Design of a novel magnetorheological transmission device

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Abstract—This paper presents a new approach in the design of a novel magnetorheological transmission device (MRTD) that employs electromagnetic coil as a part of the stator. MRTD is a torque transmission device which uses magnetorheological fluid (MR fluid) as the transmission medium. MRTD can provide controllable torque and speed by adjusting the external applied magnetic field. The novel MRTD operates under the combination of shear-squeeze mode of MR fluid, which improves the working performance and reduces the adverse effect of centrifugal force. In this study, modes of operation of MR fluids and design parameters of MRTD were described briefly. Next, the material selection was specified, magnetic circuit was conducted, as well as the theoretical torque of MRTD. Finite element analysis was created solving the total magnetic flux density within the MRTD. A prototype MRTD was fabricated, its transmission characteristics were analysed, which mainly included torque transmission and speed control analysis. The results show that torque increases gradually as the current increases, and torque is linear with respect to the input current. The output speed increases significantly with steps of (0.10 A) increment. With further increase, the MRTD can reach synchronous speed. The MRTD shows excellent performance for various application.

1. INTRODUCTION
Magnetorheological fluid (MRF, or MR fluid) is a smart material composed of micron-sized ferromagnetic particles dispersed in a carrier fluid. Under the application of an external magnetic field the rheological properties of MR fluid change. MR fluid translates from a free flow state into a semi-solid state with a high shear stress. The change in rheological property is continuous and highly reversible. MR fluids have an extensive range of working temperature which typically ranges from (-40°C – 150°C) providing simple, quiet and rapid response. These characteristics make MR fluid very attractive for various application. Magnetorheological fluid research is credited to Jacob Rabinow in 1948 [1-3]. The main aim of this project is to fabricate a reliable and competitive MRTD that can transfer controllable torque and speed by adjusting the excitation current. Within the main objective, this paper has the following sub-objectives:

- Create a finite element model of the MRTD that simulates its transmission behavior.
- Selection of proper materials for the MRTD with adequate structural and magnetic properties.
- Detailed design of MRTD with considerations to magnetic circuit path, and validation of the finite element simulations with the manufactured prototype.
2. Modes of Operation of Magnetorheological Fluids
MR fluids have three main modes of operation, which are squeeze mode, valve mode and shear mode, respectively. MR fluid can be used in any of the distinct modes or a combination of two operating modes. The novel MRTD introduced in this paper operates under the combination of shear-squeeze mode. In shear mode, the fluid is located between a pair of moving parts. The relative displacement is parallel to the poles. The apparent viscosity, and thus the drag force applied by the fluid to the moving surfaces can be controlled by modifying the magnetic field. As the magnetic field is applied, the iron particles line up in the direction of the applied magnetic field and form chains. These chains increase the resistance of MR fluid to flow. In shear mode these chains break and reform continuously, resulting in the limitation of torque under yield stress. While in squeeze mode, these chains break and form shorter and thicker chains which are more difficult to break. This causes more flow resistance in squeeze mode than shear mode [4-6].

3. Description of Magnetorheological Transmission Device
MRTD is composed of a stator and rotor.

3.1. Stator’s structure
Stator comprises a base, which supports the whole structure, housing, bearings, electromagnetic coil wire wound around a magnetic material (yoke). Stator is built in a way that it could support the rotor through housing and bearings. In design of conventional devices, coil is often limited due to the geometrical constrain. In the case of the MRTD introduced in this paper, coil is a part of the stator. This makes it flexible and customizable in terms of space usage for yoke and winding design.

3.2. Rotor’s structure
Rotor consists of an input shaft, bearings, seals, magnetic materials, output shaft and other nonmagnetic materials. The input shaft is supported by bearings and powered by an external electric motor which drives the output shaft through MR fluid.
3.3. Material selection
Materials used in MR fluid-based systems have a critical influence in magnetic field. The flow of magnetic field in a circuit depends upon the permeability of magnetic materials. By taking into consideration the electrical conductivity of materials, weight of materials, cost and availability, ARMCO pure iron was used as the magnetic material in the MRTD. Austenitic stainless steel was used as the nonmagnetic material to make the shaft and the key. Aluminum was used as the nonmagnetic material to make other parts of the stator such as housing, covers to support the bearings and so on. Copper wire was used for the coils.

3.3.1 Magnetorheological fluid selection: Carbonyl iron powder was used as the magnetic particles. Silicon oil was used as the liquid carrier.

4. MAGNETIC CIRCUIT DESIGN
Magnetic circuit was described to analyze the effect of magnetic field strength within the MR fluid gap, which in turn results to the change in viscosity of the MR fluid. MR fluid is carried in cavity within the gap between the magnetic parts of rotor. Torque is transmitted from the input shaft to the output shaft through MR fluid. In Fig. 4, A is the input shaft and it’s nonmagnetic, B and C are magnetic parts of rotor, D is the magnetic part of the stator. The arrow indicates the magnetic flux direction. Magnetic flux produced by the coil, travels from stator to the rotor in a closed loop.

5. THEORETICAL ANALYSIS OF OUTPUT TORQUE
The Bingham plastic model can be used to describe the characteristics of MR fluid under applied magnetic field [6].

\[ \tau = \tau_y + \eta \gamma \]

Where \( \tau \) is the shear stress, \( \tau_y \) is the yield stress caused by the applied magnetic field, \( \eta \) is the viscosity of the MR fluid, and \( \gamma \) is the shear strain rate of the MR fluid. In the absence of the external
magnetic field, MR fluid exhibits a Newtonian fluid-like behavior, where the shear stress of the fluid is given as:

$$\tau = \eta \gamma$$  \hspace{1cm} (2)

The above equations show that the total shear stress $\tau$ under the absence of magnetic field is relatively smaller than the shear stress under applied magnetic field. Shear stress increases gradually as the magnetic field strength rises [7, 8]. The derivative of the velocity vs radius can be given by:

$$\frac{d\omega}{dr} = \frac{d}{dr} \left( \frac{du}{dr} \right) = \omega + \tau \frac{d\omega}{dr}$$  \hspace{1cm} (3)

Where $u$ is the circumferential velocity of MR fluid $r$ is the radius and $\tau \frac{d\omega}{dr}$ denotes the shear deformation degree between different liquid surfaces, the angular velocity changes at different radius, due to the properties of MR fluids [8]. So, the theoretical output torque of MR fluid with respect to the radius $r$ can be written as:

$$T = 2\pi L \tau$$  \hspace{1cm} (4)

In presence of magnetic field, the MR fluid is in solid-like state and the torque transmitted can be given as [7-9]:

$$T_z = \frac{\pi}{2} (R_1 + R_2)^2 \omega \tau$$  \hspace{1cm} (5)

Where, $R_1$ and $R_2$ represent the radius of the inner cylinder and the outer cylinder, $L$ is axial length. In the liquid mode, when the MR fluid behaves like a Newtonian fluid and completely in the absence of magnetic field torque is given by:

$$T_2 = 4\pi \ln \left( \frac{\omega_2 - \omega_1}{\omega_1} \right) \frac{R_1^2 R_2^2}{R_2^2 - R_1^2}$$  \hspace{1cm} (6)

Where $\omega_1$ and $\omega_2$ are the angular velocity of the cylinders. The total torque transmitted by the MRTD is given as:

$$T = T_1 + T_2 = \frac{\pi}{2} (R_1 + R_2)^2 \omega \tau + 4\pi \ln \left( \frac{\omega_2 - \omega_1}{\omega_1} \right) \frac{R_1^2 R_2^2}{R_2^2 - R_1^2}$$  \hspace{1cm} (7)

6. FINITE ELEMENT SIMULATION

Magnetostatic analysis was conducted to simulate the transmission behavior of the MRTD. Ansys workbench software package was used to fulfill this purpose. Solidworks software package was used to design the MRTD. Fig. 3, it shows the magnetic field distribution in the magnetic parts and in the MR fluid gap. The flow direction of magnetic flux is indicated by the arrows in the cross-section view. Magnetic flux flows from one pole through the MR gap to the rotor, then back through the MR gap again to the poles of the magnetic parts. Magnetic particles in the MR fluid form up chains as the magnetic flux penetrates the MR fluid. Results show the maximum magnetic flux at maximum input current (2 A). Magnetic field strength increases as the current rises, which allows a flexible control over the device.

![Figure 5. Total magnetic flux density in the MRTD.](image-url)
7. EXPERIMENTAL SET UP
A prototype MRTD was manufactured and tested. The experimental platform is composed of, an electric motor, torque-speed sensors, bearings and MR powder brake. The input shaft was connected to the torque-speed sensor and powered by an electric motor. The output shaft was connected to the output torque-speed sensor and MR powder brake. The output shaft is driven by the input shaft through MR fluid. In addition, a switching power supply NES-05-24 was used to acquire signal from torque-speed sensors. MPS-010602 card was used for data acquisition, an external power supply was used to input current through the coil.

8. RESULTS AND DISCUSSION
The performance parameters of MRTD mainly include torque transmission and output speed analysis. These parameters are realized by adjusting the excitation current. Friction torque and viscosity torque were taken under consideration. For torque transmission, friction torque refers to the starting torque produced by a single torque sensor and bearing. While in the speed control analysis, friction torque refers to the sum of torque produced by the torque-speed sensors, bearings and MR powder brake.

8.1. Torque transmission
Refers to the amount of torque transmitted under the applied magnetic field, as it reflects the MRTD’s transmission ability. With an excitation current range (0 A - 2 A), results show that torque increases gradually as the current rises, and torque transmitted can be controlled by adjusting the excitation current. With steps of (0.5 A), torque increment is significant. The torque in MRTD is linear with respect to input current. When the excitation current is (2 A), the maximum torque transmitted by the MRTD is about 6.6 N/m.
8.2. Speed control of MRTD
Speed control of MRTD refers to the relationship between excitation current and the MRTD’s output speed. Results show that, with steps of (0.10 A), the output speed increment is significant. When the excitation current varies from (0 A - 0.67 A) the output speed is 0. However, MRTD starts to output speed at (0.69 A). with further increase in the input current, the output speed increases gradually and reaches a synchronous speed. By adjusting the excitation current, the MRTD can achieve synchronous speed.

9. CONCLUSION AND FUTURE SCOPE
In this paper, modes of operation of MR fluids and design parameters were introduced. Next, the material selection was specified, magnetic circuit was conducted, as well as the theoretical torque analysis of MRTD. Finite element simulation was carried out to analyse the magnetic flux distribution across the device. Finally, the MRTD was tested. Torque analysis referred to the amount of torque transmitted by the MRTD under the applied magnetic field. Speed control referred to the relationship between MRTD’s output speed and the excitation current. Results confirm that the novel MRTD has an excellent performance and it’s feasible for application, with significant advantages as follows:

1) Stator:
   a) Electromagnetic coil as a part of the stator, can overcome the limitations present in design of conventional devices due to the geometrical constrain.
   b) The stator structure allows a multi-pole design for possible improvement of MRTD.
2) Rotor:
   a) The length and diameter of rotor can be increased for possible improvement of MRTD.
Future work should focus on improvement of the MRTD such as: adding more poles and increasing the poles’ shoe length in order to make the magnetic field more efficient in the MR fluid gap, thus avoiding magnetic field loss. Also, to reduce the size of MRTD and the MR fluid gap. An improvement in the sealing system due to inevitable leakage of MR fluid during the experiment. MRTD shows good promise for various applications.

ACKNOWLEDGMENT
* This work is supported by the Shandong University of Science and Technology (College of Mechanical and Electronic Engineering).

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