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To Investigate the Braking Torque of Magnetorheological Fluid Brake with Synthetic Magnetorheological Fluid

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***Abstract*— The aim of present work was preparation of advanced material magnetorheological (MR) fluids and the basic properties of synthetic MR fluids, as their response to an external magnetic field and Magnetorheological Fluid (MRF) Brake were developed that has performance advantages over the conventional hydraulic brake. MRF Brake employed with the magnetic field sensor to measure the magnetic field strength and dynamometer to test the braking torque. In the present work, three samples of Magnetorheological Fluid were prepared. The sample having higher percentage of magnetic particle (36% by wt. of carbonyl Iron particle) were selected to investigate the Braking torque of MRF Brake at low speed ranges (350rpm to 550 rpm) applying and without applying magnetic field under the current range of 0A to 2.6A. The Total Braking torque of MRF Brake was measured which is the sum of viscous torque without magnetic field applied and torque produced due to magnetic field. First, viscous torque without applying the magnetic field (at B=0) at different speeds were measured. Secondly, total maximum braking torque at specified range of speeds was measured as 16.78 Nm, 18.59 Nm and 19.58 Nm respectively under 0A to maximum current 2.6 Ampere. And hence, magnetic torque is the difference between Total Braking torque and viscous torque, corresponding current range up to 2.6 A and speed range were measured as 0 Nm to 18.35 Nm. The Transmitting torque generated in MRF Brake was still far less than that of a conventional hydraulic Brake, which indicates that a radical change in the basic Brake configuration is required to build a feasible automotive MRF brake.**

Keywords—Magnetorheological Fluid brake, viscous torque ,transmitting torque.

INTRODUCTION

Magnetorheological (MR) fluid, consisting of magnetizable particles dispersed in nonmagnetic liquids; show the rapid but reversible change in their rheological properties following the application of an external magnetic field [1]. The change from a free-flowing liquid state to a solid-like state is reversible and is dependent on the presence of a magnetic field. Iron powder is the most popular material used as particle inclusion due to its high saturation magnetization. When they are exposed to an external magnetic field, the original particles become magnetized and acquire dipole moments which aggregate to form chains in the field direction. The fluid structure depends on the volume fraction; dilute suspensions form weakly interacting single particle chains, while in more concentrated suspensions, the particle chains cross-link laterally into a dense network. This structure is responsible for the unique rheological properties of MR fluids: the quick formation of a network in response to an external field creates a rapid liquid-to-solid transition [2].

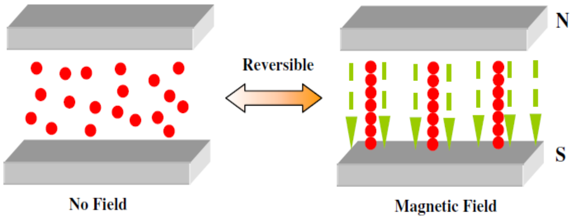


Figure1. Schematic Chain-like structure formation or MR fluid

Under the influence of a magnetic field, these iron particles are arranged to form very strong chains of “fluxes” with the pole of one particle being attracted to the opposite pole of another particle. Chain-like structure formation in controllable fluids is shown in fig.1. Once aligned in this manner, the particles are restrained from moving away from their respective flux lines and act as a barrier preventing the flow of the carrier fluid. MR fluids can be operated in three working modes depending on the type of deformation employed such as shear mode, valve mode and squeeze mode. The most important in the shear mode, the MR fluid is located between surfaces moving in relation to each other with the magnetic field flowing perpendicularly to the direction of motion of these shear surfaces. The mechanical properties of the MR fluids can be used in the construction of magnetically controlled devices such as the MR fluid Brake or Clutch.

There are many advantages of using pure electronically controlled brake systems. The properties and behavior of the brake will be easy to adapt by simply changing software parameters and electrical outputs instead of adjusting mechanical components [3]. MR devices have also found commercial application as exercise equipment. The Lord Corporation developed rotary brakes, which adopt a rotor that spins through a chamber filled with MR fluid. The magnetic field generated by the current flowing in the coil converts the fluid inside the chamber into a semi-solid, thus increasing the shear stress and torque required to turn the rotor. The brake promises high controllability, fast response time (<10 ms), and a wide torque range (0.3–5.6 N m) with very low power requirements. Besides, this device also has other benefits: easy integration, programmable functionality, rugged construction, and long service life. The objective of this project is to investigate the application of MR brake. To fulfill various virtual reality applications where large forces are needed [4].Based on the mechanical properties of certain magnetorheological (MR) fluids design method of the circular plate MR fluids brake was presented theoretically. The equation of torque transmitted by the MR fluids in brake was derived to provide the theoretical foundation in the design of brake [5].Design considerations for building an automotive magnetorheological (MR) brake a consists of multiple rotating disks immersed in a MR fluid and an enclosed electromagnet. When current is applied to the electromagnet, the MR fluid solidifies as its yield stress varies as a function of the magnetic field applied, generating the braking torque [6].MR fluids with excellent properties can be applied in various fields of civil and safety engineering, transportation and life science. However, due to sedimentation, MR fluid response to magnetic field is restricted and in an extreme situation could lead to the fail that is why further efforts must be still made in order to obtain even better results [7].

PREPARATION OF MAGNETORHEOLOGICAL FLUID

First, Magnetorheological fluid sample was prepared by using Silicone oil as a carrier fluid and is mixed with CIP (carbonyl Iron particles). In order to reduce the sedimentation, oleic acid and white lithium grease was mixed as an additive in the fluid sample. An electrical stirrer with speed control unit was used for preparation of the fluid samples. The sedimentation properties were studied by visual inspection. A severe limitation of commercially available Magnetorheological Fluids for its industrial application is its high cost ($ 750/ liter). Moreover there is only one firm in the world i.e. Lord Corp. USA, that supplies M R Fluid for research and allied work all over the world. Hence, the primary focuses of this work was to develop and preparation of Magnetorheological Fluid.

The volume fraction (in %) are basically range from 20 to 40% in MR fluid Brake and clutch. In this work, the constituents are used as per the weight percentage. Three samples are prepared by using different weights of M R Fluid constituents. One levels for each constituent are fixed and thus the three combinations are selected to represent it’s inter-effect on its properties. The levels fixed for preparing these three samples shown in Table 1.

Figure 2: Prepared three Samples of MR Fluid with different volume Fraction

TABLE 1. COMPOSITION OF CONSTITUENTS OF SAMPLE AND THEIR VOLUME PERCENTAGE

Sample No.	Total volume of MR Fluid (cc)	Vol. Fraction of CIP (%)	Mass of iron powder (gm.)	Volume of silicone oil (%)	Mass of silicon oil (gm.)	Total Mass of MR Fluid (gm)	Density of MRF (g/cm3)
MRF-36	20	36	56.16	64	16	72.16	3.61
MRF-30	20	30	46.8	70	17.5	64.3	3.22
MRF-26	20	26	40.56	74	18.5	59.06	2.95

After adding the additive such oleic acid to the above fluid for its sedimentation, the following table Indicate the weight % of each material constituents w.r.t total weight of MR fluid.

TABLE 2. COMPOSITION OF CONSTITUENTS OF SAMPLE AND THEIR WEIGHT PERCENTAGE WITH

Sample No.	Mass of iron powder (in gm.)	Mass of silicon oil (in gm.)	Mass of oleic acid (in gm.)	Wt % of material wrt. Total fluid Wt		
				CIP	Silicone	Oleic acid
MRF-36	56.16	16	2.5	75.22	21.43	3.35
MRF-30	46.8	17.5	2.5	70.06	26.2	3.74
MRF-26	40.56	18.5	2.15	66.26	30.22	3.51

According to the above three combinations, the Magneto Rheological Fluid samples are prepared. A fluid, thus, prepared, looks like a black color continuous fluid which appears similar to black liquid paint. This prepared fluid is the Magneto Rheological Fluid.

The selected Magneto Rheological Fluids (MR-36), 36%of carbonyl Iron particles, 62% of silicon oil and 2% of oleic acid have been prepared in the Engineering Materials and Metallurgy Laboratory of the Mechanical Engineering Department using the above mentioned materials as its main constituents. While preparing fluid sample, additional apparatus/equipments and other safety items e.g. latex gloves, paper towels, electronic weighing machine, glass test tubes, stainless steel container, air tight plastic containers, electrical stirrer etc are used. Electrical stirrer For the preparation of Magneto-Rheological Fluid sample. The stirrer has controllable speed, as the fluid constituents need to be stirred between 400 to 1000 rpm.

PROPERTIES OF MR FLUID

The Magnetorheological fluids are the suspensions of micron sized, magnetizable particles (mainly iron) suspended in an appropriate carrier fluid. They mainly consists of the following three components: magnetizable particles, carrier fluid and some additives The magnetizable particles in MR fluids induce polarization upon the application of an external magnetic field. The carrier fluid serves as a dispersed medium and ensures the homogeneity of particles in the fluid. A variety of additives (stabilizers and surfactants) are used to prevent gravitational settling and promote stable particles suspension, enhance lubricity and change initial viscosity of the MR fluids. The stabilizers serve to keep the particles suspended in the fluid, whilst the surfactants are adsorbed on the surface of the magnetic particles to enhance the polarization induced in the field. In the absence of an applied field, MR fluids are reasonably well approximated as Newtonian liquids. For most engineering applications a simple Bingham plastic model is effective at describing the essential, field-dependent fluid characteristics.MR fluid flows freely through the working gap between the fixed outer cylinder and the rotor. MR fluid exhibits a Newtonian-like behavior, where the shear stress of MR fluid can be described as

$$\tau=\mu\gamma \tag{1}$$

Where τ is the shear stress, μ the viscosity of MR fluid with no applied magnetic field, and γ the shear rate . When the magnetic field is applied, the behavior of the controllable fluid is often represented as the Bingham fluid having variable yield strength. The constitutive equation is derived by the least-squares method :

$$\tau=\tau_y + \mu\gamma \tag{2}$$

Where τ_y is the yield stress its value dependent upon the magnetic field B of magnetic coil and is developed in response to that applied magnetic field.

A. MR Brake Modeling

MR Fluid is magnetic field dependent fluid and it's characteristics can be described by a simple Bingham plastic model . In this model, the total shear stress is given by;

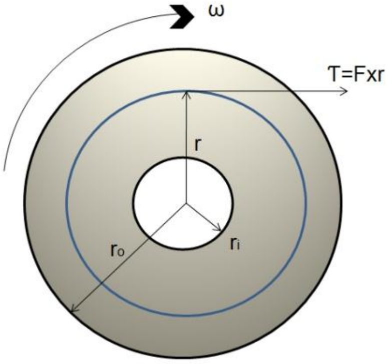


Figure 3.Torque acting on Disk at radius 'r'

$$\tau = \tau_H + \mu_p\gamma \tag{3}$$

where τ_y is the yield stress due to the applied magnetic field H, μ_p is the constant plastic viscosity, which is considered equal to the no-field viscosity of the fluid, and γ is the shear strain rate. The T_b retarding or braking torque which is caused by the friction on the interfaces between the MR fluid and the solid surfaces within the MR brake can be written as

$$T_b = 2\pi N \int_{ri}^{ro} (\tau_H + \mu_p \dot{\gamma}) r^2 dr\omega \tag{4}$$

where N is the number of surfaces of the brake disk(s) in contact with the MR fluid (e.g., 2 for one disk with MR fluid covering the both sides, 4 for two disks, etc.); ro and ri are the outer and inner radii of the brake disk, respectively, shear rate and shear stress induced due to applied magnetic field are

]

$$\dot{\gamma} = \frac{r\omega}{h} \quad \text{and} \quad \tau_H = kH^\beta \tag{5}$$

where ω is the angular velocity of the rotating disk, h is the thickness of the MR fluid gap, H is the magnetic field intensity and k and β are constant parameters that approximate the relationship between the magnetic field intensity and the yield stress for the MR fluid. Then, Equation (4) can be rewritten as

$$T_b = 2\pi N \int_{ri}^{ro} (kH^\beta + \mu_p \frac{r\omega}{h}) r^2 dr\omega \tag{6}$$

$$T_b = 2\pi N \left[kH^\beta \frac{(r_o^3 - r_i^3)}{3} + \mu_p \frac{r\omega}{h} \frac{(r_o^4 - r_i^4)}{4} \right] \tag{7}$$

Equation (7) indicates that, while carrying a one-disk configuration (hence, N = 2) would be ideal in terms of the simplicity of the design, manufacturing and weight of the MRB. In this work, one disk was selected for a detailed analysis. The applied magnetic field H can be produced within the MRB when current i is supplied to the electromagnet encircling the MR fluid, i.e.

$$H = i\alpha \tag{8}$$

where α is a proportional gain. Then, the two contributions of the resulting braking torque, can be derived by performing the integration in Equation (6) and substituting Equation (7), i.e.

$$T_b = T_H + T_{\mu} T_{\mu} \tag{9}$$

$$T_H = \frac{2\pi}{3} Nk\alpha (r_o^3 - r_i^3) i \tag{10}$$

$$T_\mu = \frac{\pi}{2h} N\mu_p (r_o^4 - r_i^4)\omega \tag{11}$$

Where ω is the rotational speed of the disk(s).

MAGNETORHEOLOGICAL FLUID BRAKE

The proposed brake is a magneto rheological brake (MRB) that potentially has some performance advantages over conventional hydraulic brake (CHB) systems. However, the CHB has a number limitations, including, (i) delayed response time (200–300 ms) due to pressure build up in the hydraulic lines, (ii) bulky size and heavy weight due to its auxiliary hydraulic components such as the master cylinder, (iii) brake pad wear due to its frictional braking mechanism, and (iv) low braking performance in high speed and high temperature situations[2]. The MR brake operates in a direct-shear mode, shearing the MR fluid filling the gap between the two surfaces (housing and rotor) moving with respect to one another. Rotor is fixed to the shaft, which is placed in bearings and can rotate in relation to housing.

Resistance torque in the MR brake depends on viscosity of the MR fluid that can be changed by magnetic field. MR brake allows for continuous control of torque. When there is no magnetic field the torque is caused by viscosity of carrier liquid, bearings and seals. [10]

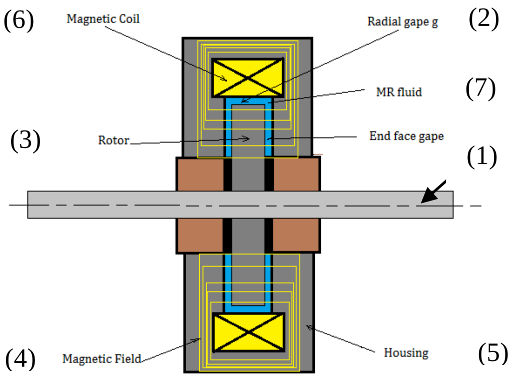


Figure 4.Basic configuration of a MR Brake

A basic configuration of a MRB was proposed for automotive applications. a rotating disk (3) is enclosed by a static casing (5), and the gap (7) between the disk and casing is filled with the MR fluid. A coil winding (6) is embedded on the perimeter of the casing and when electrical current is applied to it, magnetic fields are generated, and the MR fluid in the gap becomes solid-like instantaneously. The shear friction between the rotating disk and the solidified MR fluid provides the required braking torque[3]. In this paper, we propose a MR actuator for the brake in each wheel. The actuator consists of a rotating disk immersed in a MR fluid, enclosed in an electromagnet. In principle, the brake torque can be controlled by changing the DC current applied to the electromagnet. Magneto rheological fluid a compound containing fine iron particle in suspension - stiffens in the presence of a magnetic field. Two important characteristics of MR fluids are:

(i) they exhibit linear response, i.e., the increase in stiffness is directly proportional to the strength of the applied magnetic field and

(ii) they provide fast response, i.e., MR fluid changes from a fluid state to a near-solid state within milliseconds of exposing a magnetic field[8].

EXPERIMENTAL SETUP

In order to set up an experiment to measure the braking torque capacity of the proposed design, the optimum MR Fluid Brake and Clutch were fabricated and mounted to a test-bed. Here, in this section, the overview of the experimental setup was divided into two subsections:

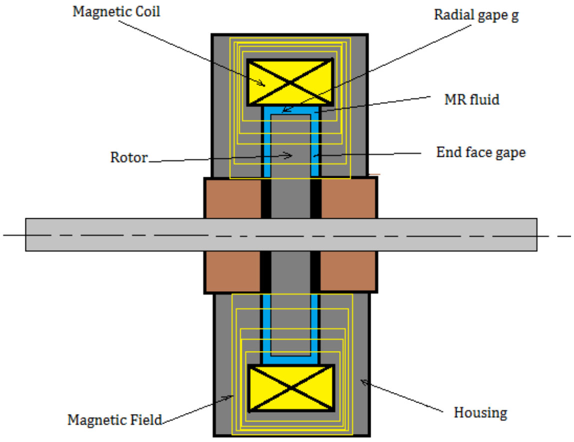
i) MR Brake and MR clutch prototype
ii) MR Brake and MR clutch test-bed, which contains the sensors and actuators used to test the braking performance of the MRB prototype.

MR Brake casing consist of Left side cup and Right side cup, these cups are mating part of the Brake. A circular disk of outer radius 39 mm with 10 mm shaft is enclosed in the casing cups. Casing cups are provided circular slots for electromagnetic coil which is adjusted inside these slots, 1 mm gap in both side of disk is filled with MR fluid. Casing cups (Left and Right) are design in such a way that it’s shape behaves like a U type electromagnet. The various external and internal parts of the fabricated MR Brakes are shown in the following figures.

Figure 5. MR fluid Brake

Figure 6. Different components of MR fluid Brake

The most challenging part of the assembly was the coil, which has to be placed within the MRB static casing that forms the electromagnet i.e. core. The coil has to be one piece for easy installation, thus, a custom bobbin was machined to wind the coil and then the coil wound around the bobbin was installed onto the MRB. In Figure 6, the coil and bobbin assembly is shown which is installed in the MRB’s electromagnetic core. Another hole was drilled onto the electromagnetic core for the terminals of the coil as shown in figure 6. Internal construction of MR Brake of Magneto rheological Fluid is shown in the figure 7.



Figur7. Construction of MR-brake

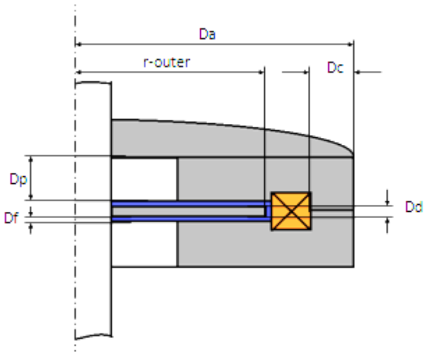


Figure 8. Dimensions of MR Brake

The experimental setup permitted to record coil current, torque simultaneously. The magnetic field strength H within the MRF was computed and as a function of the coil current. These computations showed that H is almost independent of the radius and a mean value of B as function of the coil current can be assumed.

DIMENSIONS OF MR BRAKE

With the help of half section view of the MR fluid Brake it's internal parts dimensions are shown in the following Table 3.

TABLE 3. DIMENSIONS OF THE MR BRAKE.

Symbol	Name for symbol	Dimensions (mm)
D_a	Radius of MR actuator	62
D_c	Thickness of the case	12
D_d	Thickness of the disc	2
D_f	Thickness of MRF gap	1
D_p	Thickness of the plate	14
r_{outer}	radius of the disc	39

The specifications of the MRB prototype are given in Table 4.

TABLE 4. MRB PROTOTYPE SPECIFICATIONS

Weight	3.2kg
Outer Diameter	124mm
Number of disk	1
Amount of MR fluid used	18gm
Max. current applied	2.6 A
Coil wire size	26 SWG
Number of Turn	85
Seal used	O ring
Magnetic material used	Low carbon Steel
Maxi. Braking Torque	20Nm at 2.6A

MR BRAKE TEST-BED

The experiments where made with the MRF-Brake shown in Figure 9 The MRF-36 was used in MR Brake . In MR Brake, the thickness of the gap filled with MRF was 1 mm on both sides.

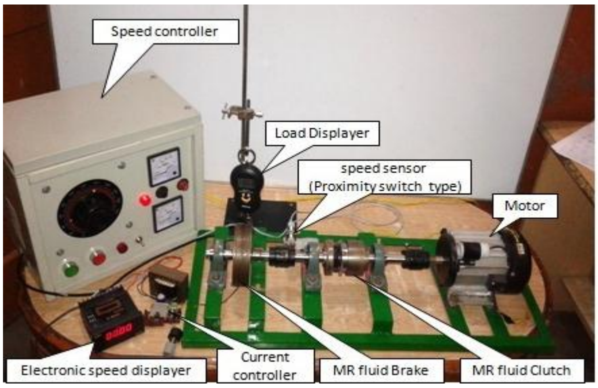


Figure 9. MRF-Brake Test Rig used for the experiment.

A controlled torque of up to 40 Nm was provided by a motor. Electric coil current and torque were controlled via Electronic control supply, and with rotational speed of 200-600 rpm was used to generate the continuous torque.

RESULTS AND DISCUSSION

During the experiments, initially, we measured the no-field torque generated by the viscosity of the MR fluid (plus the mechanical friction torque). In Table 5, the torque generated due to viscosity of the fluid at various rotational speeds is shown.

TABLE 5. THE RELATIONSHIP BETWEEN THE VISCOUS TORQUE AND ROTATIONAL SPEEDS

Speed of Brake at B=0 (rpm)	50	150	250	350	450	550
Viscous Torque in Brake Tμ (Nm)	0.03	0.07	0.12	0.18	0.24	0.28

With the help test rig viscous torque was measured at speed 50 rpm, 150 rpm, 250 rpm, 350 rpm, 450 and 550 rpm .Due to the MR fluid viscosity (μ) circular disk which was rotating with motor's shaft coupling with the shaft of brake and it experienced a dragging /resisting torque .The resisting or viscous torque (Tμ) was noted with the help of load dynamometer at given various speeds.

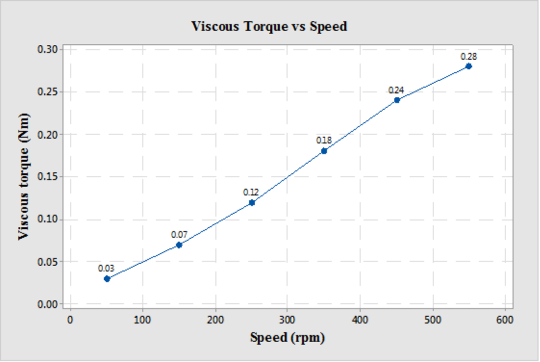


Figure 10.Viscous torque versus speeds

Initially at 0.2 A, coil current the T_b=0.18 Nm was noted which was very small value, as the current was increased step by step at constant speed 350 rpm of T_b also increased, the last value of T_b=16.78 Nm at coil current 2.6 A.

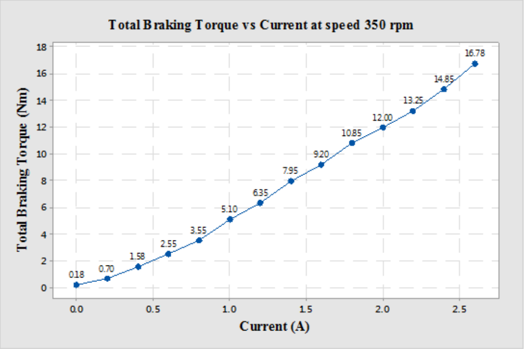


Figure 11.Total Braking Torque versus coil current at speed 350 rpm.

Second value of Total Braking Torque (T_b) was measured on the prototype MR Brake at speeds 450rpm taken as constant.First reading at 0.2 A, coil current the T_b=0.24Nm at constant speed 450 rpm the of Tb also increased, the last value of T_b=18.59Nm at coil current 2.6 A, this value also was greater than the last value of T_b at 350rpm

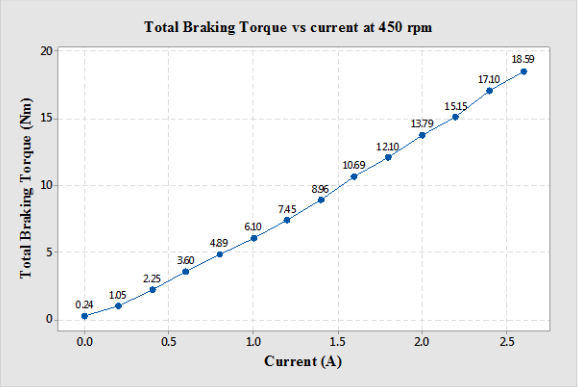


Figure 12.Total Braking Torque verses Current at Speed 450rpm

Third value of Total Braking Torque (T_b) was measured on the prototype MR Brake at speeds 550rpm taken as constant current varies from 0.2 Ampere to 2.6 Ampere .

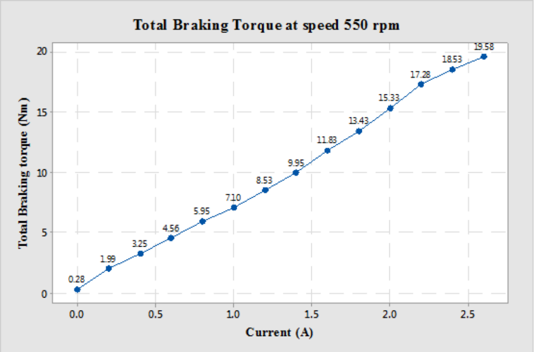


Figure13.Total Braking Torque verses Current at Speed 550rpm.

The difference between the three torque curves at speeds 350 rpm, 450 rpm and 550rpm is directly due to the brake coil current and varies the total braking torques.

The resulting plot between the torques (T_b) generated due to the applied magnetic field and the current applied is shown in Figure14. Three plots are almost identical, which shows that this quantity is speed dependent recorded with coil current initial (at 0 A) and final (at 2.6 A) values.

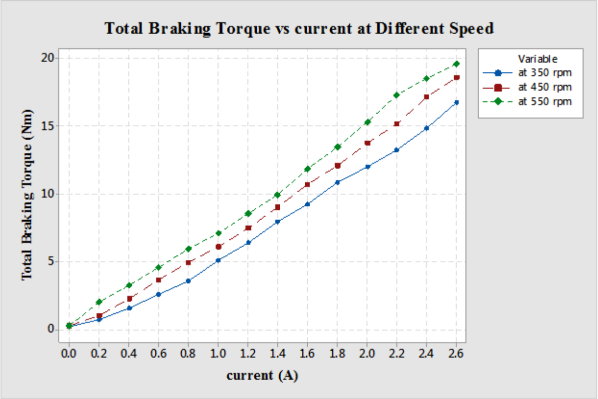


Figure 14.Torque (T_b) versus current applied at speeds 350rpm, 450rpm and 550rpm.

In order to compare the experimental results with the simulation results, the viscous and the friction effects have to be subtracted from the experimental data. The resulting plot between the torque (T_H) generated due to the applied magnetic field and the current applied is shown in Figure15.

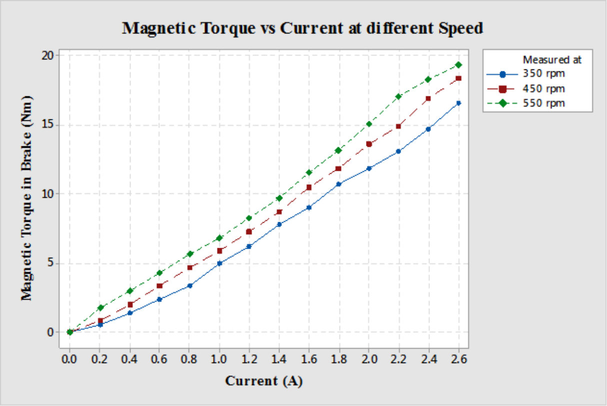


Figure15.Torque (T_H) generated due to magnetic field (without viscous and friction)

CONCLUSION

MR fluid was prepared and MR fluid braking performance was tested using an experimental apparatus that consisted of a torque sensor and a Induction motor. The experimental results showed that the braking torque increases with applied current, reaching more than 20 Nm at 2.6 A, thus confirming the theoretical predictions. There were discrepancies with respect to the simulation results due to estimated material properties used in the simulations. However, the proposed MRB configuration was not able to generate sufficient braking torque to stop a vehicle. Therefore, an improved MRB design should be suggested ,in future designs, taking into account the temperature effects and more accurate description of the material properties as well.

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