Development and performance analysis of a Magnetorheological fluid Clutch

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Abstract

Automotive industry needs smart technologies to enhance their torque capacity or clutching actions. MR fluid is one of the materials whose properties can solve the issue of improvement in torque capacity of automobiles. In this paper MR clutch is designed and developed. The theoretical torque transmission capacity of the MR clutch is found by using Bingham-Plastic constitutive model. Its performance analysis is done by simulation results. COMSOL Multiphysics 5.3a is used for simulation. Two-dimensional axi-symmetric geometry of MR clutch is used for magnetic field and computational fluid dynamics study to analyze the magnetic circuit and MR fluid flow. The magnetic fields interface of COMSOL Multiphysics 5.3a is used to compute magnetic field and induced magnetic flux distributions in the whole domain of the MR clutch. The physics interface solves Maxwell's equations formulated using the magnetic vector potential and optionally for coils, the scalar electric potential as the dependent variable on full field. For selecting the magnetic field, the full field is used. The simulation results show the relation between torques developed in MR clutch with applied coil current. To find the velocity distribution and dynamic viscosity of MR fluid through simulation it is considered as incompressible and its flow as laminar. In COMSOL Multiphysics 5.3a laminar flow study is a part of the fluid flow physics, used to simulate single phase flow of fluids. The laminar flow interface is used for simulating fluid flows at very low Reynolds numbers. The MR fluid behaves like single phase non-Newtonian fluid. The equations solved by the incompressible laminar flow interface are the Stokes equations for conservation of momentum and the continuity equation for conservation of mass. Results obtained from the simulation shown graphically as in the form of surface plot and line graphs.

Keywords: Magnetorheological fluid; torque; clutch; CFD.

1. Introduction

MR fluid has unique advantages such as easy electronic controllability with short response time and used to build simple mechanical construction without moving parts [1]. MR fluids have some advantages over other rheological fluids such as higher yield stress and comparatively low voltage requirements. Lee et al. [2] confirmed through experiments that the torque transmissibility of a MR clutch varies with its geometry and intensity of applied magnetic field. Neelakantan et al. [3] developed a model to reduce the effect of centrifuging action at high rotational speeds and subsequent sealing in conventional shear mode disc-shaped or cylindrical-shaped transmission clutches using MR fluids. They designed MR clutch where the fluid is encapsulated in a highly absorbent polyurethane foam. Kavlicoglu et al. [4] designed and manufactured a high-torque MR clutch for Limited Slip Differential (LSD) application. They demonstrated that MR LSD clutch could transfer high controllable torques with a fast response time. Saito et al. [5] developed a MR fluid safety device which was capable of controlling the output torque of a robot joint axis and securing the holding torque in case of emergency stop. A normally closed type of clutch by using the MR suspension (NC type of MR clutch) was developed and evaluated by them. Kavlicoglu et al. [6] developed a closed-loop control system for a high-torque, multi-plate MR fluid LSD clutch. Kikuchi et al. [7] developed a compact MR Clutch with compact body (237g), torque (6 Nm) and rapid response (20ms). Bucchi et al. [8] presented a theoretical and experimental characterization of a torque transmission MR fluid clutch with permanent magnet. Rizzo [9] designed and experimentally characterized an innovative multi-gap MR clutch and its electrodynamics effects. It was based on a magneto rheological clutch excited by permanent magnets, and exploits the electrodynamics effects to improve its performance of about 28%. Based on the research, the torque prediction, dynamic viscosity and velocity distribution of MR clutch using numerical study is missing, which are essential for designing a MR clutch.

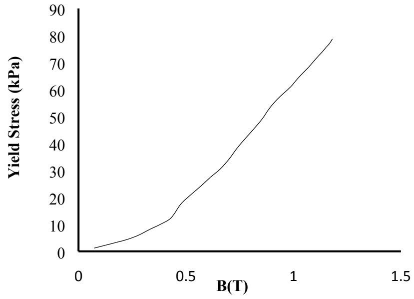
The aim of this research work is to estimate the torque capacity and response time of a MR clutch in shear mode by using a simulation technique. Commercially available MRF 241ES [10] is used for friction material between two MR clutch disc. The governing differential equations describing magnetic vector potential and incompressible flow of MR fluid between two parallel clutch discs under magnetic field are solved numerically using magnetic field and laminar flow modules in COMSOL Multiphysics v5.3a respectively. Transmitted torque is then found by calculating the yield stress and apparent viscosity under different applied current. Next section describes the laminar flow analysis of MR fluid under applied magnetic flux. Dynamic viscosity and velocity distributions in the MR gap have been analyzed.

2. Methods: MR fluid, Rheology model, Geometry and Material

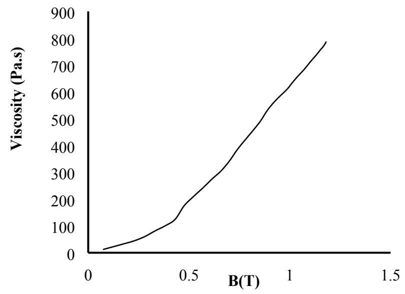
MR fluid is a type of smart material whose rheological properties (e.g. viscosity) can be rapidly varied by applying a magnetic field. It is a free-flowing liquid state in the absence of a magnetic field while its viscosity increases on application of magnetic field [11]. The commercially available working fluid MRF 241ES [12] has yield stress value 40.21 kPa at 80.60 [kA/m] magnetic induction (H), has been used in this research work. Binghan rheology model [13] shown in Eq. (1) has been used to fit the MRF241ES fluid properties.

$$\tau = \tau_{yd}(B) + \eta(B)\dot{\gamma} \tag{1}$$

Where, τ = shear stress, τ_{yd} (B) = field dependent yield stress, $\eta_{(B)}$ = field dependent apparent viscosity, $\dot{\gamma}$ = Shear rate. ANTON PAAR Magnetorheometer MCR-102 has been used to characterize the $\tau_{yd}(B)$ vs B and $\eta(B)$ vs B properties of MRF241ES fluid and plotted in figure 1.



(a)



(b)

Figure 1 Different curves for MRF241ES (a) Magnetic flux density vs. Yield stress and (b) Magnetic flux density vs. Viscosity

The 2D axi-symmetric model of the MR clutch designed in COMSOL Multiphysics v5.3a is shown in figure 2 (a) and the working mechanism of the MR clutch in shear mode is presented in figure 2 (b). Initially MR fluid particles are randomly distributed inside the MR gap as shown in figure 2 b (i) and hence no strength is developed in the MR fluid gap. When current is supplied to the coil of electromagnet it induces the magnetic field. It starts making of dipole moment in iron particles of MR fluid along the magnetic flux lines as shown in figure 2 b (ii). Multiple chains form and strength of the MR fluid increases by increasing the current in the coil. By using this mechanism torque between two discs is produced and hence the motion transfers from the input disc to the output disc. SWG22 copper wire has been used in the coil. The shafts, disc and covers are made of low carbon steel. Aluminum and stainless steel are considered for the electromagnetic core and bearing.

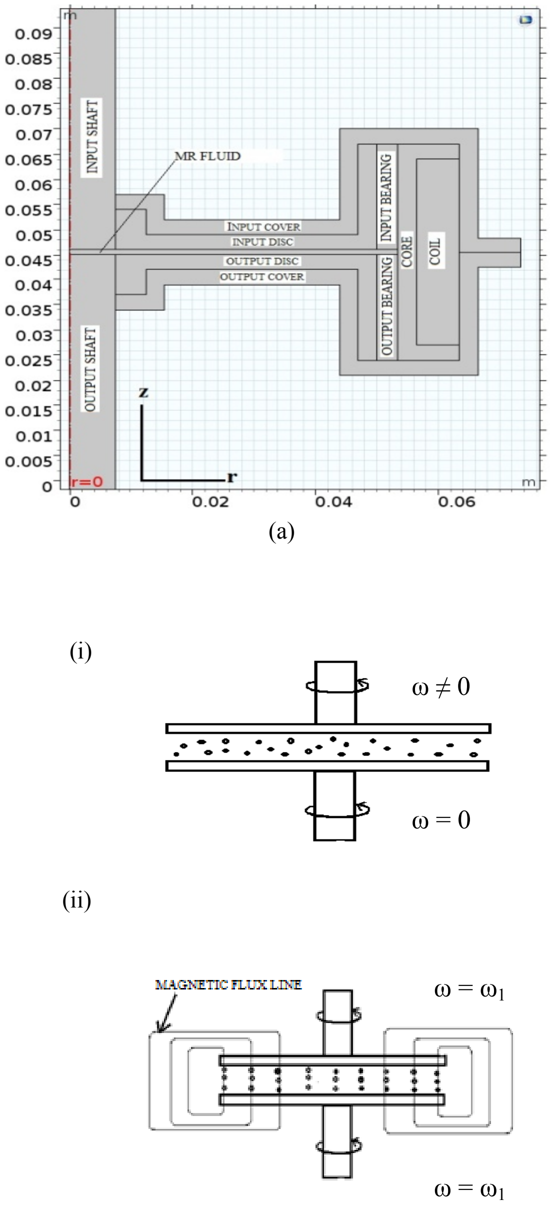


Figure 2 (a) Schematic of MR clutch with nomenclature and (b) Working mechanism of MR clutch in shear mode

3. Theory and Calculations

3.1. Governing Equations: Magnetic fields (mf)

The magnetic fields interface of COMSOL Multiphysics v5.3a is used to compute magnetic field and induced magnetic flux distributions in the whole domain of the MR clutch. The model is meshed before analyzed. Total numbers of triangular elements are 3920, edge elements are 575 and vertex elements are 52.

The Ampere's law in Maxwell's equations is written as:

$$\nabla \times H = \frac{\partial D}{\partial t} + J \tag{2}$$

The electric current density can be related to the electric field by equation

$$J = \sigma E \tag{3}$$

Where H = magnetic field intensity, J = current density, vector potential, E = electric field intensity. The needle bearing, electromagnetic core and surrounding air is treated as domain 1. Shafts, disc and cover are treated as domain 2. In domain 1 and domain 2 materials are defined by variables such as relative permeability and BH curve respectively.

The reference temperature T_{ref} = 293.15[K],

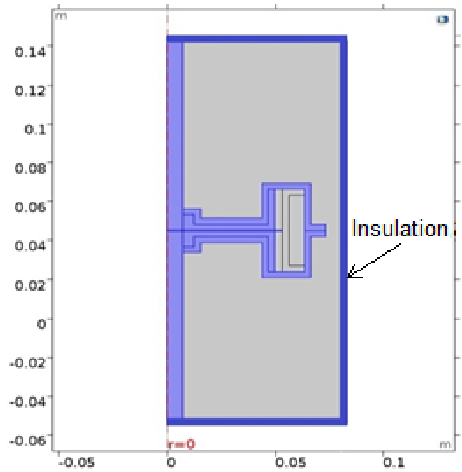


Figure 3 MR clutch domain with insulation

Magnetic field permeability $B = \mu_o \mu_r H$ and Electric field $D = \epsilon_o \epsilon_r E$ are used. The initial value of magnetic vector potential is (r, ϕ, z) = (0,0,0) Wb/m. Magnetic insulation is used on geometry as shown clearly in figure 3.The external current density by coil is as :

$$J_e = \frac{NI_{coil}}{A} e_{coil} \tag{4}$$

Here homogenized multi-turn conductor with number of turns (N) = 300, coil wire conductivity ($\sigma_{coil} = 6e7\ S/m$) and coil wire cross-section area ($A = 4.1e-7 m^2$) are used.

3.2. Torque calculation

The transmissible torque on the disc surface by the action of MR fluids is shown in figure 4.

Calculated torque is written in Eq. (5).

$$T = \frac{2\pi\tau_{yd}(B)r^3}{3} + \frac{\pi^2 \times \eta(B) \times RPM \times r^4}{60 \times h} \tag{5}$$

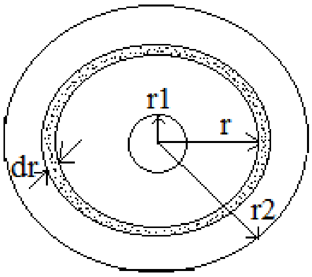


Figure 4 Single disc MR clutch scheme

3.3. Laminar flow (spf)

The MR fluid behaves like single phase non Newtonian fluid. The laminar flow interface is used for simulating fluid flows at very low Reynolds numbers. In stationary flow the governing equation for Laminar flow simulation following is used by COMSOL Multiphysics v5.3a:-

$$\rho(u.\nabla)u = \nabla\left[-PI + \mu\left(\nabla u + (\nabla u)^T\right)\right] + F \qquad (6)$$

$$\rho\nabla.(u) = 0 \qquad (7)$$

Where u is the velocity vector, ρ is the density, μ is the dynamic viscosity (it is the function of the shear rate and where the shear rate - viscosity relation is governed by the actual rheology model), I is the identity tensor and P is the pressure. F is the volume force, such as gravity (neglect here), centrifugal or electromagnetic forces.

This analysis is started by 2D axi-symmetric Laminar flows by set initial velocity field component at zero, pressure with 1E5 Pa and with the one disc rotating. An initial value for velocity field (u) is taken as zero (r, ϕ, z) = (0, 0, 0). Initially input disc has rotation U = 2×pi×r×rpm×step1(t[1/s]) and no slip wall condition takes place at the wall of MR gap which is in contact with input disc. The wall of MR gap which is in contact with output disc is treated as no slip condition as shown in figure 5. Black line shows the wall of MR gap which is in contact with rotating input disc, whereas blue line, the wall of MR gap is in contact with output disc. The MUMPS scheme of COMSOL Multiphysics v5.3a [14] is used. All numerical solutions are converged by criterion 0.001.In this physical model section swirl flow is considered and neglect inertial term and dynamic viscosity is represented as 'mud' in (Pa.s). MRF gap has a width of 0.5mm. P_{ref} is taken as 1atm and T_{ref} = 313.15K, density of MR fluid (ρ) = 3860 Kg/m^3. In COMSOL Multiphysics v5.3a the dynamic viscosity (mud) is a function of shear rate (denoted by sr), which is used in variable section of comsol as mud = tau/sr + mu0, here tau is shear stress and mu0 is field dependent apparent viscosity.

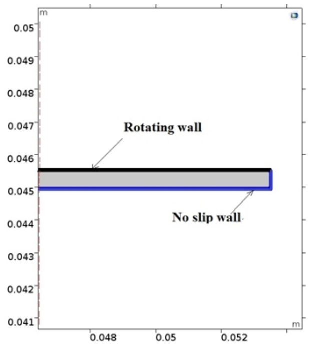


Figure 5 Boundary condition at MR gap

4. Results and discussion

4.1 Magnetic Flux Density Plot

Figure 6 shows the magnetic field developed in the MR clutch with magnetic flux lines at 0.5A, 120 rpm and 0.5mm MR gap by 2D model respectively. The magnetic flux density, z component or magnetic field intensity value was found to vary from -1.4 T to 1.41 T. For analyzing the magnetic field affect in the MRF gap a horizontal cutline is drawn in the middle of the MRF gap as shown in figure 7. In figure 8, line graph plots are shown which shows the mf.Bz plot at the horizontal cutline for various currents (0-3A). Torque at different current at 120 rpm taken at MR gap height = 45.25mm radially. This behaviour is shown in figure 9, In order to find the magnetic flux density distribution at the MR gap height ten verticle cutlines are drawn as shown in figure 10.

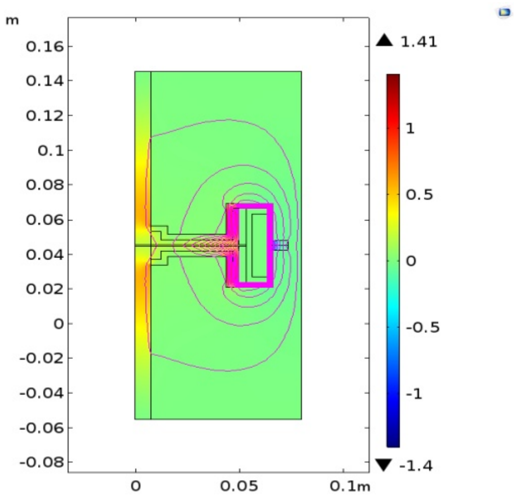


Figure 6 magnetic flux density z components with stream lines at 0.5A

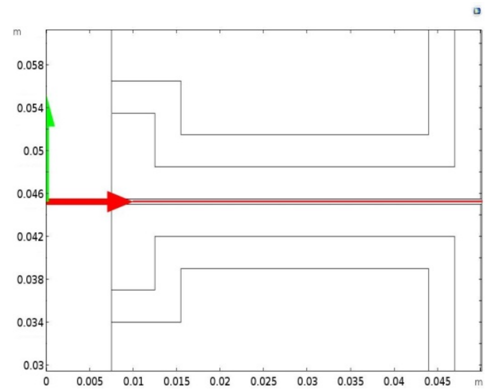


Figure 7 Cutline at z=45.25mm in MRF gap

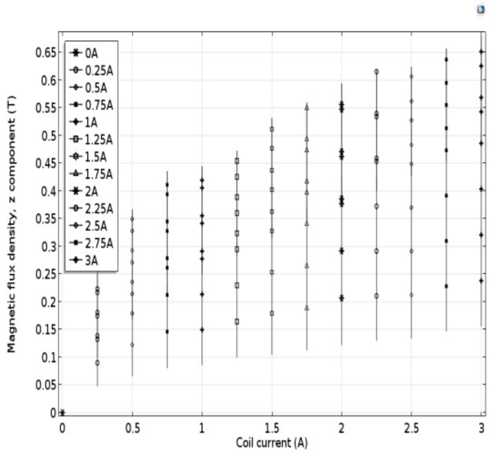


Figure 8 Magnetic flux density (mf.Bz) at different current

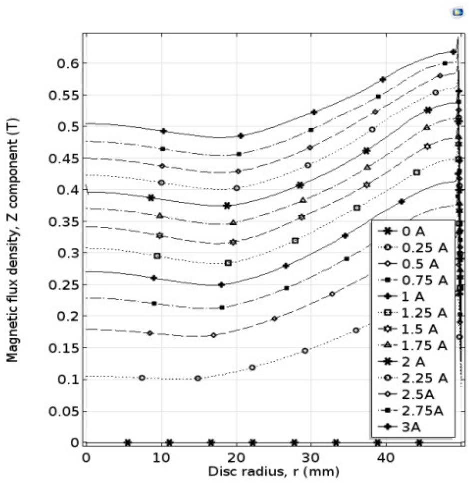


Figure 9 Magnetic flux density (mf.Bz) with disc radius(r) at 120 rpm

4.2 Braking torque Plot

Transmission torque is plotted on different rpm which is as shown in figure 11, as rpm increases the value of torque also get increases. It is 20 Nm and 11 Nm at 1000 rpm, 200 rpm at I = 3A, MR gap h = 0.5mm correspondingly.

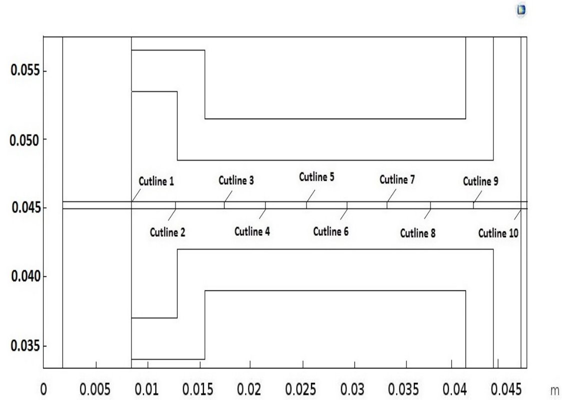
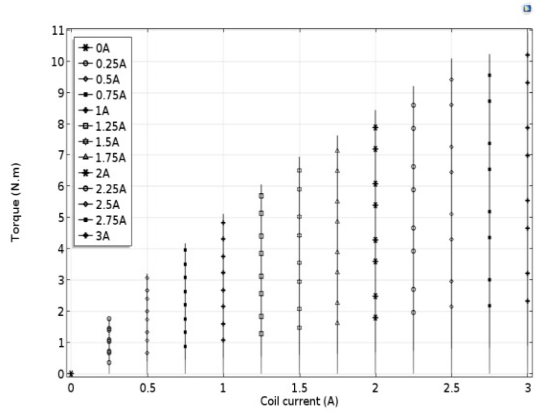
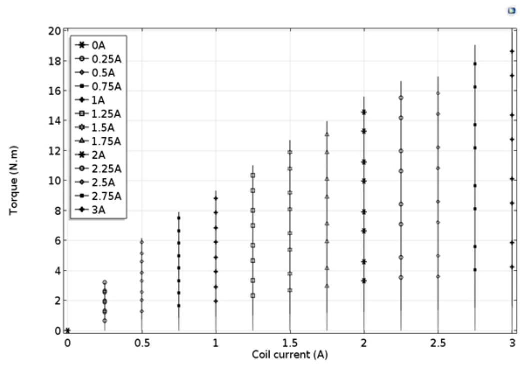


Figure 10 Parallel vertical cutlines in MR gap



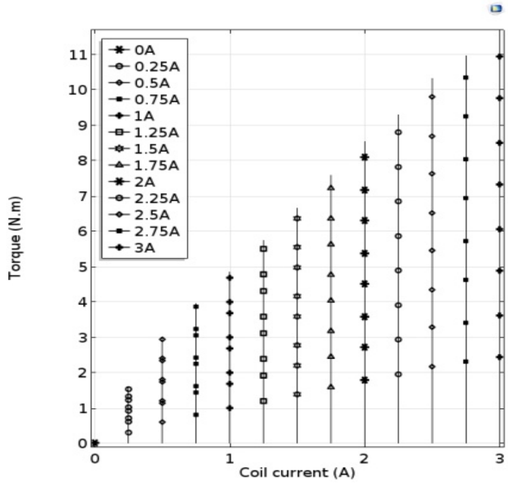
(a)



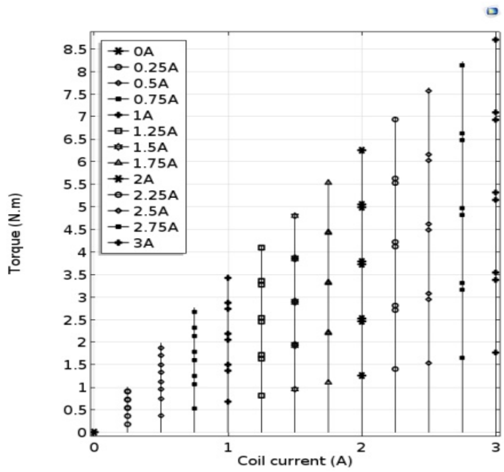
(b)

Figure 11 Torque at I 0.5A, h=0.5mm at different rpm (a) 200 rpm (b) 1000 rpm

To see the effect of MR gap width a comparison between the torques when MR gap gets changes from h = 1 mm and 2 mm is shown in figure 12. When current I = 3A the maximum torque at 1 mm MR gap is 11Nm and at 2mm MR gap is 8.5Nm. It shows that as the gap increases the value of torque decreases.



(a)



(b)

Figure 12 Torque at 1000 rpm for (a) 1mm and (b) 2mm MR fluid gap

4.3 Laminar Flow Plot

The flow pattern of fluid is shown in figure 13. The simulation results are plotted on 1000rpm, I 0.5A, B 0.5T. Figure 13 shows the surface plot of velocity (m/s) in MRF gap. The maximum value of flow velocity 0.3m/s are found near at the upper disc surface or near at rotary disc. Velocity gets transfer from upper or input disc to lower or stationary disc. Figure 14 shows the enlarge view of section A for velocity pattern inside the MR fluid gap. On the upper surface which is in the stage of rotation initially has a maximum value of 0.3m/s. Figure 15 shows the maximum value of velocity 0.28m/s nearer to the bearing end and minimum to shaft end. It shows about the state of chain formation and magnetization of MR Fluid.

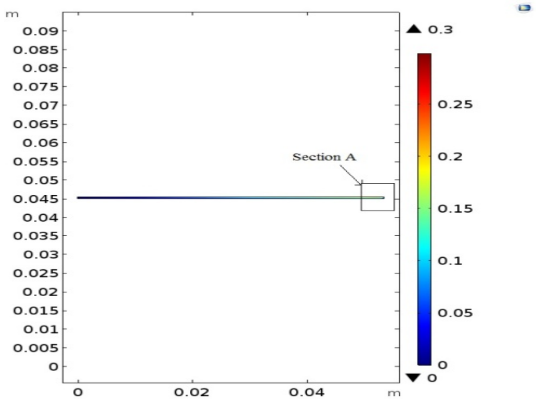


Figure 13 surface plot of velocity at 1000 rpm, 0.5A

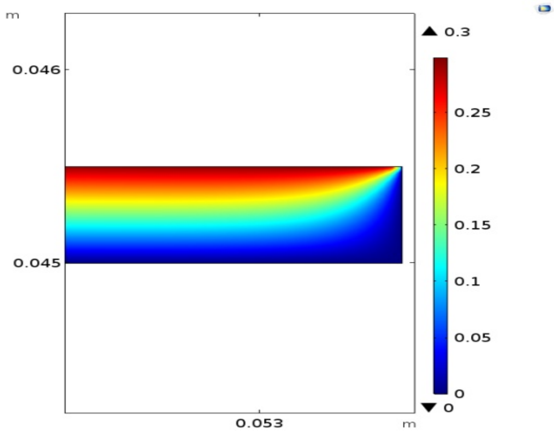


Figure 14 Zoomed view of section A

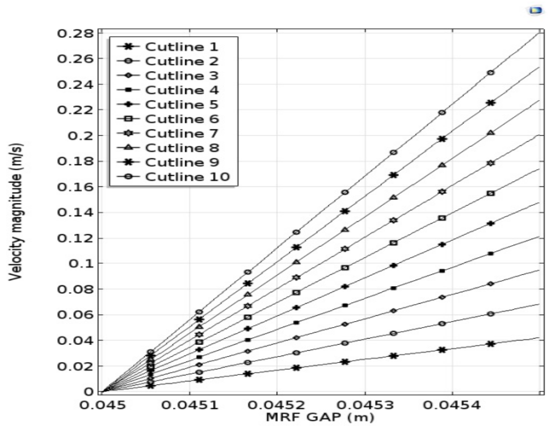


Figure 15 Velocity vs MRF gap at parallel cut lines

In figure 16, dynamic viscosity is plotted with respect to current from (0 - 3A) at horizontal cutline in the middle of the MR gap. It shows the dependency of dynamic viscosity on applied magnetic field. Figure 17 shows dynamic viscosity at parallel cut lines for 0.5A, The maximum value is at cutline 9 as 4.7245×10^{11} Pas and minimum value at cutline 10 which is nearly equal to 1.718

Pas. These results show the ability of MR fluid for transmission of torque.

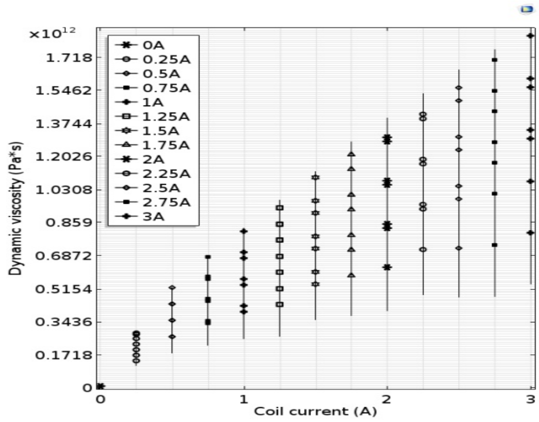


Figure 16 dynamic viscosities at different current

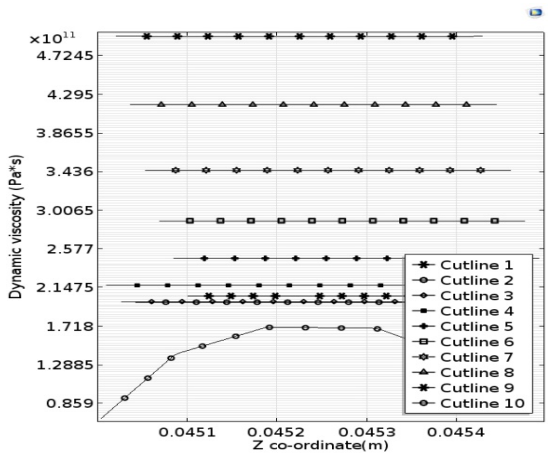


Figure 17 dynamic viscosities at I 0.5A

5. Conclusion

In this paper single disc magnetorheological fluid clutch is developed. COMSOL Multiphysics v5.3a has been used to study of the flow of a MR Fluid clutch with CFD approach. Braking torque is the main concern for the clutching application and it has maximum value of 20 Nm at 0.5 mm MR gap, 3A current and 1000 rpm. Furthermore, the velocities induced under varying magnetic field intensity and geometry (R, h) has been investigated by CFD. Velocity and dynamic viscosity also show the effective change as by change in the magnitude of currents. As change in rpm the flow velocity also changes, which is maximum at high rpm. Flow velocity changes from rotary disc to stationary disc that confirms the torque transmission can be controlled by the yield strength of the MR Fluid.

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