates that indicates an almost total absence of iron particles in this area. One explanation for this occurrence is that the chains of particles forming the field induced structure were twisted around the center of the plates due to the rotational motion and tended to gather inward. Another explanation could be that the oil in the fluid was thrown outward due to centrifugal forces while the particles moved inward to fill the vacated volume, since the magnetic field held the particles between the disks. One or both of these phenomena decreased the effective area being sheared, hence decreasing the measured shear stress.

For magnetic fields of 0.2 *T* and above there also appeared to be separation between the oil and the particles, as previously reported by this research group in Ciocanel et al. (2004, 2006) and Molyet et al. (2005). A third contribution to the decreased shear stress is that the oil may have acted as a lubricant between the rotating disk and the particles. This leads to an apparent wall slip effect, which is well known (Yoshimura and Prud'homme, 1988). In general, the amount of separation increased with increasing magnetic fields and shear rates.

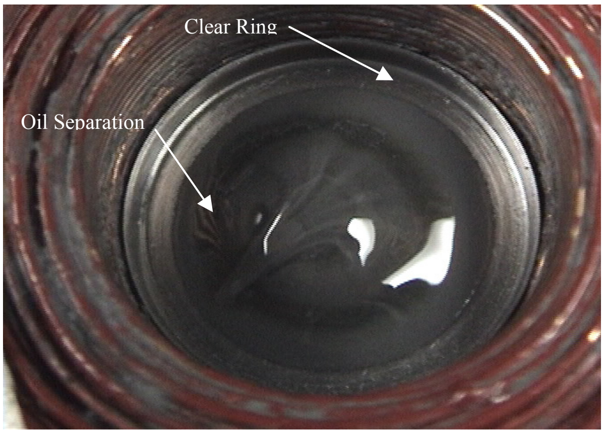

Fig. 6: *Lower plate for* $B = 0.1\ T$, $\dot{\gamma} = 150\ s^{-1}$.

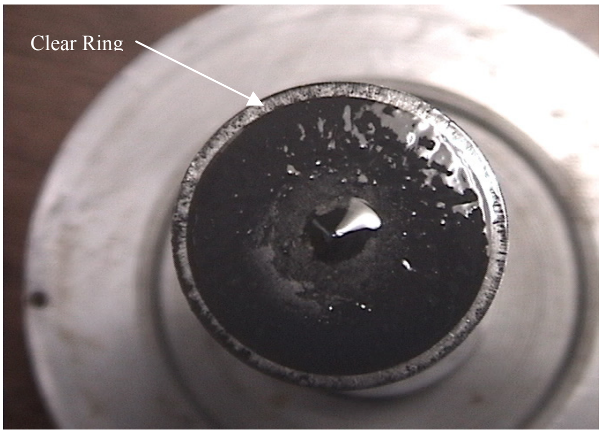

Fig. 7: *Upper plate for* $B = 0.1\ T$, $\dot{\gamma} = 150\ s^{-1}$.

Only at a magnetic field of 0.4 *T* were ring formations observed, as reported elsewhere in the literature. Figures 8 and 9 show the lower and upper plates, respectively, after a test conducted at a magnetic field of 0.4 *T* and a shear rate of 20 s^{-1}. The upper plate clearly shows alternating dark-colored and light-colored rings, with the absence of particles in the lighter rings.

Fig. 8: *Lower plate for* $B = 0.4\ T,\ \dot{\gamma} = 20\ s^{-1}$.

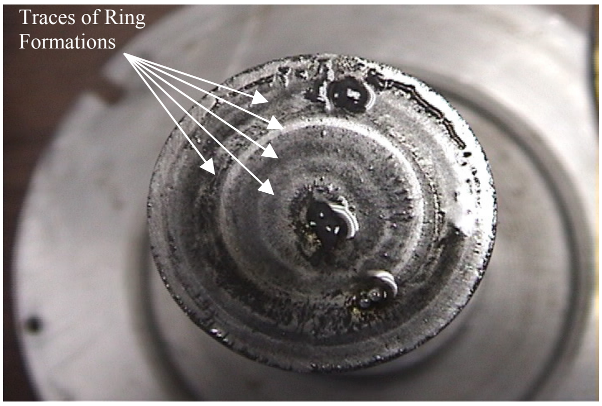

Fig. 9: *Upper plate for* $B = 0.4\ T,\ \dot{\gamma} = 20\ s^{-1}$.

The yield stress of the MR fluid was estimated using data taken from tests conducted at a shear rate of 1 s^{-1}. The shear stress data taken during the last hour of each test was averaged to determine the steady state yield stress, and these values are shown in Table 1 at each magnetic field tested. The zero field viscosity was measured to be 0.234 Pa·s ($3.39\text{x}10^{-5}$ lb·s/in^2). These properties are necessary for torque prediction, as derived in the next section. The design size (radius) of a torque transfer device can then be determined based on a desired output torque.

Table 1: Yield Stresses of MRF-132LD

Magnetic Field, T	Yield Stress, kPa (psi)
0.1	3.43 (0.497)
0.2	8.93 (1.30)
0.3	14.3 (2.08)
0.4	20.9 (3.03)

3 Torque Prediction

The torque generated by shearing MR or ER fluids in the gap between two parallel disks can be predicted (Choi et al., 2000; Lampe et al., 1998) by using the well known Bingham plastic model:

$$\tau = \tau_y + \eta\dot{\gamma} \tag{1}$$

where τ is the shear stress, τ_y is the field dependent yield stress which marks the onset of flow, η is the viscosity, and $\dot{\gamma}$ is the shear rate. Assuming a linear velocity distribution in the fluid between the disks (Fig. 10), the shear strain rate can be written as:

$$\dot{\gamma} = \frac{dV}{dz} = \frac{(\omega_2 - \omega_1)r}{s} \tag{2}$$

where ω_1 and ω_2 are the angular velocities of the disks, r is the radial distance from the center, and s is the distance between the disks. Substituting Eq. 2 into Eq. 1 results in:

$$\tau = \tau_y + \eta\left[\frac{(\omega_2 - \omega_1)r}{s}\right] \tag{3}$$

The torque transmitted by a differential area of the disks can be written as:

$$dT = 2\pi\tau r^2 dr \tag{4}$$

Substituting Eq. 3 into Eq. 4 and integrating from R_i to R_o, the inside and outside radius, respectively, results in:

$$T = \frac{2}{3}\pi\tau_y\left(R_o^3 - R_i^3\right) + \frac{\pi\eta}{2}\left[\frac{(\omega_2 - \omega_1)}{s}\right]\left(R_o^4 - R_i^4\right) \tag{5}$$

Equation 5 can be used to predict the output torque in a MR torque transfer device of parallel disk configuration, the design of which will be discussed next.

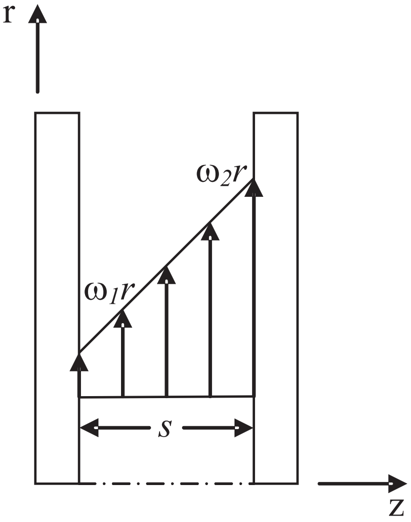

Fig. 10: *Assumed velocity distribution between two rotating disks.*

4 Design of MR Torque Transfer Device

A parallel disk type MR torque transfer device that can function as a clutch or brake was designed and built (Molyet et al., 2005). Some of the design criteria included being able to apply a uniform magnetic field adjustable up to a value of 0.4 *T*, to vary the input rotational speed, to measure the input power, and to measure the input and output speed and output torque of the device.

As shown in Fig. 11, the clutch consisted of an outer disk/housing assembly made of two halves which were bolted together. A rubber o-ring was placed in the groove between the two halves to form a seal against leakage of the MR fluid inside. The 60 mm (2.36 in.) diameter inner disk fit inside the outer disk/housing assembly with a 1 mm (0.039 in.) gap on either side for the MR fluid. An oil seal was placed in the outer housing to prevent fluid leakage along the inner disk shaft, and also a sealed radial bearing to allow relative motion between the inner and outer disks. The outer disk/housing is the input side and the inner disk is the output side.

Also shown in Fig. 11, a stationary electromagnetic coil was placed around the outside of the clutch with a steel shell enclosure to direct the magnetic field to the clutch. Gaps of 1.59 mm (0.0625 in.) separated the steel shell from the clutch on either side. The inner disk and a portion of the outer disk/housing were made of AISI 1018 steel while the rest of the outer disk/housing was made of aluminum, which direct the magnetic flux from the coil enclosure to the steel portions of the clutch, maximizing the magnetic field strength applied to the MR fluid inside. The magnetic field is concentrated on the outer section of the inner disk, which is the active portion of the clutch. This section has an outer radius of 30 mm (1.18 in.) and an inner radius of 14.3 mm (0.5625 in.).

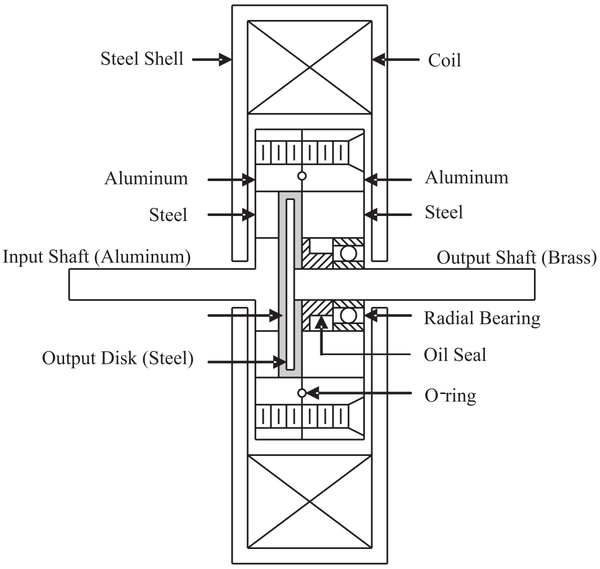

Fig. 11: *Clutch assembly and electromagnetic coil arrangement.*

The electromagnetic coil was made with 480 turns of 18 gauge copper wire, and fit inside a shell made of AISI 1018 steel. Finite element analysis was used to design the coil and clutch assembly and to determine the magnetic field strength. Figure 12 shows the magnetic field strength distribution calculated by the Maxwell software using an axisymmetric model with 2.82 A of current, giving a magnetic field strength in the fluid of about 0.4 Tesla. Figure 13 shows the radial magnetic field distribution in each of the MR fluid gaps, which are very uniform along the active portions of the disk, with a value of about 0.384 *T* for the fluid gap on the input side of the clutch, and a constant 0.4 *T* for the fluid gap on the output side of the clutch. The resistance in the wire was measured to be 4.3 Ω, and the power consumed at 2.82 A is calculated to be 34.2 watts. The magnetic field generated within the coil/shell arrangement was measured (without the clutch parts to allow probe access) and found to be in good agreement with a corresponding finite element model, verifying the validity of this simulation as well.

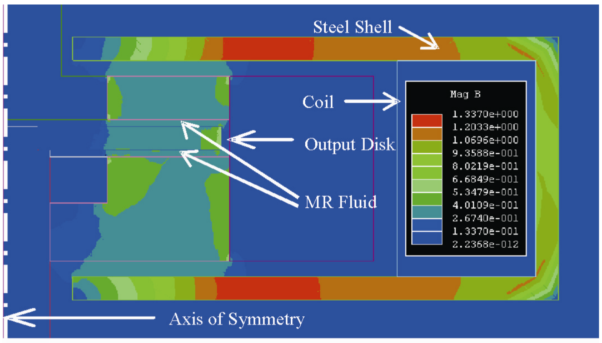

Fig. 12*:* *Axisymmetric model of magnetic field distribution (Tesla) in clutch electromagnetic coil arrangement with 2.82 A.*

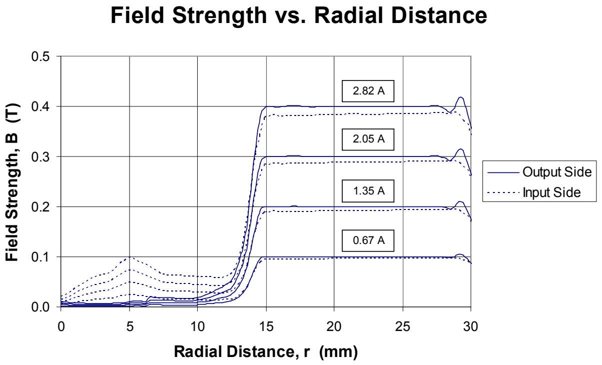

Fig. 13: *Magnetic field distribution within each MR fluid gap in clutch for various current values.*

Figure 14 shows the overall experimental setup. The clutch is placed inside the electromagnetic coil, and each shaft of the clutch assembly is supported by pillow block bearings, which are mounted on aluminum blocks. A small variable speed DC motor is used to drive the clutch. A DC power supply, model ATE 15 - 15M from Kepco Corp., with a voltage capacity of 20 V and a current capacity of 15 A, supplies power to the electromagnetic coil. A rotating torque transducer from Cooper Instruments & Systems is connected to the output shaft to measure the torque developed by the clutch, and is connected to a computer to monitor and store the data using LabView software from the National Instruments Corp. A digital encoder from the US Digital Corp. is also connected to the output shaft to measure the rotational speed of the output shaft and send the data to the computer. The speed of the input shaft is measured with a hand-held optical tachometer. The voltage and current used by the motor is measured and sent to the computer through the LabView data acquisition system so the input power can be recorded. A variable prony brake, which is a simple friction device, is used to simulate loading of the device. The prony brake consists of a 101.6 mm (4 in.) diameter aluminum disk with an adjustable leather belt rubbing against it to provide friction.

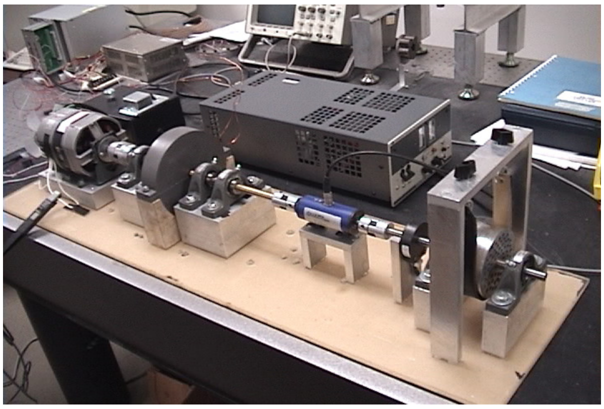

Fig. 14: *Experimental clutch setup.*

The torque transfer device was tested by using it in brake mode, with the prony brake tightened to prevent motion of the output shaft. MRF-132LD, the same fluid used in the rheometer experiments, was used in the device. Experiments were run at various constant speeds between 250-1500 rpm and magnetic fields of 0.1, 0.2 and 0.3 *T*. At the beginning of each test, the motor was turned on and set to a constant speed, then the power supply to the electromagnetic coil was turned on, with the current preset to provide a given level of magnetic field. Torque readings were measured and recorded once per second for one minute, and an average was taken. These results are plotted in Fig. 15, along with the predicted output torque calculated by applying Eq. 5 to each of the two MR fluid-filled gaps inside the device. Since the rheometer tests indicated that the effective area decreases for the MR fluid under shear, an effective outer radius of 27 mm (1.06 in.) instead of the actual outer radius of 30 mm (1.18 in.) was used in Eq. 5. The percent differences between the measured and predicted torque values for 0.2 *T* and 0.3 *T* were under 10%, while for 0.1 *T* there was about a 25 - 30 % difference.

5 Conclusions

New insights were gained into MR fluid behavior under dynamic operating conditions over long time periods from the rheometer experiments. The fluid experienced separation and a decrease in the effective shearing area in the parallel plate configuration that it was tested under. Other configurations, such as cone-plate or concentric cylinders, may provide different results.

A parallel disk type MR torque transfer device, which could function as a clutch or a brake, was successfully designed, built and operated. The magnetic field was concentrated on the outer sections of the parallel disks, which was done for two reasons: first, to concentrate the magnetic flux through a smaller area, which provides a larger magnetic field for a given amount of current, thus reducing power requirements; second, more torque is developed at points further away from the disk center. The output torque was reasonably predicted using the Bingham plastic model and a decreased effective radius, due to the decrease in the effective shearing area observed in the rheometer experiments. Since the actual effective radius of the fluid inside the device cannot be determined, as a first approximation the same effective radius was assumed for all three magnetic field strengths tested, which could explain why the percent differences at B = 0.1 *T* were much larger than the others.

The influence of temperature on the MR fluid was not considered in this research. Although the temperature of the upper plate was monitored during the rheometer testing, the only significant increase in temperature occurred at a magnetic field of 0.4 *T*, which was due to excessive heat from the electromagnetic coil. Since the maximum magnetic field applied to the MR clutch was 0.3 *T* and it was only operated for one minute at a time, temperature effects were assumed to be negligible. Temperature effects on fluid properties should be considered in future research, particularly when the fluid is exposed to high magnetic fields, high shear rates and long duration shearing.

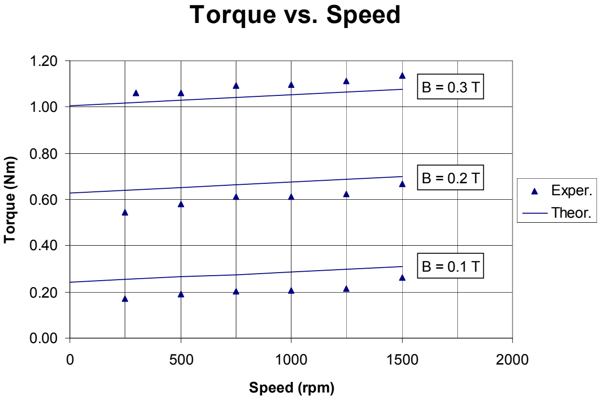

Fig. 15: *Comparison of predicted and measured output torques.*

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Nomenclature

B	magnetic field	(T)
R_i	disk inner radius	(m)
R_o	disk outer radius	(m)
r	radial distance	(m)
s	gap between disks	(m)
T	torque	(N·m)
V	velocity	(m/s)
$\dot{\gamma}$	shear rate	(s^{-1})
η	viscosity	(Pa·s)
τ	shear stress	(Pa)
τ_y	yield shear stress	(Pa)
ω_1	disk 1 angular velocity	(rad/s)
ω_2	disk 2 angular velocity	(rad/s)

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