DESIGN AND INVESTIGATION OF A NEW MIXED-MODE MAGNETORHEOLOGICAL DAMPER

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

Malaysia-Japan International Institute of Technology Universiti Teknologi Malaysia

JULY 2016
To my beloved father

MOHD YAZID DAROS

Mother
ZHRAH MOHAMAD

And

Sisters
IZYAN IRYANA
NURHIDAYAH
NUR HIDAYU

The source of all the good in me
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ABSTRACT

Magnetorheological (MR) fluids are field-responsive material with the ability to change its rheological behavior by having an external magnetic field. Therefore, they are commonly used in vibration damping, clutches, actuators and haptic devices. Generally, MR devices are fabricated utilizing the operational mechanism of a single working mode which is either flow, shear or squeeze. However, for this study a special MR damper was designed and fabricated to carry out a dynamic loading test and analyze the effect on a hydrocarbon-based MR fluid in a combination of shear and squeeze working modes. The damping force generated by shear mode is measured based on the force-displacements relationship of applied current and piston stroke length. The cushion effect generated by the squeeze mode is evaluated by the magnitude of the damping force at various piston stroke lengths. The MR damper could produce a damping force ranging from 50 to 270 N with zero input of current, up to 0.8 A without any saturation occurring from 15 to 25 mm of the piston stroke length. However, when the piston was closing to the bottom of the cylinder from 25 to 26 mm, a high peak force was observed confirming the existence of the squeeze mode. The cushion effect started as soon as the current was applied showing a high magnitude of 722 N at only 0.2 A. As the applied current increased further to 0.8 A, a very high squeeze force up to 1030N was produced when the piston nearly reached the cylindrical end. This proves that the cushion effect induced by the squeeze mode helps strengthen the damping force and consequently brings a positive impact towards a mixed mode damper when the piston is nearly closing the gap at the bottom of the cylinder. In conclusion, a high yield stress MR damper at a small gap clearance was successfully produced and this uniqueness can be utilized as a replacement of the conventional rubber stopper in dampers.
ABSTRAK

Cecair Reologi Magnet (MR) adalah bahan responsif dengan keupayaan untuk mengubah tingkah laku reologi melalui medan magnet luar. Oleh itu, cecair ini biasa digunakan dalam redaman getaran, cengkaman, penggerak dan peranti haptik. Secara umumnya, peranti MR direka menggunakan mekanisme operasi mod kerja tunggal sama ada aliran, ricih atau himpitan. Walau bagaimanapun, untuk kajian ini, sejenis peredam MR khas telah direka dan dibina untuk menjalankan ujian pembebanan dinamik dan menganalisis kesan pada cecair MR yang berasaskan hidorkarbon dalam gabungan mod kerja ricih dan himpitan. Daya redaman yang dijana oleh mod ricih diukur berdasarkan hubungan daya-anjakan yang dikenakan oleh arus dan panjang strok omboh. Kesahan kusyen yang dihasilkan oleh mod himpitan pula dinilai dengan magnitud daya redaman pada kепelbagaian panjang strok omboh. Peredam MR boleh menghasilkan daya redaman antara 50 hingga 270 N dengan input arus sifar sehingga 0.8 A tanpa berlakunya ketepuan pada 15 hingga 25 mm panjang strok omboh. Walau bagaimanapun apabila omboh menghampiri ke bahagian bawah silinder pada jarak 25 hingga 26 mm, puncak daya yang tinggi diperolehi dan mengesahkan kewujudan mod himpitan. Kesahan kusyen didapati bermula sebaik sahaja arus diinputkan dengan menunjukkan magnitud tinggi iaitu 722 N pada arus input kecil 0.2 A. Ketika arus ditingkatkan kepada 0.8 A, daya himpitan yang sangat tinggi sehingga 1030 N terhasil apabila omboh menghampiri bahagian akhir silinder. Ini membuktikan bahawa kesahan kusyen yang disebabkan oleh mod himpitan membantu menguatkan daya redaman dan seterusnya membawa kesahan yang positif terhadap peredam mod campuran apabila omboh menghampiri jurang di bahagian bawah silinder. Pada kesimpulannya, tegasan alah tinggi peredam MR pada pelepasan jurang yang kecil telah berjaya dihasilkan dan keunikan ini boleh digunakan untuk mengganti penutup getah konvensional dalam peredam.
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$B$ - Magnetic flux density
$H$ - Magnetic field intensity
$M$ - Magnetization of the material
$m$ - Magnetic dipole moment of particles
$a$ - Diameter of the particles
$\mu$ - Permeability of the material
$\mu_f$ - Specific permeability of particles
$\mu_0$ - Permeability of vacuum
$\mu_p$ - Specific permeability of carrier liquid
$\mu_sM_s$ - Saturation magnetization of the particles
$\tau$ - Shear stress
$\tau_y$ - Yield stress
$\eta$ - Viscosity
$\rho$ - Density
$\phi$ - Volume fraction of the suspended solutes or particles
$I_s$ - Saturation polarization of the particles
$L_1$ - Length of cylinder
$D_D$ - Diameter of piston
$D_R$ - Diameter of piston rod
$S$ - Thickness of shear gap
$S_1$ - Thickness of squeeze gap
$L_D$ - Length of piston pole
$T$ - Thickness of cylinder
$J$ - Current density
$I_m$ - Maximum current supplied to the coil
$A_w$ - Surface area of the uncoated wire
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<td>Magnetic vector potential</td>
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<tr>
<td>$A$</td>
<td>Ampere</td>
</tr>
<tr>
<td>$\mu_r$</td>
<td>Relative magnetic permeability</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>Permeability of free space</td>
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<td>$n$</td>
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<td>$I$</td>
<td>Current input</td>
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<tr>
<td>$L_{coil}$</td>
<td>Length of coil</td>
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<td>MR</td>
<td>Magnetorheological</td>
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<td>MRF</td>
<td>Magnetorheological fluid</td>
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<tr>
<td>FEM</td>
<td>Finite Element Method</td>
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<td>FEMM</td>
<td>Finite Element Method Magnetics</td>
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<tr>
<td>VSM</td>
<td>Vibrating Sample Magnetometer</td>
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<tr>
<td>AGM</td>
<td>Alternating Gradient Magnetometer</td>
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<td>CAD</td>
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<tr>
<td>AWG</td>
<td>American Wire Gauge</td>
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<td>CI</td>
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| CIP   | Carbonyl iron particle
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CHAPTER 1

INTRODUCTION

1.1 Introduction

Magnetorheological (MR) fluids are smart materials whose rheological properties are sensitive to magnetic field [1–4]. They are comprised of carrier liquid, iron particles and surfactant additives that are used to discourage particle sedimentation. Several different carrier fluids are utilized in MR fluids such as hydrocarbon-based oil, silicon oil, and water [1]. The viscosity of MR fluids changes significantly 10^5-10^6 times within milliseconds when the magnetic field is applied [5]. Additionally, their properties have been investigated since the late 1940s [6] and lately have gained attention because they can produce the highest stress, which is useful in many applications [7–9].

MR fluids can operate in three different working modes depending on the type of deformation employed such as the flow mode, the shear mode, and the squeeze mode [10–12]. In the flow mode, the MR fluid is made to flow between static plates, while in the shear mode, the MR fluid is located between two plates and sheared parallel to the plate that slides or rotates relative to the other plate. Meanwhile, in squeeze mode, the MR fluid is squeezed by a force in the same direction of the magnetic field under compression or tension loadings. In practice, the MR devices can use a combination of these three modes to overcome the performance limitation of a single working mode [12,13].
1.2 Motivation of Study

MR fluid is a smart material that responds to an applied magnetic field with a change in its rheological behavior. The essential characteristic of MR fluid is the ability to reversibly change from free-flowing, linear and viscous liquid to a semi-solid with a controllable yield strength instantaneously when exposed to the magnetic field. Recently, devices using MR fluid have been actively studied as controllable engineering components because of their continuously adjustable mechanical properties and rapid response. MR devices can be operated in different ways depending on the requirements of the application. The three common operational modes that have been applied in MR devices are the flow, the shear, and the squeeze modes. In practice, MR devices may utilize a combination of available modes to overcome performance limitation of a single working mode [12,13]. Most previous studies involving mixed working modes have focused on the combination of flow and shear modes. However, in recent years, researchers have begun to explore the combination of two other modes which involved shear and squeeze modes [14,15].

The effectiveness of the combination of shear and squeeze modes in the MR device was investigated by Kulkarni et al. [16]. Their results showed that although the squeeze mode could produce the highest strength compared to all the working modes, the introduction of squeeze mode to shear mode does not always increase the yield stress of MR fluid. In another experimental study done by See and Tanner [17], the performance of the combination of shear and squeeze modes for the MR fluid was also investigated. They observed a normal force was arising from the MR fluid that sandwiched between two plates where the magnetic field applied normally to the plate surfaces. When the MR fluid was not subjected to any deformation, it was found that the normal force was increased with the increasing magnetic flux density. However, when the MR fluid was subjected to continuous shearing, the normal force of the fluid has decreased with shear strain, eventually reaching a plateau value which became lower with higher shear rates. This behavior was referred to the breakage of the chain-like structure of particles due to the shear forces. According to Tang et al. [18], the yield stress of MR fluid strongly depended on the arrangement of magnetic particles structure in a magnetic field. The MR fluid with the thick column structure will have
a higher yield stress compared than the MR fluid with the single-chain structure. The phenomenon resulted from the formation of thicker and stronger columns of particles that were able to increase the yield stress of MR fluid up to 800 kPa. A further study about the physical mechanism and microstructure of MR fluid was investigated by Tao [3]. They have found that the weak points of the MR microstructure under the shear force occurred at the end of the chains. Thus, a compression-aggregation process was developed to change the induced MR structure to the structure that consists of robust thick columns with strong ends. Zhang et al. [19] studied the mechanism of the squeeze-strengthen effect in MR fluids. They proposed an apparatus to analyze the effect of mechanical compression on MR fluid in shear mode condition. Their results revealed that a very high compression stress could enhance the yield stress of MR fluid for a given magnetic field, which showing the squeeze strengthen effect. When the MR fluid was compressed, the distances between the iron particles in the MR fluid were decreased, whereby the magnetic forces between the particles were increased. In another study, Spaggiari and Dragoni [20] had confirmed that by having the squeeze-strengthen effect, it could increase the yield stress of MR fluid due to the influence of magnetic field and the applied pressure. Moreover, Becnel et al. [21] suggested the method to increase the yield stress of MR fluids by combining the shear and squeeze modes to manipulate the particle chain structures due to the squeeze strengthening. A further study about the detailed investigation of the relationship between the compression force and the shear stress enhancement of the MR fluid in rotational actuator was presented in Hegger and Maas [22]. They developed a conical MR fluid test actuator with a conical shear gap to compress the MR fluid. From their results, they concluded that the shear stress of MR fluid could be increased by the squeeze strengthening effect at least two times than the normal shear stress of MR fluid.

The excellent results on the squeeze strengthening effect of MR fluid have a potential to be used in the MR devices, particularly in the MR damper. This effect will be very useful for the MR damper whether to enhance the performance or to give an additional feature in the MR damper. There are many research works on the development of MR damper especially in terms of providing the damper to be used in real applications. In several studies, the success of MR damper is proven by the improvements and modifications that had been made to the features on the MR damper. For example, Bai et al. [23] proposed an MR damper with an inner bypass to produce
high dynamic range and low off-state stroking load for the ground vehicle suspensions. Meanwhile, Sohn et al. [24] presented an MR damper featuring piston bypass holes to achieve a low slope of the damping force at low piston velocity and high magnitude of the damping force at high piston velocity. In several studies, some researchers have investigated the effects of temperature on the performance of MR damper [5,25,26]. Besides that, Wang and Wang [27] suggested an integrated relative displacement sensor technology into MR damper for the semi-active vehicle suspension systems that can reduce the cost and improve the system reliability. Hu et al. [28] proposed an MR damper which has a self-sensing ability by developing a linear variable differential sensor based on the electromagnetic induction mechanism. Although many types of researches have been studied on the features of MR dampers, however, to the best of author’s knowledge, the cushion effect in the design of MR damper has been not discovered. Normally, the cushion effect in a damper is produced by a rubber stopper. The cushion effect is necessary as a damper protection from unwanted impact in order to reduce a risk of damage on the damper operated under severe environmental vibrating conditions. However, the installation of rubber stopper is not suitable due to an incompatibility of the rubber with the hydrocarbon oil that is contained in the MR fluid [1]. Furthermore, in this case study, based on the design of the damper, the rubber stopper will limit the stroke length of the piston and the overall size of MR damper.

1.3 Research Objectives

MR fluids exhibit excellent properties as a result of rapid changes, dramatic and reversible consistency in a magnetic field. The priority for any type of MR fluid or working modes depending on the application requirements. Thus, the investigation on the behavior of MR fluid under dynamic loading condition has attracted some attention of academic researchers and engineers. The potentials of MR fluid can only be fully exploited if the properties and the design of the device are accommodated to each other. The main objective of this study is to analyze the behavior of MR fluid by having a combination of shear and squeeze working modes. More specifically, the aims of this study can be summarized as follows:
1. To simulate the magnetic field generated by the coils to improve magnetic field strength at the effective areas.

2. To develop a test rig in order to carry out the dynamic loading test under a combination of shear and squeeze working modes.

3. To analyze the squeeze strengthening effect of MR fluid in the test rig by having a combination of shear and squeeze working modes.

4. To evaluate the influence of applied currents and piston stroke lengths on the behavior of MR fluid in test rig by having a combination of shear and squeeze working modes.

1.4 Research Scope

Consequently, the technical originality of this study is to introduce a mixed mode MR damper in which the cushion effect can be produced to reduce the unwanted impact. In order to achieve this goal, a custom test rig in the forms of MR damper with a combination of shear and squeeze working modes was developed to analyze the behavior of squeeze strengthening effect of MR fluid. The shear mode that is generated by the movement of the piston is used to provide the damping force. Meanwhile, the squeeze mode generated when the piston nearly reaches to the bottom of the cylinder is used to obtain the cushioning effect. The magnetic field strength generated by the coils in the MR damper is simulated using Finite Element Method Magnetics (FEMM) software package. All aspects of geometry parameters involving the selection of materials, the position of coils, the type of coils, the number of turns of coils and the polarity of coils are considered and adjusted efficiently within FEMM in order to increase the magnetic field strength at the effective areas. In addition, the magnetic circuit design in the MR damper is analyzed based on the several parameters including the effect of applied currents, the gap sizes and the position of the piston in the cylinder. Then, the MR damper is fabricated based on the magnetic field simulation studies. An experimental assessment is conducted by measuring the damping force under dynamic...
loading testing with two different parameters namely the applied current and the piston stroke length. However, the parameter involving the velocity of the piston movement will not be included. The damping force produced by the MR damper is measured based on the relationship between force and displacements. After characterizing the effect of applied current on the behavior of damping force of the proposed MR damper, the cushioning effect is investigated by changing the piston stroke lengths. This effect is evaluated by the magnitude of damping force at a certain piston location with the applied current.

1.5 Outline of Thesis

This thesis is organized in five chapters. A concise and inclusive review of the highlighted research process is shown in Figure 1.1. Each respective chapter in this thesis ends with a brief summary outlining the achievements and findings that were established in the chapter. Apart from this introduction chapter, the remainder of this thesis is organized as shown:

Chapter 2: This chapter thoroughly reflects the theoretical background and previous works related to the MR fluid including properties of MR fluid, working modes and applications.

Chapter 3: This chapter covers the simulation and experimental procedures related to the design of test rig in order to increase the magnetic field strength that generated by the coils at the effective areas.

Chapter 4: This chapter provides the results and discussions of the simulation studies of magnetic field and behavior of MR fluid in the MR damper.

Chapter 5: This chapter presents the conclusions and highlights of the research contribution with recommendations for future research work.
Figure 1.1 Summary of the research process in Chapter 1
of the cylinder. The answer to this issue will be beneficial to understand the basic knowledge of the squeeze behavior and also as an advantage to design the device by using a squeeze mode to be worked under severe dynamic loadings.

c) It would be interesting to model the behavior of MR damper by having the presence of a cushioning effect. It is remarked here that the cushioning indeed provides additional complexity that is represented by another degree of non-linearity caused by the sudden increase of the damping force. This complexity is not favorable in control of the damping force of MR damper, especially it is integrated with the inherent hysteresis behavior of the damper. Therefore, it will become a challenge to the controller design to equip suitable controller for the MR damper if the cushioning force is considered in the operation.
REFERENCES


