DESIGN ANALYSIS AND CONTROL OF A MAGNETORHEOLOGICAL FLUID BASED TORQUE TRANSFER DEVICE

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Abstract

In this paper, a magnetorheological (MR) torque transfer device is presented. Design, modeling and control aspects are particularly emphasized. 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 as actuators. The MR torque transfer device proposed here can function as either a clutch or a brake. A model providing torque output as a function of magnetic field and rotational speed is proposed and verified experimentally. An acceptable correlation is found between model predictions and clutch performance. A PID controller is designed and experimentally evaluated. In the experimental control setup, the output variables are the position, velocity, and torque at the output shaft and the control input is the electromagnet current. The closed loop performance of the system was studied for torque regulation and torque tracking. Both regulation as well as tracking torque control were successfully achieved with this controller.

Keywords: magnetorheological (MR) fluid, clutch, control

1 Introduction

A torque transfer device is commonly used to transfer rotating energy between two mechanical components. Torque transfer devices mostly are based on friction. Wear, variable loading, engagement shocks, and temperature variations represent common phenomena that affect the performance and life of the device. In an attempt to eliminate the wear, engagement shock and variable loading during operation, a magnetorheological fluid based clutch is proposed. Magnetorheological (MR) fluids are suspensions of micron-sized iron particles dispersed in a 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 the fluid strength by developing a yield stress. MR fluids 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.

The idea of developing a fluid based torque transfer device, or clutch, has been explored by several researchers during the past decade. Early studies have focused on implementing ER fluids as the torque transfer element (Whittle et al., 1995), (Johnson et al., 1999), (Tan et al., 2002), (Nakamura et al., 2002) and (Brookfield et al., 1998), while more recently the attention has switched toward MR fluids (Choi et al., 2001), (Lampe et al., 1998), (Lee et al., 2000) and (Molyet et al., 2005). Unlike ER fluids, MR fluids can withstand higher torque and require lower voltage (and moderately large currents) to be activated. A disadvantage of using MR fluids is the added weight to the device due to the required electromagnets needed to activate the MR fluid. However, this can be minimized through appropriate design solutions for the magnetic circuit. In

This manuscript was received on 4 April 2008 and was accepted after revision for publication on 29 July 2008

addition, if the clutch is stationary, the performance is the critical design parameter not the weight.

The performance of a MR clutch can be enhanced by an adequate control strategy. To date, a closed loop proportional-integral-derivative (PID) controller has been explored for an ER clutch (Brookfield et al., 1998). This paper presents the design, modeling, and control of a MR fluid based parallel disk torque-transfer device, which can function as a clutch or brake. The theoretical predictions and experimental results are compared and sources of errors are discussed.

2 Design and Modelling

When designing with ER or MR fluids it becomes difficult to predict the system's output torque because of the many nonlinearities (fluid model, electromagnetic field distribution, etc.) associated with the system and because of the coupling between the electromagnetic effect and the fluid motion. A simplified approach to deriving the output torque is to assume that the fluid behaves as a Bingham plastic solution (Choi et al., 2001). Under this assumption, the equations for the transmitted torque in an MR clutch can be derived including the effect of the clutch geometry (Lampe et al., 1998), the magnetic field variations and complicated flow patterns (Lee et al., 2000).

2.1 Design

A parallel disk type MR fluid torque transfer device, that can function as a clutch or brake, was designed and built (Molyet et al., 2005). Special attention was given to the magnetic circuit that was designed to generate a uniform magnetic field, of up to 0.4 T, within the active MR fluid. In addition, an experimental setup was built to allow variable input rotational speed. The setup allows the measurement of the input power, the input and output speed, and the output torque of the device.

Figure 1 shows a cross section through the clutch. The output disk is 60 mm (2.36 in.) in diameter and fits inside the outer disk/housing assembly with a 1 mm (0.039 in.) gap on either side for the MR fluid. A stationary electromagnetic coil is placed around the clutch with a steel shell enclosure to direct the magnetic field to the active regions of the clutch. The electromagnetic coil has 480 turns of 18 gauge copper wire. Gaps of 1.59 mm (0.0625 in.) separate the steel shell from the clutch on either side.

It is important to notice that different materials were used to manufacture the clutch components. The output 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. This combination of materials was chosen to 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.).

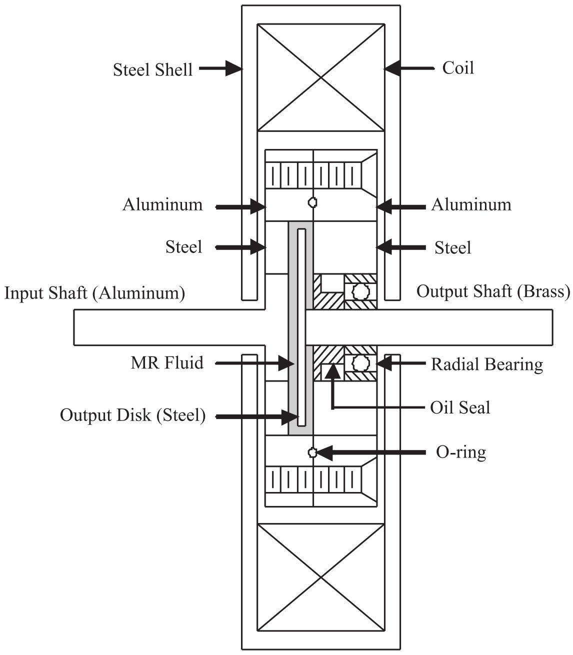

Fig. 1: *Cross section through the clutch assembly. The electromagnet is located on the outer circumference and is represented by a crossed box.*

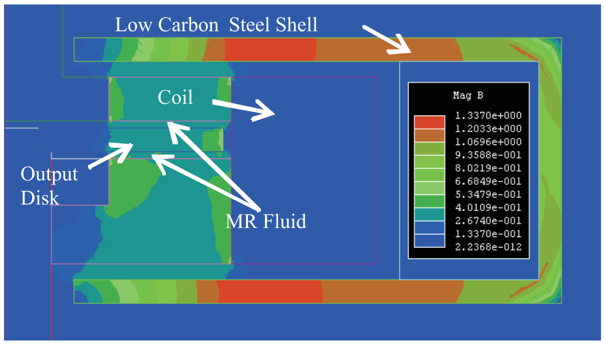

Fig. 2: *The magnetic flux density distribution (in Tesla) inside the axisymmetrical finite element model of the clutch for a current of 2.82 A passing through the coil*

The 2D magnetostatic module of the Maxwell finite element code was used to optimize the magnetic circuit. Figure 2 shows the magnetic flux density inside the axisymmetric model for a 2.82 A current. For this current, a magnetic flux density of about 0.4 Tesla was generated inside the MR fluid. Plots of the magnetic flux density along the radial direction in each of the MR fluid gaps are shown in Fig. 3. These plots indicate that the magnetic field is 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.

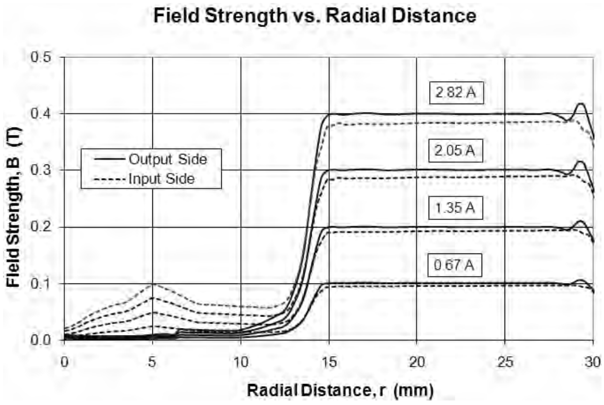

Fig. 3: *Magnetic flux density distribution within each MR fluid gap for various current values*

The actual torque transducer device and the experimental setup are shown in Fig. 4. The clutch is placed inside a steel housing 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 with a voltage capacity of 20 V and a current capacity of 15 A, supplies power to the electromagnetic coil. A rotating torque transducer 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. A digital encoder is also connected to the output shaft to measure the rotational speed of the output shaft. 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 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.

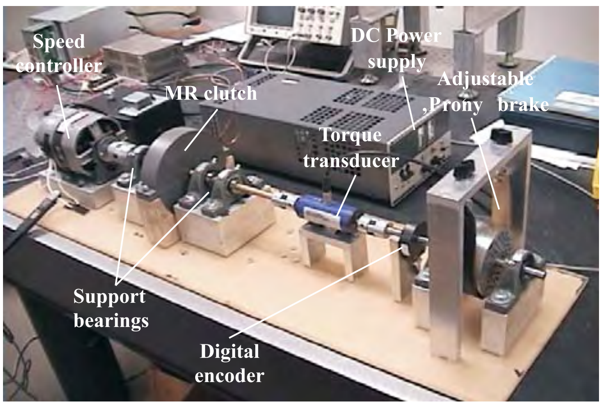

Fig. 4: *Experimental clutch setup*

The torque transfer device was tested by using it in brake mode, with the prony brake tightened to prevent motion of the output shaft. MR fluid MRF-132LD provided by Lord Corporation was used in the device. Experiments were run at various constant speeds between 250-1500 rpm and magnetic flux densities 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, and then the power supply to the electromagnetic coil was turned on, with the current preset to provide a given level of magnetic field. A dSPACE hardware-in-the-loop system is used to study the closed-loop torque-transfer behavior of the device.

2.2 Modelling

The torque generated by shearing the MR fluid between two parallel disks can be predicted by using the well-known Bingham plastic model and the schematic shown in Fig. 5:

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

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, 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.

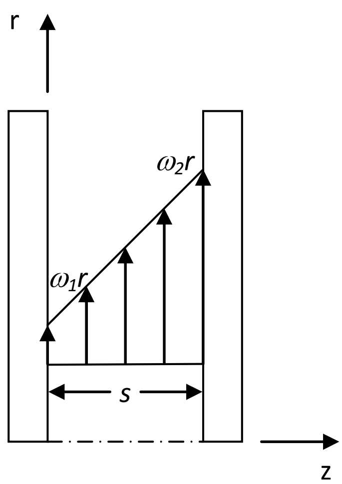

Fig. 5: *Assumed velocity distribution inside the fluid gaps*

When calculating the torque with Eq. 5 an effective outer radius of 27 mm instead of the actual outer radius of 30 mm (1.18 in.) was used based on experimental observations reported by (Molyet et al., 2006). Torque measurements were recorded once per second for one minute, and an average was taken. 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 30% difference. These results are plotted in Fig. 6, along with the predicted output torque calculated with Eq. 5 to each of the two MR fluid-filled gaps inside the device.

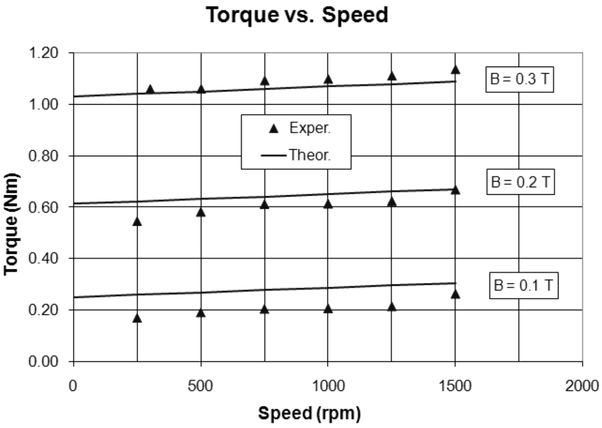

Fig. 6: *Comparison between the predicted and measured output torques*

3 Control Experiments

In order to demonstrate the controllability of the MR torque-transfer device, a PID controller was designed to regulate the output shaft torque. To this end, the measured torque is compared to the desired value in order to adjust the applied electric voltage to the electromagnet. The torque error is defined as the difference between the desired torque and the measured torque:

$$e = T_{\text{d}} - T \tag{6}$$

where τ and τ_d are the measured and desired torques, respectively. The PID controller adjusts the voltage to the electromagnet as:

$$U = [K_{\text{P}} + K_{\text{D}} s + \frac{K_{\text{I}}}{s}]e \tag{7}$$

Where K_{P}, K_{D} and K_{I} are the proportional, derivative, and integral control gains, respectively. This section presents the results from the control experiments with both constant as well as variable desired torques. The controller was developed in Simulink and was implemented with the dSPACE control solution.

Figures 7 through 12 illustrate the closed-loop torque transfer performance of the device. In the experimental results shown in Fig. 7 and 8, the desired torque varies from 0.1 Nm to 1 Nm. The controller gains for these experiments are shown in Table 1. It can be seen that the performance of the system depends on both the desired torque as well as the controller gains. In other words, the regulation performance of the PID controller is acceptable for certain set-points. However, the performance deteriorates for other desired torques. Figure 9 further illustrates the effect of controller gains on the regulation performance of the device. In this experiment, the desired torque is maintained at 0.6 Nm.

Table 1: PID controller gain for the regulation torque-transfer experiments

Controller	K_P	K_D	K_I
Fig. 7	0.1	0.1	0.1
Fig. 8	0.5	0.1	0.2

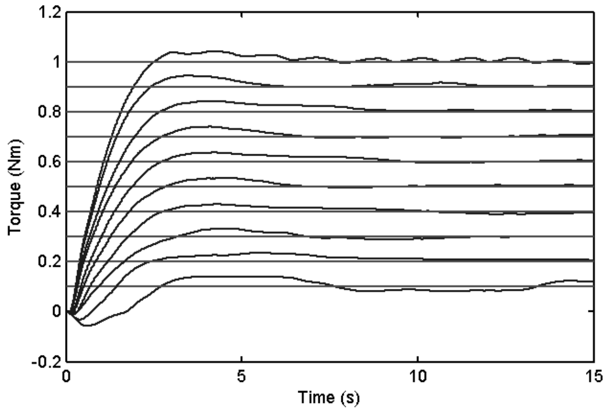

Fig. 7: *Close-loop performance of the MR clutch in regulating the output torque*

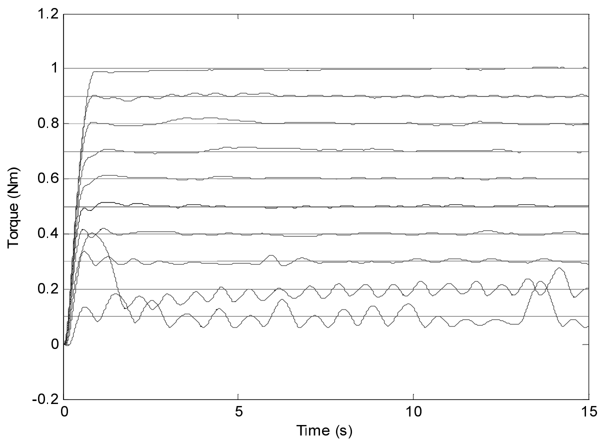

Fig. 8: *Close-loop performance of the MR clutch in regulatng the output torque with the updated controller gains*

Figure 10 represents a tracking control experiment. In this experiment, the torque transfer device is to follow a user-defined desired torque profile. Similar results are shown in Fig. 11, where the desired torque profile is a sinusoidal function. It can be seen that the tracking performance of the device is frequency dependent. That is, the tracking error is larger for higher frequencies.

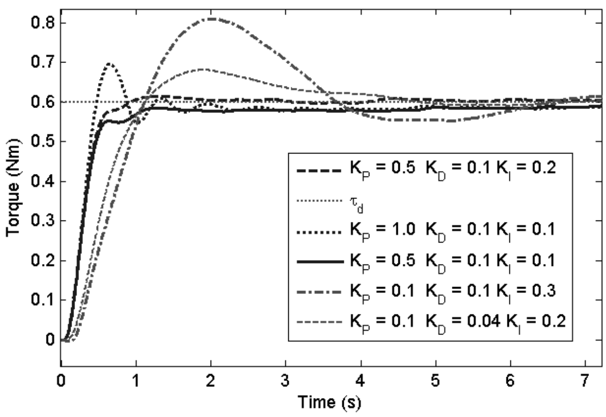

Fig. 9: *Effect of controller gains on the close-loop performance of the MR clutch*

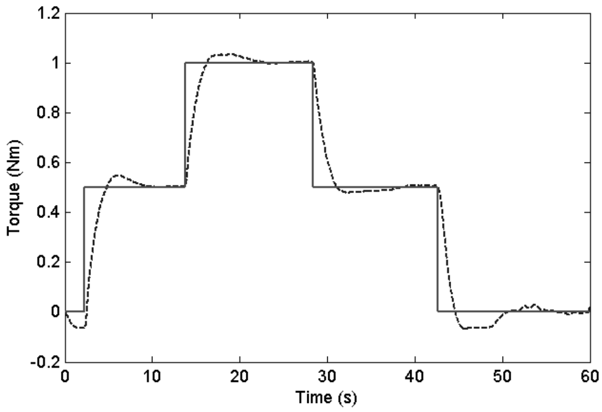

Fig. 10: *Close-loop performance of the MR clutch in following torque command*

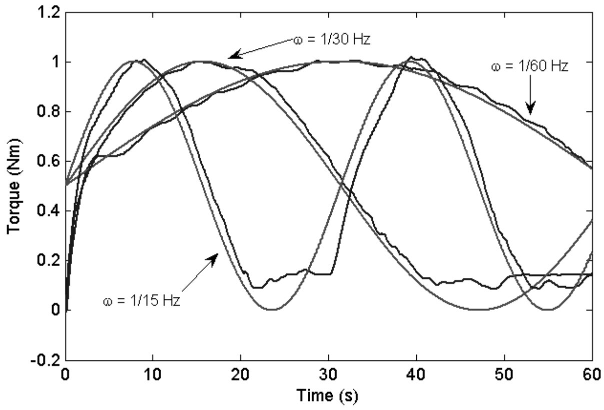

Fig. 11: *Close-loop performance of the MR clutch in following sinusoidal commands*

For all the experiments, the measured signal of the torque transducer was filtered for high frequency noise. It is essential to remove the high-frequency noise in order to improve the quality of the control results. High frequency noise, for example, is amplified through the derivative element of the PID controller, which leads to large high-frequency control input (to the electromagnet). To this end an analog second order low pass Bessel filter was used. The pass-band edge-frequency of the filter is 20 Hz. The sampling time of 0.05 seconds was chosen for all the experiments. Figure 12 illustrates the measured torque and the filtered signal for a tracking control experiment.

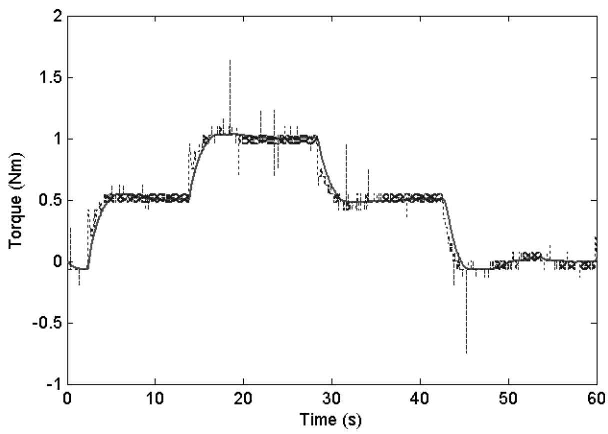

Fig. 12: *Filtering of the measured torque output of the MR*

Conclusion

Torque transfer devices are an essential part of variety of electromechanical/robotics systems. It was shown in this paper that MR fluid-based torque transfer devices can be analyzed and designed based on material behavior models. A model for predicting the transferred torque for a MR clutch was developed. This model was experimentally verified and acceptable correlation between the model prediction and the clutch performance was established. Furthermore, controllability of a MR clutch was experimentally demonstrated. A PID controller was designed to regulate the transferred torque. Both regulation as well as tracking torque control was successfully achieved with this controller. Based on the experimental results, however, it is evident that there is a need for more advanced control methods. These controllers will provide robust torque transfer behavior over a wide range of working conditions and for a range of desired torques.

Future work should consider the thermal and hysteresis effects on the response of the clutch and the coupling between the electromagnetic effect and the MR fluid motion model. Furthermore, the inherent slipping at the beginning of the coupling stage needs to be accounted for as well.

Nomenclature

e	torque error	N·m
K_D	derivative control gain	V·s/(N·m)
K_I	integral control gain	V/(N·m·s)
K_P	proportional control gain	V·s/(N·m)
r	radial distance	m
R_i	inner radius	m
R_o	outer radius	m
s	distance between the rotating disks	m
T	torque	N·m
U	applied voltage	V
V	fluid's linear velocity	m/s
z	z space coordinate	
η	dynamic viscosity of the MR fluid	N·s/m^2
$\dot{\gamma}$	shear rate	1/s
τ	shear stress	N/m^2
τ_y	magnetic field dependent yield stress	N/m^2
$\omega_{1,2}$	angular velocities of the disks that shear the MR fluid	rad/s

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