THE EFFECT OF DILUTION OIL IN THE TORQUE PERFORMANCE OF MAGNETORHEOLOGICAL GREASE

KHAIRUL ANWAR BIN ABDUL KADIR

UNIVERSITI TEKNOLOGI MALAYSIA

THE EFFECT OF DILUTION OIL IN THE TORQUE PERFORMANCE OF MAGNETORHEOLOGICAL GREASE

KHAIRUL ANWAR BIN ABDUL KADIR

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Malaysia-Japan International Institute of Technology
Universiti Teknologi Malaysia

JUNE 2022

DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my wife and family, who also supporting me and give the best motivations to complete this journey without any regret and taught me that knowledge is the key of the blissful and successful life.

ACKNOWLEDGEMENT

Alhamdulillah to almighty Allah for his uncountable mercy and blessing for me finish this thesis. In preparing this thesis, I was in contact with many people, researchers, academicians, and practitioners. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Ts. Dr. Nurhazimah Nazmi, for encouragement, guidance, critics and friendship. I am also very thankful to my co-supervisor Dr Shahir Yasin bin Mohd Yusuf and Professor Dr. Saiful Amri bin Mazlan for their guidance, advice and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Malaysia-International Institute of Technology for Scholarship offered which help me to sustain in life while completing my master study. My fellow postgraduate student should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed.

Lastly, to my father, Abdul Kadir bin Che Ngah for his everlasting loves and pray for his kid. To my wife and my siblings, thanks for their support and understanding for over these two years. Without them, this journey may not be possible to be finished.

ABSTRACT

Magnetorheological (MR) brake is a device that uses MR material to produce braking torque according to induced current. Even though MR Fluid (MRF) is widely used in MR brake as it has high response and is easy to fabricate, the sedimentation issue has degraded the performance of MR brake. Therefore, MR grease (MRG) is introduced to overcome the drawbacks of MRF. Another important benefit of MRG is its self-sealing property which can solve the leaking problem in MRF. Despite the advantageous of no sedimentation of MRG, high viscosity of MRG lower the MR response to the current induced. Thus, the high viscosity of MRG can be reduced by adding dilution oil. Furthermore, the effect of the oil in diluted MRG in MR brake has not been investigated. Several samples of MRGs with different types of dilution oil were prepared by mixing grease and spherical carbonyl iron particles (CIP) using mechanical stirrers. The rheological properties in rotational mode were tested by using rheometer meanwhile the torque performance of MRGs in MR brake were evaluated by changing the current of 0A, 0.4A, 0.8A and 1.2A and fixed the angular speed. The result shows that MRG 3 has the lowest viscosity which is almost 93% reduction while the reduction of viscosity of MRG 2 was 25%. Yet, the torque performances generated by MRG 3 was the highest, 1.44 Nm, followed by MRG 2 and MRG 1. This phenomenon indicated that the improvement of torque performance was dependent on the viscosity of MRGs without the occurrence of sedimentation. Thus, the use of MRG with dilution oil as a substitution of MRF could reduce the sedimentation in MR device and improve the torque performance of MRGs in MR brake.

ABSTRAK

Brek reologi magnet (MR) ialah peranti yang menggunakan bahan MR untuk menghasilkan kilas pembrekan mengikut arus teraruh. Walaupun bendalir MR (MRF) telah digunakan secara meluas dalam brek MR kerana ia mempunyai tindak balas yang tinggi dan senang untuk direka, masalah pemendapan pada MRF telah merendahkan prestasi brek MR. Oleh itu, gris MR (MRG) telah diperkenalkan bagi mengatasi kelemahan yang ada pada MRF. Kelebihan MRG yang lain adalah sifat *self-sealing* yang boleh digunakan untuk menyelesaikan masalah kebocoran dalam MRF. Walaupun MRG mampu menyelesaikan masalah pemendapan, kelikatan MRG yang tinggi telah merendahkan tindak balas MR kepada arus teraruh. Disebabkan itu, kelikatan yang tinggi ini boleh dikurangkan dengan tambahan pencairan minyak. Tambahan pula, kesan MRG yang dicairkan dengan menggunakan minyak di dalam brek MR masih belum dikaji. Beberapa sampel MRG dengan tambahan beberapa jenis pencairan minyak yang berbeza telah disediakan dengan mencampurkan gris dan zarah besi karbonil (CIP) yang berbentuk sfera menggunakan pengacau mekanik. Sifat reologi dalam mod putaran telah diuji dengan menggunakan reometer manakala prestasi tork MRG dalam brek MR dinilai dengan menukar arus 0A, 0.4A, 0.8A dan 1.2A dan kelajuan sudut yang telah ditetapkan. Hasil kajian menunjukkan bahawa MRG 3 mempunyai kelikatan yang paling rendah iaitu hampir 93% pengurangan manakala penurunan kelikatan pada MRG 2 ialah 25%. Namun, prestasi tork yang dihasilkan oleh MRG 3 adalah tertinggi, iaitu 1.44 Nm diikuti oleh MRG 2 dan MRG 1. Fenomena ini menunjukkan bahawa peningkatan prestasi tork adalah bergantung kepada kelikatan MRG tanpa berlakunya pemendapan. Oleh itu, penggunaan MRG dengan minyak pencairan sebagai penggantian MRF boleh mengurangkan pemendapan dalam peranti MR dan meningkatkan prestasi tork MRG dalam brek MR.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

MR	-	Magnetorheological
MRF	-	Magnetorheological Fluid
MRG	-	Magnetorheological Grease
MRE	-	Magnetorheological Elastomer
MRPG	-	Magnetorheological Polymer Gels
MRP	-	Magnetorheological Plastomer
CIP	-	Carbonyl Iron Particle
UTM	-	Universiti Teknologi Malaysia
NGLI	-	National Lubricating Grease Institute

LIST OF SYMBOLS

$\dot{\gamma}$	-	Shear rate
τ	-	Shear Stress
τ_y	-	Yield Stress along with magnetic field
η	-	Viscosity
Pa	-	Pascal
T	-	Magnetic flux density
Wt%	-	Weight Percentage

CHAPTER 1

INTRODUCTION

1.1 Problem Background

The last two decades have seen a growing trend towards development of magnetorheological (MR) brake in order to slow and restrict the rotary speed of a shaft via the MR effect [1]. Compared to conventional friction brakes, MR brake has a simple design, low-cost manufacturing, smooth and dependable operating mechanism, fast and reversible reaction, low power consumption and is easy to control with the presence of a magnetic field [2,3]. As such, MR brakes have a wide range of potential uses in various fields and machineries, including the automotive industry, construction, fitness equipment, and machine tools by using computer numerical control [2]. MR brake actuator was firstly proposed by Carlson et al [4] in 1998 by utilizing MR fluid (MRF) as a medium and the maximum generated torque was up to 4 Nm with applied current of 1A. This outcome was sufficient to be applied to low torque devices such as ankle foot orthoses [5,6]. Hence, the same concept has been proposed in vehicle braking systems [7,8] by aiming for at least 400 Nm torque when using 3500 kg automotive brakes [9]. As such, various approaches have been implemented to enhance the torque performances of MR brake for the automotive application. Researchers suggested a modification on the design of disk-type MR brake [10,11], drum-type MR brake [12,13] and T-shape MR brake [14,15], as well as improving the active fluid gap in the MR brake [5] as well as improving the active fluid gap in the MR brake [7,16].

Another factor that can influence torque performance is by improving the rheological properties of the carrier fluid. It has been proven that increasing the weight percentages of magnetic particles [17,18] and the addition of additives [19,20] could enhance the rheological properties of MRF subsequently increased the torque performance in MR brake. Beside, the commercial MRF has a high viscosity in which generated high off-state torque and low power consumption [21]. Even so, utilizing MRF has few drawbacks as its usage in application such as leakage and sedimentation issues, which degraded their performance for long term operations [22]. Therefore, MR grease (MRG) has been introduced and suggested to overcome the problem by using highly viscous grease as a carrier fluid [23–25].

Generally, MRG is prepared by dispersing soft magnetic particles such as Carbonyl Iron Particle (CIP) in grease as the carrier matrix. Commercial grease is a colloidal system which is made up of various thickeners in base oil. Grease thickener is made up of fibres that entangle and form a network [26]. The thickener has formed the three-dimensional fibrous structure that allows increases the apparent viscosity of grease and then stabilized the magnetic particles from suspend in equilibrium against gravitational forces. Therefore, the grease has a high viscosity and thus does not flow easily [27]. The presence of CIP could alter the grease properties through the magnetic field applied. Besides that, MRG exhibits a high initial yield stress that maintain the magnetic particles suspended in equilibrium against gravity. The earlier study on MRG was reported in 1999 which found that MRG able to solve the sedimentation issues in MRF. This occasion happened because the grease medium is a thixotropic material due to the nature of the gelling agent and base oil, which led the MRG act as a non-Newtonian fluid under both off-state and on-state conditions. The behaviour has prevented the magnetic particles to flow in device applications even without an external force. In other words, MRG had self-sealing capability that prevents leaks from the device [28]. Therefore, the properties of MRG that are high viscosity and non-settling properties are critical for industrial applications that require a long-term operation with no leakage, subsequently, reduce the manufacturing cost [29–32].

1.2 Motivation of the Study

Due to the advantages of MRG over MRF, there were a few studies conducted on the torque transfer application of MRG particularly in MR clutches and MR brakes. Gordaninejad et al. [33] compared the braking torque performance of MRG with a with a different weight percentage (wt%) of CIP with MRF in an MR clutch at different operating speeds ranging from 300 to 1200 rpm. They discovered that the torque generated by MRG increased as the weight percentage of CIP increased. At off-state, the initial torque of an MR clutch employing MRG with 99 wt% CIP was 200% greater than the similar clutch using commercial MRF. While in the on-state condition, the torque generated by MRG was 75% more than that of MRF. The findings, however, were not comparable since the wt % of CIP in MRF was lower than in MRG. Then, Sukhwani et al [34] extended the research in MR brake by using the same wt% of CIP, 90 wt% in MRG as well as MRF. The study revealed that the initial brake power output of MRG was two times higher than MRF at off-state condition. Yet, at on-state condition, the brake power output of MRG was two times lower than MRF. Thus, to improve the torque performance of MRG, Singh et al [35] have designed a new wedge-shaped drum MR clutch by utilizing 50 and 75 wt% of CIP in MRG. The obtained torque has increased by 150% higher than the traditional MR clutch. However, the off-state torque of MRG has increased nearly 8% as the CIP content increased from 50 to 75 wt%. This phenomenon was presumably caused by the influences of rheological properties of MRG to the torque performance of MRG in MR brake. Thus, Dai et al [22] explored the effect of wt% on the rheological properties and their performance in speed reduction of MR brake. The viscosity, shear stress and yield stress of MRG have reduced with increasing the wt% CIP at off-state condition. For the performance of MRG brake test, the initial rotational speed at off-state condition was fixed at 13000 r/min. With the increased of the magnetic field, the rotational speed of MR brake was decreased for all samples. Nevertheless, the rotational speed reduction produced by MRG with 50 wt% of CIP was higher than 30 and 10wt% of CIP. Thus, the increment of wt% of CIP has enhanced the chain formation in MRG brake. However, the high initial viscosity of carrier fluid was a drawback, therefore, it should be reduced considerably to reduce the brake's viscous drag in the off-state condition [36]. In a study done by Li et al [37] mentioned that when the MR brake rotated, the high viscous drag produced a high heat energy due to the device's zero-field friction. This problem became more severe when the MR brake was used in a high torque and high-power device, which also increased the MR brake's size. As a result, an effort has been taken in order to reduce the initial viscosity of MRG such as by introducing the additives.

Numerous research has reported that the addition of dilution oil capable to lower the initial viscosity of MRG. Kim et al [38] discovered that addition 5 wt%

kerosene oil in MRG reduced the initial viscosity which indicated a better dispersion of magnetic particles in the grease medium. Then, Mohamad et al [39] investigated the compatibility of various oils including kerosene, hydraulic, and castor toward MRG behaviour. Interestingly, the result showed that the hydraulic oil was the most compatible with the grease medium compared to other types of dilution oil, and the initial apparent viscosity of the MRG decreased as the percentage of dilution oil increased. This phenomenon occurred due to the addition of oils, which reacted as a lubricant in the MRG and enhanced the distribution of CIP in the grease medium. In another study, the effect of oil percentages particularly silicone oil and castor oil as additives, and their optimum wt% of dilution oil in MRG without the occurrence of sedimentation was explored [40]. They found that the dilution oil changed the structure of the magnetizable particles in the grease medium, thus, indirectly reduced the off-state viscosity MRG. Furthermore, the addition of oil less than 10 wt% could produce a stable MRG.

1.3 Problem Statement

MRG has proven as a potential candidate to be utilized in MR brake since, it overcome the sedimentation and leakage issues in MRF. However, MRG exhibited a high initial viscosity which had caused a viscous drag at off-state condition of the brake. Although the addition of oil in MRG able to reduce the initial viscosity, research related on its performance in MR brake has not been reported yet. Therefore, what is the impact of the MRG with dilution of oil on the torque of MR brake is investigated. Furthermore, what is the correlation between the viscosity of MRG and their torque performance in MR brake is explored.

1.4 Research Objective

The main objective of this study is to investigate the effect of addition oil in MRG to the torque performance of MR brake. Meanwhile the specific objectives are as follow:

(a) To fabricate MRG with the dilution of 10wt% hydraulic oil and 10wt% of kerosene oil.

(b) To analyse the rheological properties of MRG under rotational mode.

(c) To evaluate the torque performance of MRG in MR brake under various of magnetic field.

1.5 Research Scope

The scopes of research are detailed on the experimental investigation of the rheological properties of MRG and their torque performance in MR brake. The scopes of the research are listed as below:

(a) Fabrication of MRG with 10wt% of hydraulic oil and 10wt% of kerosene oil as additive by using mechanical stirrer.

(b) Rheological characterization of MRG samples on the apparent viscosity and shear stress were investigated under rotational using rheometer under various current from 0A to 1.2A at room temperature.

(c) The torque performance of MRG samples were evaluated with increasing current from 0A to 1.2A by using MR brake's test rig.

1.6 Research Contribution

In this work, oil dilution was added into MRG as an additive, and the obtained findings show that decreasing the initial viscosity of MRG in the off-state condition is capable of reducing the viscous drag of MRG in MR brake. Furthermore, MRG with oil dilution can be employed to increase MR brake torque performance. As a result, MRG with oil dilution was proposed to be considered in MR brake devices. The following are the research's contributions:

(a) The improvement of the torque performance of MRG brake by reducing the viscosity of the MRG which has enhanced the distribution of CIP and the mobility of CIP in grease medium indirectly enhanced the chain formation in MRG with application of magnetic field.

(b) The research also contributed to the correlation between the rheological properties of MRG and their torque performance in MR brake. According to the findings, the rheological properties in term of yield stress may be used to control the braking torque of an MRG brake.

1.7 Thesis Outline

This thesis is organized into five chapters. The first chapter briefly explains introduction to the topic examined, the purpose for the study in relation to past relevant studies, the problem statement, the objectives that aim to be accomplished in the scope of this research, and the significance of the research. An overview of each chapter is also presented in this chapter.

Chapter two contains a review of the literature on the development of MR brakes, MR material particularly on MRG, the potential additives that can used in MRG brake to reduce the initial torque of MR brake in off-state condition, as well as an explanation of the rheological properties of MR materials and many examples of applications that could be used with MRG.

The third chapter details the experiment's preparation, which includes material selection, the fabrication of MRG samples using a traditional mixing method, a report on the rheological testing on all of the samples in rotational mode at different magnetic field strengths, and the torque performance of MRG samples in the MR brake.

The fourth chapter presented the results of rheological testing and torque performance of MRG in MR brake under current applications of 0A, 0.4A, 0.8A, and 1.2A. The acquired results were analysed in the form of a graph, table and figure, and were thoroughly discussed in order to provide a correlation between MRG viscosity and torque performance in an MR brake.

Chapter five summarises the findings of the research, as well as the contribution and suggestions for possible future works.

REFERENCES

1. Sohn JW, Gang HG, Choi SB. An experimental study on torque characteristics of magnetorheological brake with modified magnetic core shape. Adv Mech Eng. 2018;10(1):1–8.
2. Wang DM, Hou YF, Tian ZZ. A novel high-torque magnetorheological brake with a water cooling method for heat dissipation. Smart Mater Struct. 2013;22(2):11.
3. Hu G, Wu L, Li L. Torque Characteristics Analysis of a Magnetorheological Brake with Double Brake Disc. Actuators. 2021;10(23):1–17.
4. Carlson JD, LeRoy DF, Holzheimer JC, Prindle DR, Marjoram RH. Controllable Brake. United States Patent. 1998.
5. Abdul Rahman MA, Adiputra D. Personalized Gait Treatment Using Passive Controllable Ankle Foot Orthosis. IOP Conf Ser Mater Sci Eng. 2021;1096(1):012002.
6. Adiputra D, Azizi Abdul Rahman M, Bahiuddin I, Ubaidillah, Imaduddin F, Nazmi N. Sensor Number Optimization Using Neural Network for Ankle Foot Orthosis Equipped with Magnetorheological Brake. Open Eng. 2020;11(1):91–101.
7. Hu G, Wu L, Li L, Yu L. Performance analysis of rotary magnetorheological brake with multiple fluid flow channels. IEEE Access. 2020;8:173323–35.
8. Li S, Meng W, Wang Y. Numerical and experimental studies on a novel magneto-rheological fluid brake based on fluid–solid coupling. Sci Prog. 2020;103(1):1–33.
9. Razmi-Ishak M, Abu-Bakar AR, Belhocine A, Mohd-Taib J, Wan-Omar WZ. Brake torque analysis of fully mechanical parking brake system: Theoretical and experimental approach. Ing Investig y Tecnol. 2018;19(1):37–49.
10. Ningning Wang , Xinhua Liu , Grzegorz Królczyk, Zhixiong Li WL. Effect of Temperature on the Transmission Characteristics of High- Torque Magnetorheological Brakes. Smart Mater Struct. 2019;28(5):1–20.
11. Zhou W, Chew CM, Hong GS. Development of a compact double-disk magneto-rheological fluid brake. Robotica. 2007;25(4):493–500.

12. Kikuchi T, Kobayashi K. Development of cylindrical magnetorheological fluid brake for virtual cycling system. In: 2011 IEEE International Conference on Robotics and Biomimetics, ROBIO 2011. IEEE; 2011. p. 2547–52.
13. Khafaji SOW, Manring N. Sensitivity analysis and Taguchi optimization procedure for a single-shoe drum brake. Proc Inst Mech Eng Part C J Mech Eng Sci. 2019;233(10):3690–8.
14. Adiputra D, Rahman MAA, Ubaidillah, Mazlan SA. Improving Passive Ankle Foot Orthosis System Using Estimated Ankle Velocity Reference. IEEE Access. 2020;8:194780–94.
15. Nya'Ubit IR, Priyandoko G, Imaduddin F, Adiputra D, Ubaidillah. Torque Characterization of T-shaped Magnetorheological Brake Featuring Serpentine Magnetic Flux. J Adv Res Fluid Mech Therm Sci. 2020;78(2):85–97.
16. Avraam M, Horodinca M, Romanescu I, Preumont A. Computer controlled rotational MR-brake for wrist rehabilitation device. J Intell Mater Syst Struct. 2010;21(15):1543–57.
17. Acharya S, Shyam Saini Tak R, Bhanu Singh S, Kumar H. Characterization of magnetorheological brake utilizing synthesized and commercial fluids. In: Materials Today: Proceedings. Elsevier Ltd; 2020. p. 1–6.
18. Sun W, Yu J, Cai Y. Influence of magnetic field, magnetic particle percentages, and particle diameters on the stiffness of magnetorheological fluids. J Intell Mater Syst Struct. 2020;31(20):2312–25.
19. Thakur MK, Sarkar C. Thermal and Tribological Performance of Graphite Flake-Based Magnetorheological Fluid Under Shear Mode Clutch. J Tribol. 2021;143(12).
20. Vadillo V, Gómez A, Berasategi J, Gutiérrez J, Insausti M, Gil de Muro I, et al. High magnetization FeCo nanoparticles for magnetorheological fluids with enhanced response. Soft Matter. 2021;17(4):840–52.
21. Quoc NV, Tuan LD, Hiep LD, Quoc HN, Choi SB. Material characterization of MR fluid on performance of MRF based brake. Front Mater. 2019;6(125):1–15.
22. Dai J, Chang H, Zhao R, Huang J, Li K, Xie S. Investigation of the relationship among the microstructure, rheological properties of MR grease and the speed reduction performance of a rotary micro-brake. Mech Syst Signal Process. 2019;116:741–50.

23. Tarmizi S.M.A., Nordin N.A*, Mazlan S.A., Mohamad N., Rahman H.A A, S.A.A., Nazmi N. AM. Incorporation of Cobalt Ferrite on the Field Dependent Performances of Magnetorheological Grease. Sci Total Environ. 2020;9(6):15566–74.
24. Mohamad N, Mazlan SA, Ubaidillah, Choi SB, Imaduddin F, Abdul Aziz SA. The field-dependent viscoelastic and transient responses of plate-like carbonyl iron particle based magnetorheological greases. J Intell Mater Syst Struct. 2019;30(5):788–97.
25. Mohd Nasir NA, Nazmi N, Mohamad N, Ubaidillah U, Nordin NA, Mazlan SA, et al. Rheological performance of magnetorheological grease with embedded graphite additives. Materials (Basel). 2021;14(17):1–15.
26. Meijer RJ, Lugt PM. The Grease Worker and Its Applicability to Study Mechanical Aging of Lubricating Greases for Rolling Bearings. Tribol Trans [Internet]. 2021;65(1):32–45. Available from: https://doi.org/10.1080/10402004.2021.1979151
27. Wang K, Dong X, Li J, Shi K, Li K. Effects of silicone oil viscosity and carbonyl iron particleweight fraction and size on yield stress for magnetorheological grease based on a new preparation technique. Materials (Basel). 2019;12(11):7–9.
28. Bahiuddin I, Mazlan SA, Shapiai MI, Mohamad N, Imaduddin F. A model of magnetorheological grease using machine learning method. Key Eng Mater. 2018;775 KEM:191–7.
29. Mohamad N, Mazlan SA, Ubaidillah, Choi SB, Nordin MFM. The Field-Dependent Rheological Properties of Magnetorheological Grease Based on Carbonyl-Iron-Particles. Smart Mater Struct. 2016;25(9):1–10.
30. Park BO, Park BJ, Hato MJ, Choi HJ. Soft magnetic carbonyl iron microsphere dispersed in grease and its rheological characteristics under magnetic field. Colloid Polym Sci. 2011;289(4):381–6.
31. Sahin H, Wang X, Gordaninejad F. Temperature dependence of magneto-rheological materials. J Intell Mater Syst Struct. 2009;20(18):2215–22.
32. Wang H, Zhang G, Wang J. Normal force of lithium-based magnetorheological grease under quasi-static shear with large deformation. RSC Adv. 2019;9(47):27167–75.
33. Gordaninejad F, Kavlicoglu BM, Wang X. Study of a magneto-rheological

grease (MRG) clutch. In: Active and Passive Smart Structures and Integrated Systems 2007. 2007. p. 1–7.

34. Sukhwani VK, Hirani H. A Comparative Study of Magnetorheological-Fluid-Brake and Magnetorheological-Grease-Brake. Tribol Online. 2008;3(1):31–5.

35. Singh A, Kumar Thakur M, Sarkar C. Design and development of a wedge shaped magnetorheological clutch. Proc Inst Mech Eng Part L J Mater Des Appl. 2020;234(9):1252–66.

36. Patil SR, Sawant SM. Experimental studies on magnetorheological brake for automotive application. Int J Automot Mech Eng. 2018;15(1):4893–908.

37. Li W, Haiping Du, Huan Zhang, Ning D, Sun S, Li W, et al. Design and testing of a novel two-way controllable overrunning clutch based magneto-rheological brake. Smart Mater Struct. 2019;

38. Kim JE, Ko J Do, Liu YD, Kim IG, Choi HJ. Effect of medium oil on magnetorheology of soft carbonyl iron particles. IEEE Trans Magn. 2012;48(11):3442–5.

39. Mohamad N, Rosli MA, Ubaidillah, Aziz SAA, Mazlan SA, Nordin NA, et al. Intrinsic Apparent Viscosity and Rheological Properties of Magnetorheological Grease with Dilution Oils. In: Proceedings of the 6th International Conference and Exhibition on Sustainable Energy and Advanced Materials Lecture Notes in Mechanical Engineering Springer, Singapore. Proceedings of the 6th International Conference and Exhibition on Sustainable Energy and Advanced Materials; 2019. p. 171–80.

40. Mohamad N, Yasser A, Fatah A, Mazlan SA, Nordin NA, Nabil M. Dilution dependent of different types of redispersing oils on magnetorheological greases. Int J Eng Technol. 2019;8(1.7):107–11.

41. Naik N, Karan C, Padte V. Design and Fabrication of Magnetorheological Brake. Int Res J Eng Technol [Internet]. 2019;6(8):918–28. Available from: www.irjet.net

42. Andrade RM de, Storch AP, Paulo L de A, Filho AB, Vimieiro CBS, Marcos Pinotti. Transient Thermal Analysis of a Magnetorheological Knee for Prostheses and Exoskeletons during Over-Ground Walking. Intech [Internet]. 2021;13. Available from: http://dx.doi.org/10.1039/C7RA00172J%0Ahttps://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-

biometrics%0Ahttp://dx.doi.org/10.1016/j.colsurfa.2011.12.014

43. Shamieh H, Sedaghati R. Development, optimization, and control of a novel magnetorheological brake with no zero-field viscous torque for automotive applications. J Intell Mater Syst Struct. 2018;29(16):3199–213.
44. Bhau K. Kumbhar, Vikas R. Khalkar, Pravin N. Jadhav SRP. Design of Magneto-Rheological Brake for Automotive. Int J Eng Sci Res Technol. 2015;4(2):238–49.
45. Lijesh KP, Kumar D, Gangadharan K V. Design of magneto-rheological brake for optimum dimension. J Brazilian Soc Mech Sci Eng [Internet]. 2018;40(3):1–12. Available from: https://doi.org/10.1007/s40430-018-1089-5
46. Li WH, Du H. Design and experimental evaluation of a magnetorheological brake. Int J Adv Manuf Technol. 2003;21(7):508–15.
47. Wu J, Hu H, Li Q, Wang S, Liang J. Simulation and experimental investigation of a multi-pole multi-layer magnetorheological brake with superimposed magnetic fields. Mechatronics. 2020;65(May 2019).
48. Song W, Wang S, Choi SB, Wang N, Xiu S. Thermal and tribological characteristics of a disc-type magnetorheological brake operated by the shear mode. J Intell Mater Syst Struct. 2019;30(5):722–33.
49. Nya'Ubit IR, Priyandoko G, Imaduddin F, Adiputra D, Ubaidillah U. Characterization of T-shaped magneto-rheological brake. J Adv Res Mater Sci. 2020;71(1):1–11.
50. Nguyen HQ, Le TD, Nguyen DN, Le TD, Lang T V., Ngo T V. Development of 3-DOF force feedback system using spherical arm mechanism and mr brakes. Int J Mech Eng Robot Res. 2020;9(2):170–6.
51. Ahamed R, Choi SB, Ferdaus MM. A state of art on magneto-rheological materials and their potential applications. J Intell Mater Syst Struct. 2018;29(10):2051–95.
52. Ahmad Khairi MH, Mazlan SA, Ubaidillah, Choi SB, Abdul Aziz SA, Mohamad N, et al. Role of Additives in Enhancing the Rheological Properties of Magnetorheological Solids: A Review. Adv Eng Mater. 2019;21(3):1–13.
53. Kumar JS, Paul PS, Raghunathan G, Alex DG. A review of challenges and solutions in the preparation and use of magnetorheological fluids. Int J Mech Mater Eng. 2019;14(1).
54. Dong YZ, Han WJ, Choi HJ. Additive effect of rod-like magnetite/sepiolite

composite particles on magnetorheology. J Ind Eng Chem. 2021;93:210–5.
55. Aruna MN, Rahman MR, Joladarashi S, Kumar H. Influence of additives on the synthesis of carbonyl iron suspension on rheological and sedimentation properties of magnetorheological (MR) fluids. Mater Res Express. 2019;6(8).
56. Han JK, Lee JY, Choi HJ. Rheological effect of Zn-doped ferrite nanoparticle additive with enhanced magnetism on micro-spherical carbonyl iron based magnetorheological suspension. Colloids Surfaces A Physicochem Eng Asp. 2019;571(March):168–73.
57. Fei C, Haopeng L, Mengmeng H, Zuzhi T, Aimin L. Preparation of magnetorheological fluid with excellent sedimentation stability. Mater Manuf Process. 2020;35(10):1077–83.
58. Mohamad N, Ubaidillah, Mazlan SA, Choi SB, Aziz SAA, Sugimoto M. The effect of particle shapes on the field-dependent rheological properties of magnetorheological greases. Int J Mol Sci. 2019;20(7):1–13.
59. Wang K, Dong X, Li J, Shi K. Yield dimensionless magnetic effect and shear thinning for magnetorheological grease. Results Phys. 2020;18(May):103328.
60. Rankin PJ, Horvath AT, Klingenberg DJ. Magnetorheology in viscoplastic media. Rheol Acta. 1999;38(5):471–7.
61. Jopen M, Degen P, Henzler S, Grabe B, Hiller W, Weberskirch R. Polyurea Thickened Lubricating Grease—The Effect of Degree of Polymerization on Rheological and Tribological Properties. Polymers (Basel). 2022;14(4):1–18.
62. Jinaga R, Thimmaiah J, Kolekar S, Choi S-B. Design, fabrication and testing of a magnetorheologic fluid braking system for machine tool application. SN Appl Sci. 2019;1(4):1–12.
63. Wu C, Cheng C, El-Aty AA, Li T, Qin Y, Yang Q, et al. Influence of particles size and concentration of carbonyl iron powder on magnetorheological properties of silicone rubber-based magnetorheological elastomer. Mater Res Express. 2020;7(8).
64. Mohamad N, Ubaidillah, Mazlan SA, Choi SB, Halim NA. Improvement of magnetorheological greases with superparamagnetic nanoparticles. MATEC Web Conf. 2018;159:8–12.
65. Bahiuddin I, Wahab NAA, Shapiai MI, Mazlan SA, Mohamad N, Imaduddin F, et al. Prediction of field-dependent rheological properties of magnetorheological grease using extreme learning machine method. J Intell

Mater Syst Struct. 2019;30(11):1727–42.

66. Wang Y, Zhang P, Lin J, Gao X. Rheological and Tribological Properties of Lithium Grease and Polyurea Grease with Different Consistencies. coatings. 2022;12:527.

67. Pisuwala M, Upadhyay R V., Parekh K. Evaluation of Static and Dynamic Yield Stress for Isotropic and Anisotropic Particle–Based MR Fluids: Modeling and Analysis. Brazilian J Phys. 2020;50(4):399–409.

68. Patel SR, Upadhyay R V. Life-Cycle Evaluation of Anisotropic Particle-Based Magnetorheological Fluid in MR Brake Performance. Brazilian J Phys. 2020;50:525–533.

69. Zhang E, Li W, Zhao G, Wang Z, Wang X. A Study on Microstructure, Friction and Rheology of Four Lithium Greases Formulated with Four Different Base Oils. Tribol Lett [Internet]. 2021;69(3):1–9. Available from: https://doi.org/10.1007/s11249-021-01469-z

70. Gang HG, Choi S-B, Sohn JW. Experimental Performance Evaluation of a MR Brake-Based Haptic System for Teleoperation. Front Mater. 2019;6:113–22.

71. Qin H, Song A, Zeng X, Hu S. Design and evaluation of a small-scale multi-drum magnetorheological brake. J Intell Mater Syst Struct. 2018;29(12):2607–18.

LIST OF PUBLICATIONS

Conference Paper

1. Khairul Anwar Abdul Kadir, Nurhazimah Nazmi, Shinichirou Yamamoto, Saiful Amri Mazlan, Nur Azmah Nordin, and Shahir Mohd Yusuf. “A Review on Torque Performance for Different Type of Carrier Fluid in Magnetorheological Brake.” 6^{th} International Conference on Mechanical Engineering Research 2021. Lecture Notes in Mechanical Engineering. (Indexed by SCOPUS) (Status: Accepted)