International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Shear Behavior of Magnetorheological Fluid and its effect on MR brake performance

Chiranjit Sarkar†

†Mechanical Engineering Department, Delhi Technological University, Shahbad Daluatpur, Bawana Road, Delhi – 110042, India

Accepted 08 April 2015, Available online 14 April 2015, **Vol.5, No.2 (April 2015)**

Abstract

The aim of this paper is review the viscosity of magnetorheological (MR) fluid as function of shear rate. The different rheological models of shear stress as a function of shear rate have been reviewed. MR fluid has been characterized at various shear rates for different magnetic fields to observe the shear behavior of MR fluid. In order to confirm the shear behavior of MR fluids, experiments have been conducted in MR brake test rig. The results show that with increase in shear rate, there is decrease in braking torque.

Keywords: *MR fluid, MR brake, Shear behavior.*

1. Introduction

Magnetorhelogical (MR) suspensions are known for dramatic change in their apparent viscosity. Due to their variable viscosity, MR fluids are used in engineering applications requiring controllable dynamic performance. One such application is magnetorheological brake in which MR fluid is treated as a brake lining material. This material does not wear-away and provides desirable friction resistance by just controlling the magnetic field passing through it. As MR brake involves electromagnetism and magnetisable friction material, this system can be named as "electromagnetic brake" (Gupta and Hirani, 2011). It is interesting to note that this brake in off state condition can work as bearings (Hirani, 2009, Hirani *et al*, 2000, Hirani *et al*, 1999, Hirani *et al*, 1998, Muzakkir *et al*, 2011, Hirani, 2005, Hirani *et al*, 2001, Muzakkir *et al*, 2013, Hirani 2004, Muzakkir *et al*, 2015, Hirani, Verma, 2009, Hirani, Suh, 2005, Hirani *et al*, 2001, Rao *et al*, 2000, Hirani *et al*, 2000, Hirani *et al*, 2002).

A typical MR fluid consists of 20-40 volume percentage of pure-iron (purity > 99%) particles (size: Ø3-10 micrometers), suspended in a carrier liquid such as mineral oil, synthetic oil, water or glycol. A variety of proprietary additives to avoid gravitational settling, to elude wear and to promote particle suspension, are added to MR fluids. MR fluids exhibit maximum yield strengths of 50-100 kPa for applied magnetic fields of 150-250 kA/m. MR brake has been studied by various researchers (Muzakkir and Hirani, 2015, Muzakkir and Hirani, 2015, Muzakkir and Hirani, 2015, Sarkar and Hirani, 2015), (Sarkar and Hirani, 2013), (Sukhwani, *et al*, 2009), (Sukhwani and Hirani, 2008), (Sukhwani and Hirani, 2008), (Hirani and Manjunatha, 2007), (Sukhwani, *et al*, 2007), (Sukhwani, *et al*, 2006), (Gupta and Hirani, 2011). In their research, shear thinning behaviour of MR fluid (theoretical model and experimental data) was observed. It appears that none of the researchers has measured the shear behaviour using magnetorheometer.

Table 1 Various viscosity shear rate models

Name	Equation	Comment
Bingham[1916]	$\eta = \frac{(\tau - \tau_o)}{\gamma}$	Frequently used model for plastic and viscous materials.
Casson[1959]	$\eta = \frac{\left(\sqrt{\tau} - \sqrt{\tau_o}\right)^2}{\gamma}$	It provides better fit than Bingham but the value of parameters depend on the range of shear rate considered.
Power Law[1921]	$\eta = k\gamma^{n-1}$ For shear thinning n<1 and for thickening fluids n>1.	At high shear rate, it is observed that fluid having n<1 (i.e. pseudo plastic fluid) becomes Newtonian.
Herschel-Bulkley [1926]	$\eta = \frac{(\tau - \tau_o)}{\gamma^n}$	Combination of power law and Bingham model.
De Kee [1975]	$\eta = \frac{\tau - \tau_o}{\gamma e^{\alpha\gamma}}$	-

In application such as MR brake, the true behaviour of MR fluid cannot be obtained. Therefore in the present study, the shear behavior of MR fluid using magnetorheometer as well as MR brake test setup has been presented.

*Corresponding author: **Chiranjit Sarkar**

2. Viscosity-shear rate model of MR fluids

As per Chen, *et al* (2014) MR fluid exhibits Newtonian fluid-like behavior in absence of the external magnetic field, and the constitutive equation is given as

$$\tau = \eta\dot{\gamma} \qquad (1)$$

The rheological performance of MR fluid under shearing flowing model in presence of the external magnetic field can be described through Herschel-Bulkey model

$$\tau = \tau(H) + \eta(T)\dot{\gamma}^{n} \qquad (2)$$

Where, $\tau(H)$ represents the dynamic yield stress of MR fluid, which varies along with the strength of the external magnetic field, $\eta(T)$ represents the viscosity of MR fluid as function of the operating temperature T, $\dot{\gamma}$ represents the shear strain rate of MR fluid, and n is constant.

There are a number of similar models presented in the Literature and the most widely used models (Larson, 1999) for viscosity-shear rate relation are summarized in Table 1.Due to lack of any reliable model, expressing shear behaviour of MRF, it is necessary to perform experimental study on MRF using magnetorheometer and setup incorporating MR brake so that the viscosity variation with shear rate can be modelled.

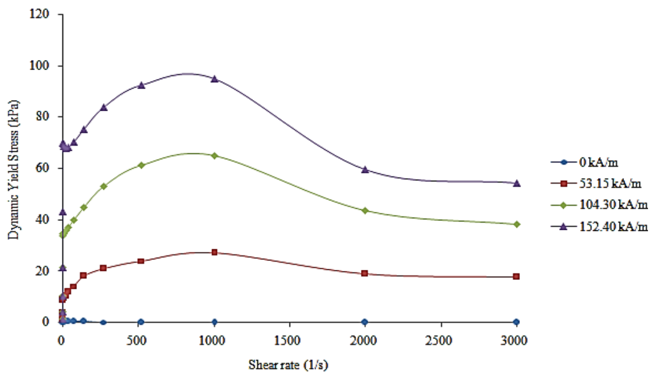
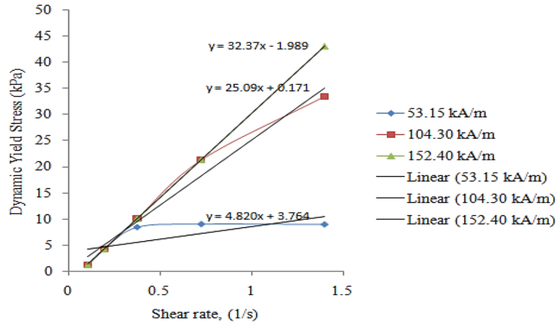
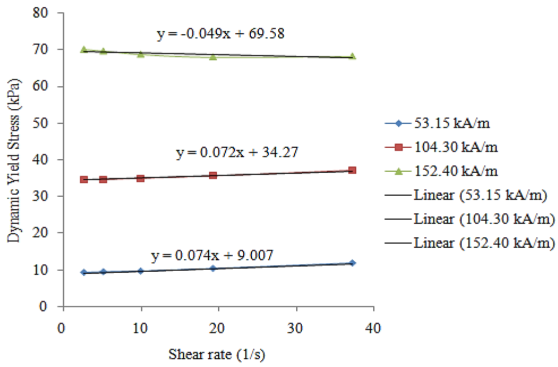


Figure 1 Shear behavior of MR fluids

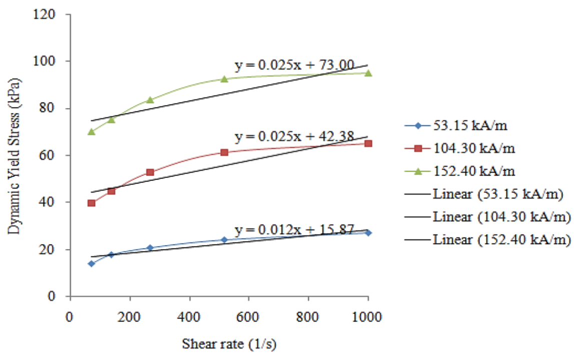
In the present study, ANTON PAAR modular compact rheometer MCR-102 has been used to measure the shear stress flow curve of MR fluid (85% by iron particles) at different magnetic fields in controlled shear rate (CSR) mode. The measurements were performed in a parallel plate system with a diameter of 20 mm at a gap of 1 mm for various input currents (0.1 to 4.8 A). The resulting flow responses have been examined as a function of magnetic field strength ranging from 0 to 152.4 kA/m. The magnetic field strength (A/m) has been calculated from the magnetorheological cell 70/1T MRD. The operating temperature of 30ºC was maintained. The results of yield strength as function of shear rate are plotted in Figure 1. The maximum value of shear rate is 3000, which is the limitation of used Magnetorheometer. It appears that dynamic yield strength increases with increase in shear rate up to 1000 s^{-1}, but there is decrease in yield strength beyond 1000 shear rate. The trend of shear thinning behaviour (from 0 to 1000 s^{-1} shear rate) remains same even when magnetic field is changed from 53.15 kA/m to 152.40 kA/m. However, there is reduction (figure 1) in dynamic strength with increase in shear rate at zero magnetic field. To confirm the shear thinning behaviour, the dynamic yield stress at different shear rate (up to 1000 s^{-1} shear rate) ranges have been plotted in Figure 2. It shows that the slope of the dynamic yield stress vs. shear rate for different magnetic fields reduces.



(a) From shear rate 0 to 1.5s^{-1}



(b) From shear rate 2 to 40s^{-1}



(c) From shear rate 70 to 1000s^{-1}

Figure 2 Shear behavior for different range of shear rate

To study the shear behaviour of MR fluids, the comparison between different available models and synthesised MR fluid model have been plotted in Figure 3.

From this figure it can be concluded that the MR fluid undergoes shear thinning behaviour up to 1000 s^{-1} shear rate, but beyond that it does not follow any particular model. Therefore, it can be concluded that a deeper study is required to model the shear behaviour of MR fluid.

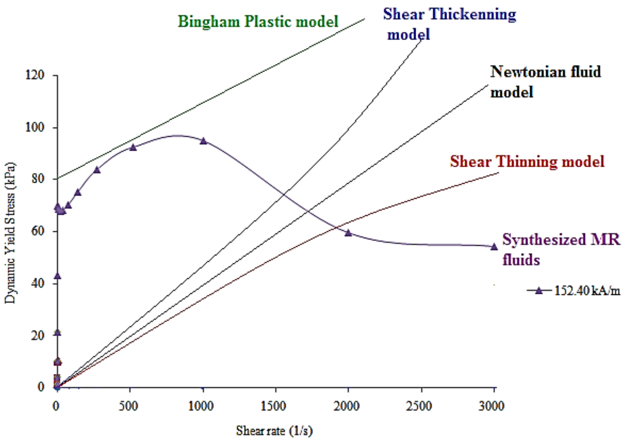


Figure 3 Comparison of MR fluids behaviour with other models

3. Analysis of shear behavior on MR Brake

To understand the rheological behavior of the MR fluid, an experimental study was performed on MR brake. The analysis specially involves study of braking torque vs. temperature at different magnetic field.

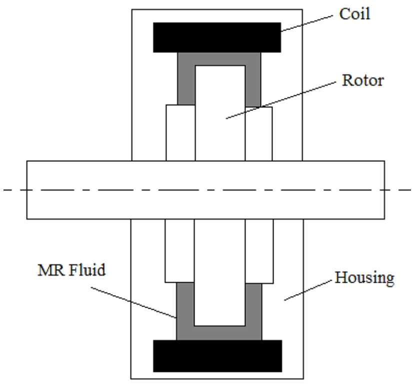


Figure 4 MR brake (Seval, 2002)

3.1. Construction of MR brake

Construction of brake is shown in Figure 4. It consists of rotor fixed to the shaft, which is placed in bearing and can rotate in relation to housing. Between rotor and housing plate, there is a gap filled with MR fluid. Theoretically, a smaller gap will be better because the magnetic flux density in the gap decreases sharply with increasing air gap. In addition, a smaller constant gap can easily maintain a uniform distribution of the magnetic flux in the gap. Practical gap generally range from 0.25 to 2 mm.

Current in the coil, supplied with 12 VDC, creates magnetic field in the gap. Magnetic field strength depends on the current in the coil. Value of the current can be set from 0 to 1 A. Viscosity of the fluid influences torque. When the current in the coil is equal to zero, no magnetic field is generated and brake torque equal to minimum M_{min} is exerted on the shaft. The M_{min} is equal to the torque caused by bearing, seal and viscosity of the carrier liquid. When current is the maximum (1A) then magnetic field is created and brake has highest possible value of the torque M_{max}, that is limited only by maximum current in the coil I_{max} and the construction of the brake.

A heat exchanger was designed and mounted on the circumference of the MR brake to analyze temperature effect on the dynamic viscosity of the MR fluid. The outer diameter of 110 mm was kept and the water was used a circulating coolant to take away heat from MR brake. A schematic block of the experimental set up is shown in Figure 5.

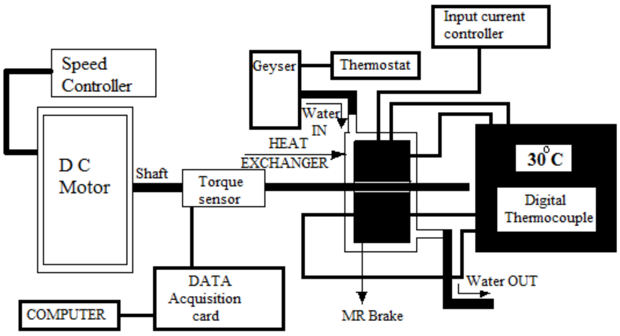


Figure 5. Schematic block of the experimental set up (Sukhwani, *et al*, 2006)

3.2. Experimental set up

An experimental apparatus for evaluating the performance of the MR brake (Lord Corporation MRB 2107-3) was set up. The schematic block diagram is shown in Figure 5. The system is composed of four main parts: DC motor (with associated analog speed regulator), Torque sensor, MR brake and the Heat Exchanger. Torque sensor is connected through a data acquisition card to a computer where values are obtained. The number of samples taken for each reading was 2000 data.

3.3. Procedure

A testing procedure, listed below, was followed

(1) Rotate shaft of MR brake at speed of 200 RPM for 1 min as an initial condition, which stirs the MR fluid in the brake to distribute it evenly. Circulate water at partial opening through the nozzle control gap.
(2) Supply the required current using the 12 VDC power supply source to provide the required current for flux generation.

(3) Control the operating temperature is to the desired level between room temperature to 70ºC.
(4) Measure the torque from the torque sensor. Repeat all sets of reading at 200 and 600 RPM by keeping the temperature constant (i.e. 30˚C). While taking reading it is necessary to check the presence of noise present in the reading. The required values are obtained by averaging all the points.

3.4. Results

To study the shear behavior of MR fluids, the experiments have been done on the experimental set up as described in Sarkar and Hirani (2015). Figure 6 shows the histogram of the braking torque at 200 RPM and 600 RPM. The corresponding shear rates for 200 RPM and 600 RPM are 1000 s^{-1} and 3000 s^{-1}. It shows that with increase in RPM, there is a decrease in braking torque.

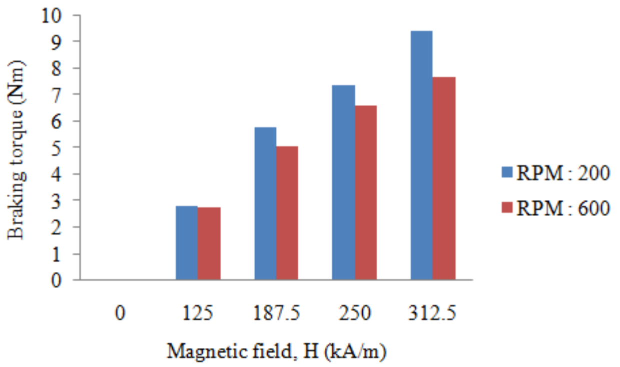


Figure 6 Braking torque at different RPM

Conclusions

In this study, performance of a MR fluid brake has been evaluated to investigate its shear behavior of MR fluid. Following conclusions can be drawn from this study:

1. With increase in speed there is decrease in braking torque.
2. The dynamic yield strength increases with increase in shear rate up to 1000 s^{-1}, but decrease in yield strength beyond 1000 shear rate.
3. If shear rate is larger than 1000 s^{-1}, the MR fluid does not follow any particular model. The trend of shear thinning remains same even when magnetic field is changed from 53.15 kA/m to 152.40 kA/m up to 1000 s^{-1} shear rate. To confirm such behavior of MR fluid, comprehensive study is required.

References

S. Gupta, H. Hirani, (2011), Optimization of magnetorheological brake, *ASME/STLE 2011 International Joint Tribology Conference*, pp 405-406.

H. Hirani, (2009),"Root cause failure analysis of outer ring fracture of four row cylindrical roller bearing", *Tribology Transactions*, vol.52, no.2, pp.180-190.

H.Hirani, K.Athre, S.Biswas, (2000), A Hybrid Solution Scheme for Performance Evaluation of Crankshaft Bearings, *Trans. ASME, Journal of Tribology*, vol. 122, no. 4, pp. 733-740.

H.Hirani, K.Athre, S.Biswas, (1999), Dynamic Analysis of Engine Bearings, *International Journal of Rotating Machinery*, vol. 5, no.4, pp. 283-293.

H.Hirani, K.Athre, S.Biswas, (1998), Rapid and Globally Convergent Method for Dynamically Loaded Journal Bearing Design, *Proc. IMechE (UK), Journal of Engineering Tribology*, vol. 212, pp. 207-214.

S.M.Muzakkir, H.Hirani, G.D.Thakre, M.R.Tyagi, (2011), Tribological Failure Analysis of Journal Bearings used in Sugar Mill, *Engineering Failure Analysis*, vol. 18, no. 8, pp. 2093-2103.

H.Hirani, (2005), Multiobjective optimization of journal bearing using mass conserving and genetic algorithms, *Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology*, vol. 219, no. 3, pp. 235-248.

H.,Hirani, K.,Athre and S.,Biswas," (2001), "Lubricant Shear Thinning Analysis of Engine Journal Bearings", *STLE, Journal of Tribology Transaction*, vol 44, no. 1, pp 125-131.

S.M.Muzakkir, H.Hirani and G.D.Thakre, (2013), "Lubricant for Heavily-Loaded Slow Speed Journal Bearing," Tribology Transactions, vol.56, no. 6, pp. 1060-1068.

H Hirani (2004), "Multiobjective Optimization of a journal bearing using the Pareto optimal concept," *Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology*, vol. 218, no. 4, pp. 323-336.

H Hirani, T Rao, K Athre and S Biswas, (1997), Rapid performance evaluation of journal bearings, *Tribology international*, vol. 30, no.11, pp. 825-834.

H Hirani, K Athre, S Biswas, (1999), "Dynamically loaded finite length journal bearings: analytical method of solution". *Journal of tribology*, vol. 121, no. 4, pp. 844-852.

S M Muzakkir, K P Lijesh, H Hirani, and G D Thakre, (2015) "Effect of Cylindricity on the Tribological Performance of Heavily-Loaded Slow Speed Journal Bearing, Proc. Institute Mech. Engineers., *Part J, Journal of Engineering Tribology*, 2015, vol 229, no.2, pp.178-195.

K.P.Lijesh, H.Hirani, (2015), "Design and Development of Halbach Electromagnet for Active Magnetic Bearing", *Progress In Electromagnetics Research C*, vol. 56, 173–181.

H Hirani and M Verma, (2009), "Tribological study of elastomeric bearings of marine shaft system", *Tribology International*, vol. 42, no. 2, pp. 378-390.

H Hirani and N P Suh, (2005), "Journal Bearing Design using Multiobjective Genetic Algorithm and Axiomatic Design Approaches", *Tribology International*, vol. 38, no. 5, pp. 481-491.

H Hirani, K Athre and S Biswas, (2001),"A Simplified Mass Conserving Algorithm for Journal Bearing under Dynamic Loads", *International Journal of Rotating Machinery*, vol. 1, pp. 41-51.

T V V L N Rao, H Hirani, K Athre, S Biswas, (2000),"An Analytical Approach to Evaluate Dynamic Coefficients and Non-linear Transient Analysis of a Hydrodynamic Journal Bearing", *STLE Tribology Transactions*, vol. 23, no.1, pp. 109-115.

H Hirani, K Athre and S Biswas, (2000), "Transient Trajectory of Journal in Hydrodynamic Bearing", *Applied Mechanics and Engineering*. vol. 5, no 2.

H Hirani, K Athre and S Biswas, (2002),"Comprehensive Design Methodology for Engine Journal Bearing", *IMechE*

(UK), Part J, Journal of Engineering Tribology, vol 214, pp. 401-412.

Muzakkir, S.M. & Hirani, H. (2015), A Magnetorheological Fluid Based Design Of Variable Valve Timing System For Internal Combustion Engine Using Axiomatic Design, *International Journal of Current Engineering Research,* Vol.5, No.2 (April 2015), pp 603-612.

Muzakkir, S.M. & Hirani, H., (2015), Design of Innovative Engine Valve: Background and Need, *International Journal of Scientific Engineering and Technology*, Volume No.4 Issue No.3, pp : 178-181.

Muzakkir, S.M. & Hirani, H., (2015), Design of Innovative Engine Valve, *International Journal of Scientific Engineering and Technology*, Volume No.4 Issue No.3, pp: 212-217.

C. Sarkar, H. Hirani, (2013), Theoretical and experimental studies on a magnetorheological brake operating under compression plus shear mode, *Smart Materials and Structures*, 22, art. no. 115032.

C. Sarkar, H. Hirani, (2013), Synthesis and characterization of antifriction magnetorheological fluids for brake, *Defence Science Journal*, 63, pp. 408-412.

C. Sarkar, H. Hirani, (2013), Design of a squeeze film magnetorheological brake considering compression enhanced shear yield stress of magnetorheologicalfluid, *Journal of Physics: Conference Series*, 412, 012045.

C. Sarkar, H. Hirani, (2015), Transient thermoelasticanalysis of disk brake, International Journal of Current Engineering and Technology, 5, pp. 413-418.

C. Sarkar, H. Hirani, (2015), Magnetorheological smart automotive engine mount, International Journal of Current Engineering and Technology, 5, pp. 419-428.

C. Sarkar, H. Hirani, (2015), Finite element analysis of magnetorheological brake using ANSYS, International Journal of Current Engineering and Technology, 5, pp. 725-732.

C. Sarkar, H. Hirani, (2015), Design of Magnetorheological Brake using Parabolic Shaped Rotating Disc, International Journal of Current Engineering and Technology, 5, pp. 719-724.

C. Sarkar, H. Hirani, (2015), Synthesis and characterization of nano-copper-powder based magnetorheological fluids for brake, International Journal of Scientific Engineering and Technology, 4, pp. 76-82.

C. Sarkar, H. Hirani, (2015), Effect of particle size on shear stress of magnetorheological fluids, *Smart Science,* (in press).

C. Sarkar, H. Hirani, (2015), Development of magnetorheological brake with slotted disc, *Proc. IMechE, Part D: Journal of Automobile Engineering*, pp 1-18.DOI: 10.1177/0954407015574204.

G. Seval, (2002), Synthesis and properties of Magnetorheological fluids, Dissertation, University of Pitsburgh.

H. Hirani, C. S. Manjunatha, (2007), Performance evaluation of magnetorheological fluid variable valve, *Proc. of the Institution of Mechanical Engineers, Part D, Journal of Automobile Engineering*, 221, pp. 83-93.

J. M. Ginder, L. C. Davis,(1994), Shear Stresses in Magnetorheological fluids: Role of Magnetic Saturation, Applied Physics Letters, 65, pp. 3410-3412

R. G. Larson, (1999), The structure and rheology of complex fluids, Oxford University press, New York.

S. Chen, J. Huang, K. Jian, J. Ding, (2014), Analysis of Influence of Temperature on MagnetorheologicalFluid and Transmission Performance, Advances in Materials Science and Engineering, Article ID 583076, pp 1-7.

V. K. Sukhwani, V. Lakshmi, H. Hirani, (2006), Performance evaluation of MR brake: an experimental study, *Indian Journal of Tribology*, pp. 67-52.

V. K. Sukhwani, H. Hirani, T. Singh,(2007), Synthesis of magnetorheologicalgrease, *Greasetech India*.

V. K. Sukhwani, H. Hirani, (2007), Synthesis and characterization of low cost magnetorheological (MR) fluids, *The 14th International Symposium on: Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring*, 65262R-65262R-12.

V. K. Sukhwani, H. Hirani, (2008), A comparative study of magnetorheological-fluid-brake and magnetorheological-grease-brake, *Tribology Online*, 3, pp. 31-35.

V. K. Sukhwani, H. Hirani, T. Singh, (2008), Synthesis and performance evaluation of MR grease, *NLGI Spokesman*,71.

V. K. Sukhwani, H. Hirani, (2008), Design, development and performance evaluation of high speed MR brake, *Proc. Institute Mech. Engineers., Part L, Journal of Materials: Design and Applications*, 222,pp.73-82.

V. K. Sukhwani, H. Hirani, T. Singh, (2009), Performance evaluation of a magnetorheological grease brake, *Greasetech India*, 9, pp. 5-11.