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Design Analysis and Experimental Evaluation of an MR Fluid Clutch

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ABSTRACT: An MRC (Magneto-Rheological Clutch), a device to transmit torque by shear stress of MR fluids, has the property that its power transmissibility changes quickly in response to control signal. In this study, we consider methods to predict performance of an MRC. First, we anticipate the performance of an MRC with a simplified mathematical model and second, we predict the performance in consideration of the applied magnetic field and viscosity distribution of fluids caused by the field. Between the two methods, compared with experimental results, it is shown that the numerical method is closer to reality than the simplified one.

INTRODUCTION

SINCE an MRC (MR-Clutch) using MR fluids, unlike conventional mechanical clutches having only on/off strategy, has a distinguished merit of changing its transmissibility continuously upon control signal within certain range, it has the potential of large applicability. Other properties which an MRC should have are fast response to control signal, broad range of torque transmissibility, strong coupling force and so on. To design an MRC for a given specification, we must be able to predict the performance of an MRC in consideration of its geometry and applied magnetic field.

Associated with geometry shape and magnetic field onto an MRC, an array of mathematical models to anticipate the performance has been devised. Mathematical models of an MRC are based on geometry in essence and can be largely divided into two, that is to say, bell mode and disc mode [1]. However, these simplified mathematical models, based only on geometry, are applicable under restricted condition of fluid flow. Therefore, the performance of a clutch cannot be predicted well when its fluid flow gets complicated and gets out of the limited condition. It is assumed that viscosity of fluids is equal regardless of its position in the simplified mathematical model. In reality, the viscosity distribution is not uniform because the intensity of applied magnetic field is not equal all over the MRC. For accurate prediction of performance, the actual fluid flow and viscosity influenced by distribution of magnetic field should be considered.

In this study, first, the performance of MRC is anticipated using a simplified mathematical model and compared with experimental results. Second, the FEM analysis of the magnetic field and CFD (Computational Fluid Dynamics) analysis of fluid flow, which are numerical methods to analyze the viscosity distribution by magnetic field and fluid flow, are given.

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PROPERTIES OF MR FLUIDS AND DESIGN CONSIDERATION OF MRC

The MRC changes its torque transmissibility as the viscosity of MR fluids inside it varies in response to the field. Initially, the relation between the applied magnetic field and viscosity of MR fluids should be formulated.

The viscosity of MR fluids on application of magnetic field is measured with a viscometer of Haake Inc. Figure 1 shows the layout of experimental apparatus. A PC with D/A and A/D converter supplied electric current input and recorded the data. While control signals via D/A converter changed into electric currents according to its voltage level and then the electric currents were amplified and transmitted for the driving motor to cause shear rate in the fluid between inner cylinder and vessel, the torque transducer read the resultant force of total shear stress on the inner cylinder.

Figure 2 shows the relation, obtained from the experiment, between shear rate and shear stress depending upon the intensity of applied magnetic field. As stated above, the properties of MR fluids are determined by the applied field. Under an assumption that MR fluids have the attributes of Bingham fluid [2], the Equations (1), (2) and (3) are derived by the least square method. In Figure 2, the yield strengths are estimated.

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

$$\eta = 0.1864 \times B + 0.6067 \tag{2}$$

$$\tau_o = 5.497 \times B \tag{3}$$

where B is the intensity of applied magnetic field in a unit of mT, τ_o is the yield strength , η is the kimematic viscosity and $\dot{\gamma}$ is the shear rate.

A clutch is a device to transmit torque, by the transmitting medium, from input member to output member. Currently,

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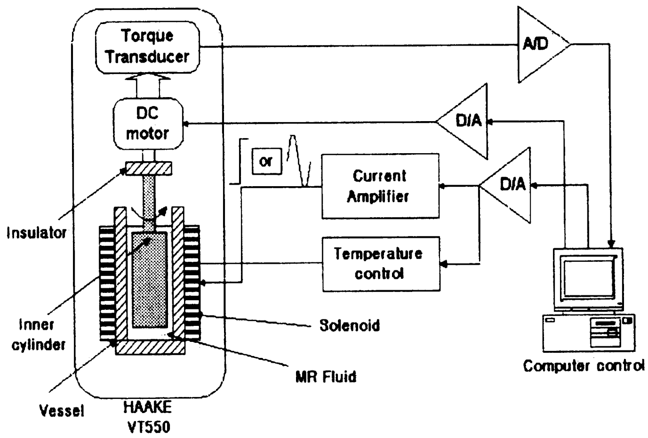


Figure 1. *Schematic layout of the experimental apparatus for measuring the shear stress of MR fluids.*

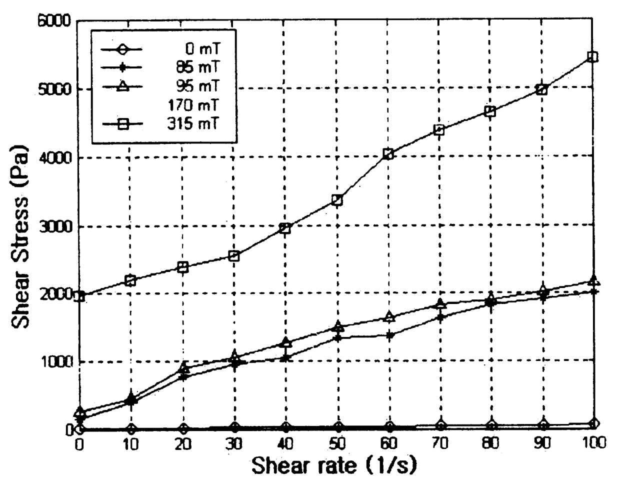
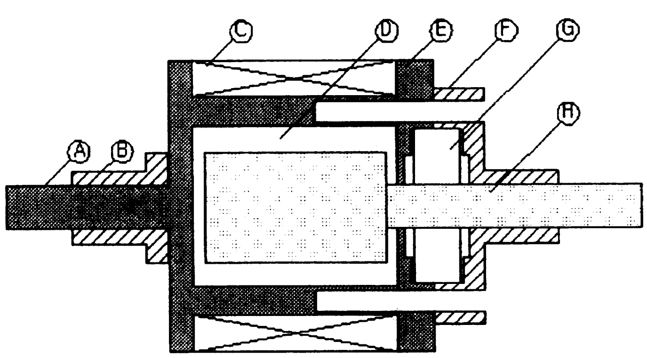


Figure 2. *Shear stress and shear rate under different magnetic fields.*



A : Input member (Aluminum)
B : Insulator
C : Coil
D : Magneto-Rheological fluid
E : Cap (Aluminum)
F : Insulator
G : Rolling element bearing
H : Output member (Stainless steel)

Figure 3. *Cross section of the MR Clutch.*

there are many kinds of clutches and they are classified into the dry type in which friction force is used and the wet type in which shear stress of fluid flow is used. MRC transmits power by shear stress of MR fluids and, in general, there are two kinds of MRC. The disk mode clutch uses shear stress acting on the surface of the disks connected to the rotating axis perpendicularly. The bell mode clutch uses shear stress acting on wall between the inner and outer cylinders parallel to the axis. Each has merits and demerits, but in this study, we confine our interest to bell mode clutch. One of this type of clutch was constructed and its performance was examined. Figure 3 shows the cross section of the MRC: H is the output member and A is the input member. Coils in C generate the magnetic field whose intensity is adjusted by input current. MR fluids are filled in D.

ANALYSIS OF THE MRC

The viscosity of MR fluids between two rotating cylinders is the factor to determine transmissibility and varies according to the intensity and form of applied magnetic field. So the intensity of magnetic field, applied to MRC with respect to position, should be found out. The distribution of the field is determined by the geometry of solenoid, part C of Figure 3, the property of material which the magnetic field goes through and the geometry of MRC itself. According to Biot-Savart law [3], the magnetic field is:

$$B = \frac{\mu_o I}{4\pi} \oint_c \frac{dl' \times a_R}{R^2} \; (T) \tag{4}$$

where μ_o denotes the permeability constant, I the input current, dl' the length element of coil, R the distance and a_R the uint vector directed from the source to field point.

Now that it is not realizable to derive a mathematical description of magnetic field applied to MRC of complex geometry from this equation, the ANSYS, a commercial FEM code, is used to discover the distribution of magnetic field applied to MR fluids. To verify the result of ANSYS, the ANSYS was applied to MRC and the field intensity of several points was compared to the measurements.

Figure 4 shows the magnetic field distribution by ANSYS and the comparison of analysis and measurements along the z axis. Now it has been verified that output of ANSYS is credible since two results are almost the same. Based on this fact, the ANSYS is used when analyzing the magnetic field of MRCs which are similar but have different sizes of inner cylinders. The intensity of magnetic field is known to be proportional to the electric current so that the magnetic field generated by different current can be calculated without redundant ANSYS operation. For instance, when the value of input current is doubled, the value of magnetic field is doubled.

Even though it is hard to derive a mathematical description of fluid flow inside an MRC from Navier-Stokes equation, the equation of fluid flow can be formulated in a few

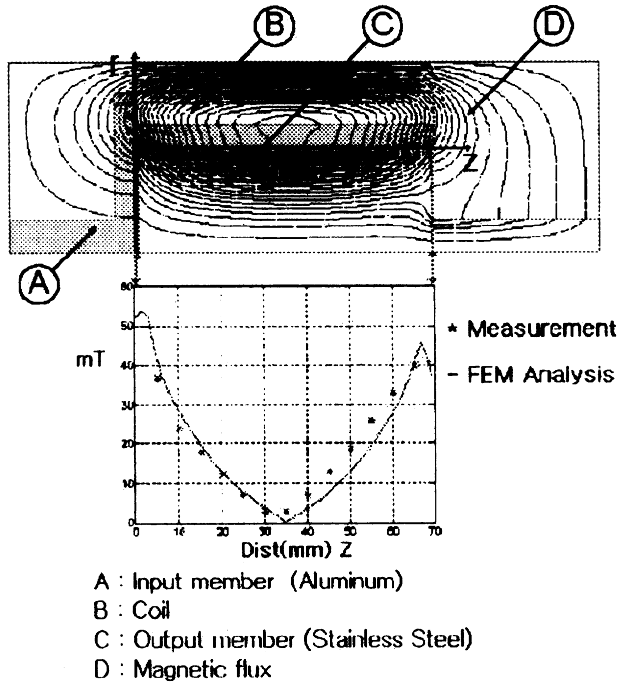


Figure 4. *Comparison of numerical analysis and measured data.*

simple cases given the following assumptions: (1) steady-state, incompressible flow; (2) the velocity of flow is only function of *r*; (3) there is no flow in axial and radial direction.

Integrating the Navier-Stokes equation and applying boundary condition of the MRC, the shear rate becomes [4]:

$$\dot{\gamma} = 2\frac{r_o^2(\varpi_o - \varpi_i)}{r_i^2 - r_o^2} \tag{5}$$

where r_o and r_i are the radius of inner and outer cylinder respectively and ϖ_o and ϖ_i are the rotational speed of inner and outer cylinder, respectively.

Referring to the look-up table which contains the relation of shear stress and shear rate under the applied magnetic field in Figure 2, τ, shear stress, can be determined by the shear rate in Equation (5) and *T*, resultant torque, can be obtained by multiplying the area of inner cylinder wall by shear as follows:

$$T = \tau \times \text{ surface area } \times r_i = 2\tau\pi r_i^2 L \text{ (Nm)} \tag{6}$$

where *L* is the length of output member.

This method of assuming the uniform flow distribution, however, is applicable only to limited situations of small gap sizes. In the case of larger gap, the flow distribution deviates from the ideal uniform one and hence shows large discrepancies with experiments. Moreover, since the viscosity of the MR fluids also varies according to the magnetic field distribution, the detailed analyses for the magnetic field and flow distribution are required for the accurate prediction of the torque transmission performance of the MRC. In the present study, a computational fluid dynamics approach is utilized to obtain the velocity distribution of the MR fluids under the influence of the magnetic field by using the viscosity distribution obtained by Equation (2). In computation, the STAR-CD, a commercial CFD code, was used and viscosity distribution was implemented through programming the user's subroutine using the results of magnetic field analysis by ANSYS [5].

The governing equations of the present CFD analysis are the steady incompressible 3-D continuity and momentum equations, and in tensor notation they are as follows:

$$\frac{\partial}{\partial x_j}(\rho u_j) = 0 \tag{7}$$

$$\frac{\partial}{\partial x_j}(\rho u_j u_i - \tau_{ij}) = -\frac{\partial p}{\partial x_j} \tag{8}$$

where x_j denotes the coordinates system in *j*-direction and u_j the corresponding velocity component ρ and *p* denotes the density and the pressure of the fluid, respectively. τ_{ij} is the stress tensor in the equation.

Flow analyses are performed for the cases of various rotational speeds of the inner cylinder while the outer cylinder is fixed at rotational speed of 1500 RPM. Four different gap sizes of 1, 3.5, 6 and 8.5 mm are considered for the analysis. For the analysis of the effect of magnetic field intensity, three different electric currents of 0, 0.75 and 1.5 A are applied for the case of gap size 3.5 mm.

Figure 5 shows the computational mesh in a case of gap size 3.5 mm and about 40,000 computational cells are used. For the case of larger gap sizes, about 80,000 cells are used. Since the flow in the gap is axisymmetric, only 1/60 of circumference of the full domain are computed by using cyclic boundary condition. Rotating velocities are given on the solid walls. Typical computation took about ninety minutes of CPU time with Origin 2000 Workstation.

The shear stresses acting on the cylinder surface can be ob-

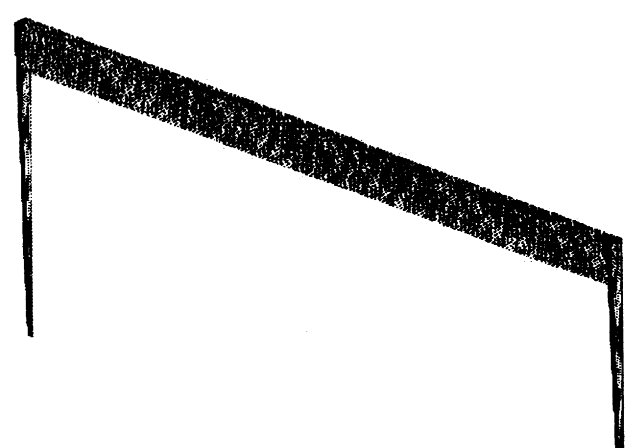


Figure 5. *Computational mesh for the gap size of 3.5 mm.*

tained from the previously computed viscosity distribution and velocity distribution as follow:

$$\tau = \eta\left[\gamma \frac{\partial}{\partial y}\left(\frac{\upsilon_\theta}{\gamma}\right)\right] \tag{9}$$

where η is the viscosity of the fluid, υ_θ the circumferential velocity component, and r the radial coordinates.

Figure 6 shows the results of shear stresses along axial direction for various differential rotational speeds of the inner and outer cylinders in the case of 3.5 mm gap. The distribution of magnetic field is also shown in the figure. It is seen from the figure that the high shear occurs at the high differential rotating speed (lower rotating speed of the inner cylinder) due to higher velocity gradient. Since the viscosity is higher at the ends of the cylinder due to stronger magnetic field, the shear stress is higher there compared to the central part of the cylinder.

The torque values required for the dynamics analysis of the MRC can be obtained through the integration of the shear stress obtained over the cylinder surface area as follow:

$$T = \int r\tau \, dA \tag{10}$$

Figure 7 shows the variation of the transmitted torque for various rotating speeds of the inner cylinder and gap size between the cylinders. It is seen from the figure that as the gap size gets larger the torque becomes lower due to lower shear stress as explained earlier. It is also found that as the differential rotating speed of the two cylinders becomes higher, the torque is increasing almost linearly. This is due to the fact that the velocity gradient at the cylinder surface is increasing almost linearly as the differential rotating speed. The results obtained by the simplified model utilizing viscosity and strain rate as expressed in Equations (1) through (6) without detailed CFD analysis are compared in the figure. Results by the simplified model are not very much different from the results by the detailed CFD for the case of small gap size since the velocity distribution becomes similar to the expression in Equation (5). As the gap becomes larger, however, the discrepancies between the two results much bigger as explained earlier.

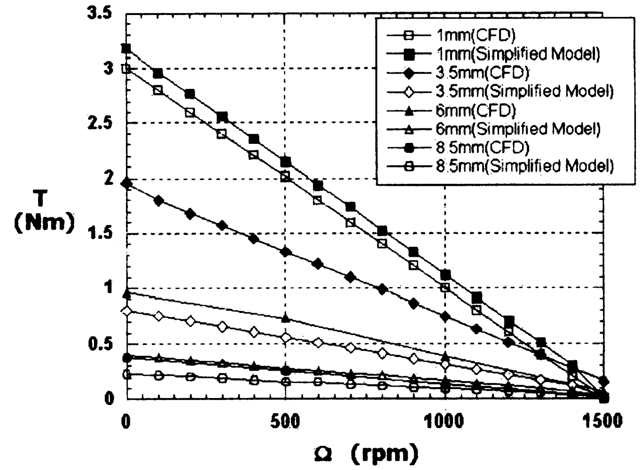


Figure 7. Variation of transmitted torque for various rotating speeds of the inner cylinder and gap size between the cylinders.

The effect of magnetic field intensity on transmitted torque is shown in Figure 8 in the case of 3.5 mm gap size when three different levels of electric current are applied. Results by both the simplified model and CFD analysis are also compared in the figure. When electric current is not applied, the torque value is lowest since the viscosity is lowest. As higher electric current is applied, the torque becomes higher. In the figure the discrepancies between the results by the simplified model and those by the detailed CFD analysis are also seen. Therefore it can be concluded from the present analysis that for accurate prediction of the dynamic behavior of an MRC, a detailed CFD analysis has to be done, and when

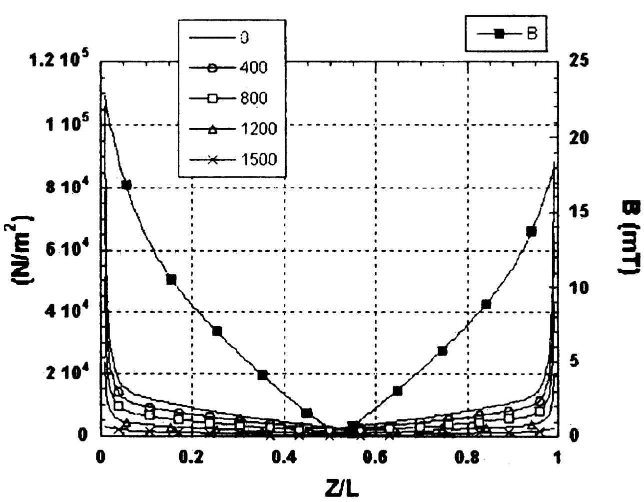


Figure 6. Shear stress distribution along the axis of the cylinder.

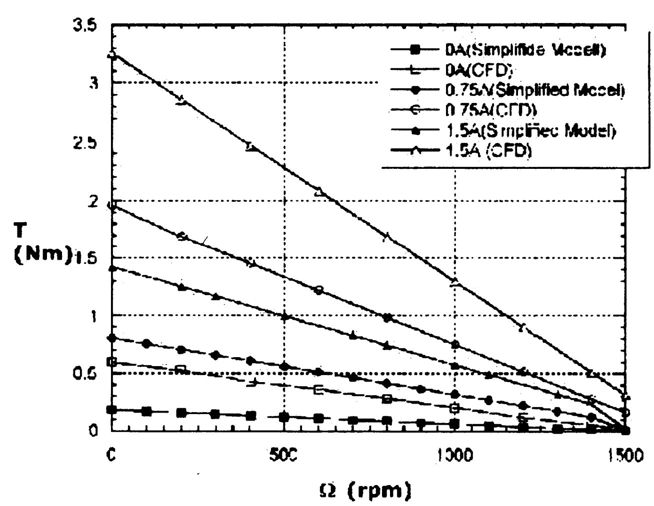


Figure 8. Comparison of transmitted torque obtained by CFD analysis and simplified model (for various rotating speeds of the inner cylinder magnetic field intensity for the gap size of 3.5 mm).

the geometry of the MRC is complicated the performance prediction may be possible only through the CFD analysis.

EXPERIMENTAL RESULTS

The experimental apparatus for evaluating the performance of the MRC is shown in Figure 9. In the apparatus, the input member of the MRC is connected to a servo motor A and rotates at a given velocity. The output member is connected to a mass through a lead screw and its velocity is measured by an encoder G. The equation of motion of the experimental system is found as Equation (11).

$$J_{eq}\ddot{\theta}_{output} + C_{f.eq}\dot{\theta}_{output} = T_{MRC} + C_{b.eq}(\dot{\theta}_{input} - \dot{\theta}_{output})$$
$$= T_{MRC} + T_{bearing} \quad (11)$$

where $\dot{\theta}_{input}$ and $\dot{\theta}_{output}$ denote the rotating speed of input and output member, respectively. $C_{f.eq}$ is frictional damping coefficient on rigid link and $C_{b.eq}$ is the frictional damping coefficient of the MRC bearing.

The parameters in Equation (11) were determined from the Bode plot obtained by a dynamic signal analyzer when the motor was connected directly to the lead screw without the MRC and sinusoidal torque with various frequencies are applied. The transfer function from the Bode plot is :

$$\frac{\theta_{output}}{T} = \frac{5160.6}{S^2 + 6.1956S}\left(\frac{\text{rad}}{\text{Nm}}\right) \quad (12)$$

From Equation (12), the parameters of Equation (11) are given as: $J_{eq} = 0.0001978$ (kg·m^2), $C_{f.eq} = 0.0012$ (kg/s) and $C_{b.eq} = 0.00046251$ (kg/s). The input torque, T, in Equation (12) is a summation of T_{MRC}, torque transmitted by MRC and $T_{bearing}$, torque by friction in the bearing.

Numerical simulation of the system, governed by Equation (11), when input member of MRC is forced to rotate, has been done by Runge-Kutta method. In the case of simplified mathematical model, T of Equation (6) is substituted by T_{MRC}, resultant torque of flow of MR fluids. As far as CFD analysis is concerned, the torque is estimated by linear interpolation of torque data obtained by CFD analysis given the magnetic field and resultant velocity as shown in Figure 7. Experiments, where the performance of the MRC is investigated under different magnetic fields and input velocities are administered by the following procedure: (1) rotate input member at angular velocities of 0, 220, 470, 735, 1030 and 1300 RPM; (2) supply input current of 0, 0.75 and 1.5 A and measure the velocity of output member in each case; (3) repeat experiments under condition (1) and (2), changing the gap size to 1, 3.5, 6 and 8.5 mm to find out the influence of geometry of MRC.

At first, the input current of 0, 0.75 and 1.5 A is applied and the input member is forced to rotate at 735 and 1300 RPM to find out the response of the clutch under different magnetic fields. In Figure 10, it is shown that the torque transmissibility increases proportional to input current. This stems from the fact that magnetic field intensity and viscosity increase as input current does, which results in the increment of shear stress even if there exists the same shear rate.

The velocity of output member is measured at input member velocity of 470 RPM with 0.75 A to investigate the change of torque transmissibility when the diameter of inner cylinder decreases. As can be seen in Figure 11, the torque transmissibility decreases as the diameter of inner cylinder

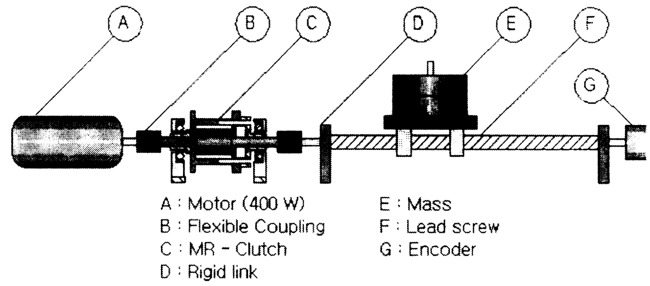
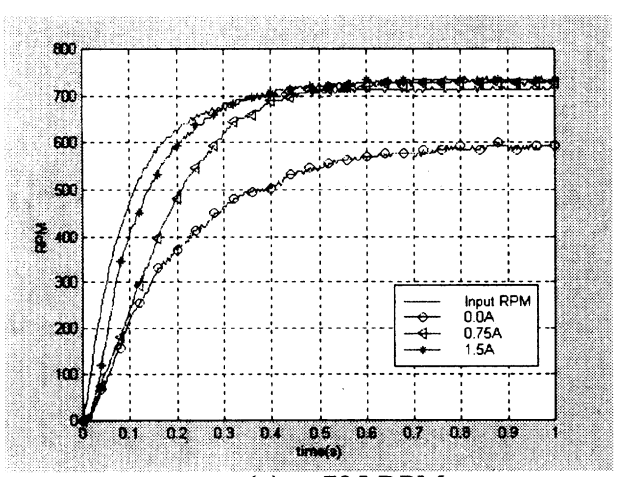
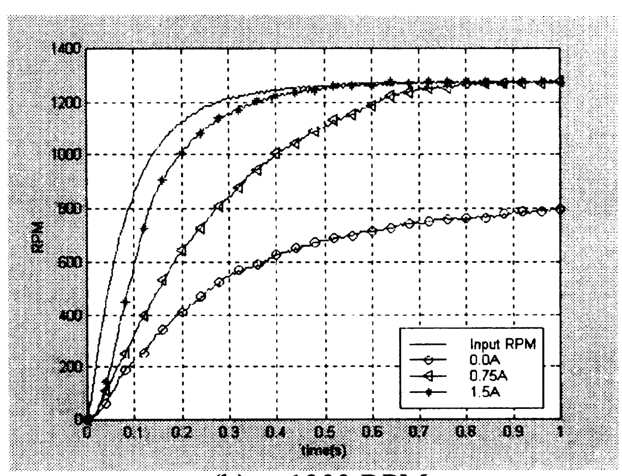


Figure 9. *Schematic layout of experimental set-up.*



(a) at 735 RPM



(b) at 1300 RPM

Figure 10. *Response of output member to input member rotation with input currents.*

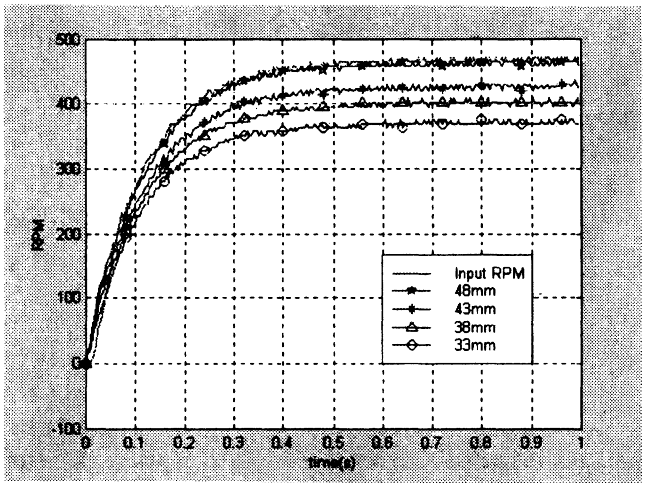
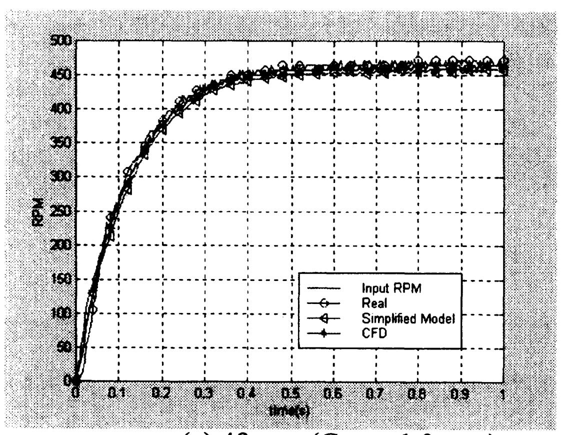


Figure 11. *Response of output member to input member rotation at 470 RPM with 0.75 A [diameters of inner cylinder (48, 43, 38, 33 mm) (gap = 1, 3.5, 6, 8.5 mm)].*

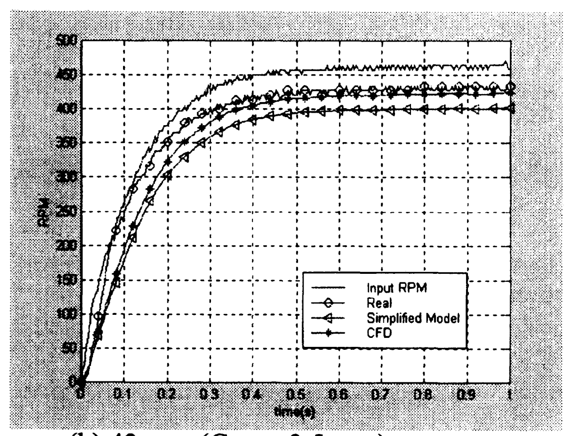
does at the fixed input velocity and input current. It is because, when the diameter of inner cylinder reduces, the shear rate decreases and correspondingly the shear stress does, which is easily known from the expression (5). Moreover, in expression (6), the area of inner cylinder wall decreases also so that the resultant torque does. It should be noticed that the output velocity keeps track of reference velocity perfectly when gap size is 1 mm. Its corollary is the fact that the resultant torque of MRC, integration of yield strength over surface area, is greater than required to drive the system in the velocity same as input velocity since the fluid doesn't yield and behaves like a solid, and in conclusion, there is no slip between the two cylinders.

The influence of geometry as well as magnetic field, which determines the property of an MRC, are known. Based on that, it is possible to predict the performance of an MRC with the numerical simulation using the torque data of CFD analysis or simplified model.

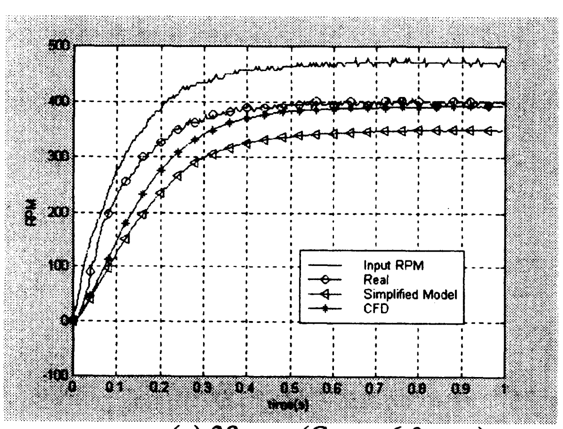
Experimental results and two kinds of numerical simulation results are compared in Figure 12 when the input angular velocity is 470 RPM with input current 0.75 A. While the numerical simulation of the simplified model shows large discrepancy with experimental results, the numerical simulation by CFD analysis is almost the same as experiments even if the diameter of inner cylinder decreases. As considered, the larger gap sizes between the inner and outer cylinder, the more significant is the effect of fluid flow in radial and axial directions. Therefore, the simulation results based on CFD analysis, which includes fluid flow in all direction, are more



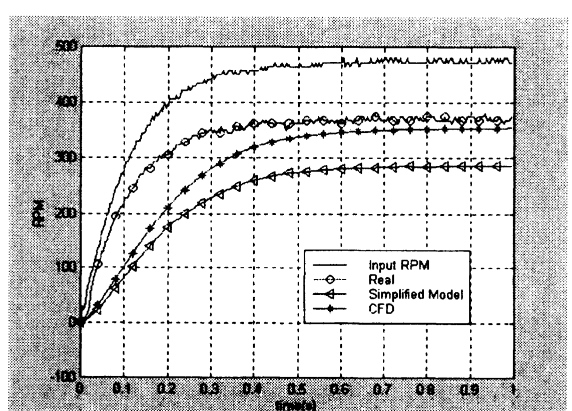
(a) 48 mm (Gap = 1.0 mm)



(b) 43 mm (Gap = 3.5 mm)



(c) 38 mm (Gap = 6.0 mm)



(d) 33mm (Gap = 8.5 mm)

Figure 12. *Comparison of output member velocity (experiments, CFD and simplified model).*

similar to experimental results than the simplified model. Though it is beyond coverage of this study to predict the fluid flow precisely during transient, it should be noticed, as seen from Figure 12, that there is a great difference between experimental results and numerical simulations during the transient section, e.g., during 0–0.4 sec in Figure 10(a). Because the shear rate of the fluids changes continually during this section, it is certain that there exists different fluid flow other than steady state flow which is a basic assumption of the two numerical simulations.

CONCLUSION

It is confirmed, through experiments, that the torque transmissibility of an MRC varies depending upon its geometry and intensity of applied magnetic field and that the errors of simulation results increase as the gap sizes do. It is because the magnetic field distribution is not uniform and, neither is the viscosity distribution. Also, the fluid flow cannot be accurately expressed by only function of r and the fluid flow in axial and radial directions cannot be disregarded when the gap sizes increase.

To overcome this problem, the magnetic field is analyzed using ANSYS; the viscosity distribution is found and the flow of MR fluids is considered in all directions: In doing so, it is assured that the prediction of performance by the numerical methods shows more reliable results than the simplified model.

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