A NOVEL MAGNETORHEOLOGICAL VALVE WITH MEANDERING FLOW PATH STRUCTURE

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To my father, my mother, my wife and my brothers

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ABSTRACT

The development of a new Magnetorheological (MR) valve with meandering flow path as a new approach to improve the MR valve performance is presented in this research. The meandering flow path was formed by the arrangement of multiple annular and radial channel so that the total effective area in an MR valve can be increased without compromising the size and power requirement of the valve. The main objective of this research is to explore the achievable pressure drop of the MR valve with meandering flow path. This research was started with the concept development where the meandering flow path structure is analytically modeled and numerically simulated to predict and analyze the effect of variables involved. The prediction results showed that the meandering flow path structure is able to increase the achievable pressure drop of an MR valve significantly. The gap size analysis showed that the size of annular gaps mainly contributed to determine the viscous pressure drop component. Meanwhile, the field-dependent pressure drops were mainly determined by the size of radial gaps. The prediction results of the concept was also assessed and confirmed by the experimental work using a dynamic test machine. Based on the experimental data, two hysteresis models, namely the polynomial model and the modified LuGre model, were developed to model the hysteresis behavior. The assessment results of the hysteresis models indicated that both model were able to replicate the hysteresis behavior. However, the modified LuGre model, though 9.5% less accurate than the polynomial model, was showing better consistency in a wider range of input values. In general, the new concept contributes in the development of a new type of MR valve that could achieve pressure drop nearly three times than the annular, radial and annular-radial type MR valve.

ABSTRAK

Pembangunan konsep baru injap reologi magnet (MR) dengan menggunakan laluan aliran yang berliku-liku sebagai pendekatan baru untuk meningkatkan prestasi injap MR dibentangkan dalam kajian ini. Laluan aliran yang berliku-liku dibentuk melalui beberapa susunan saluran gegelang dan tebaran jejari secara berurutan supaya jumlah kawasan yang berkesan di dalam injap MR boleh ditingkatkan tanpa menjejaskan saiz keseluruhan dan prestasi injap. Tujuan utama kajian ini adalah untuk meneroka kebolehcapaian nilai susutan daripada injap MR dengan menggunakan laluan aliran yang berliku-liku. Kajian ini bermula dengan pembangunan konsep, di mana injap dengan laluan aliran yang berliku-liku dimodelkan secara analitikal dan disimulasikan secara berangka untuk meramalkan prestasi injap dan juga untuk mengambil kira kesan pembolehubah yang terlibat. Keputusan simulasi menunjukkan bahawa konsep injap dengan laluan aliran yang berliku-liku mampu meningkatkan kebolehcapaian yang ketara dari segi nilai susutan tekanan daripada injap MR. Berdasarkan kepada analisis saiz saluran telah dijalankan, hasil menunjukkan bahawa saiz saluran gegelang lebih menyumbang kearah menentukan komponen kelikatan dari susutan tekanan manakala komponen susutan tekanan akibat medan magnet ditentukan terutamanya oleh saiz saluran dari tebaran jejari. Konsep ini turut dinilai melalui kerja eksperimen menggunakan mesin ujian dinamik, yang telah mengesahkan keputusan yang diramalkan oleh simulasi. Berdasarkan data eksperimen, dua model histerisis, iaitu model polinomial dan model LuGre yang telah diubahsuai, telah dibangunkan untuk mengilustrasikan tingkah laku histerisis injap MR. Keputusan penilaian model histerisis menunjukkan bahawa kedua-dua model dapat mereplikasi ciri-ciri histerisis daripada injap MR. Walau bagaimanapun, model LuGre yang telah diubahsuai, walaupun 9.5% kurang tepat berbanding model polinomial, telah menunjukkan konsistensi yang lebih baik dalam pelbagai ruang lingkup data masukan yang lebih besar. Secara umumnya, konsep baru injap MR ini dapat memberikan pendekatan baru dalam membangunkan sebuah injap MR yang dapat meningkatkan kebolehcapaian susutan tekanan sehingga tiga kali ganda berbanding injap MR jenis gegelang, jejari dan gegelang-jejari.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDIX

CHAPTER 1

INTRODUCTION

1.1 Introduction

Magnetorheological (MR) fluid is one of the fluids in the class of field responsive material [1, 2], that has sensitive rheological properties to magnetic field [3–7]. The development of the fluid, together with the progressing research in the understanding of its behavior, has convinced researchers and engineers that MR fluid is a promising material for future applications [8–10]. This is because of their adaptive force capacity and their inherent ability to provide a simple, fast and robust interface between electronic controls and mechanical components. The fluid was first introduced in Rabinow's Magnetic clutch in 1948 [11] and has gained in popularity since entering the automotive market. MR fluid is very responsive to magnetic field, with an estimated response time of less than 10 milliseconds [12], and requires relatively low power to operate. The advantages of MR fluid have created great interest in MR based device development in a wide range of applications.

One of the most popular devices that utilized the unique characteristics of MR fluid is MR damper [13], which has been commercially available for high-end passenger vehicles as a semi-active suspension or adjustable suspension [14]. The working principle of an MR damper is basically similar to a conventional viscous damper which employs flow restriction concept to generate damping. The flow restriction in a conventional viscous damper is normally generated by an orifice channel which act as the valve. Since the gap of the orifice channel is fixed, the flow restriction that can be generated by the valve of the conventional viscous damper is also fixed. The MR dampers use different approach by employing MR fluids as its working fluid and an MR valve in its flow restriction mechanism. Although the gap size of the channel in an MR valve also can be fixed, the magnetic field strength in the flow channel of the MR valve can be regulated [15]. Therefore, the flow of MR fluid that pass through the MR valve can be controlled without having to modify the gap size of the channel. On the other hand, it can be said that the performance of the MR valve to generate flow restriction highly determines the overall performance of the MR damper.

Considering the importance of MR valve, many designs of MR valve have been proposed. One of the earliest design of stand-alone MR valve was proposed in Kordonski et al. [16] which later elaborated by Gorodkin et al. [17]. In the literatures, annular MR valve designs with optimize-able geometry and controllable MR fluid flow resistance were provided. A simpler concept of annular MR valve was proposed by Yokota et al. [18], which consisted of annular flow channel and electromagnetic coil installed in adjacent to the flow channel. The works were improved by Yoshida et al. [19] by proposing a three-port annular MR valve using permanent magnet. In the same time, a meso-scale (less than 25 mm outer diameter) annular MR valve were proposed by Yoo and Wereley [20] using internal double coils with counter flux direction. While the advancement of annular type MR valve were continuously explored, Wang et al. [21] started to discuss about the radial type MR valve for the large-scale seismic bypass damper configuration. The benefit of radial MR valve over annular MR valve in terms of pressure drop rating as well as the benefit of external bypass MR valve configuration was compared in the literature. Performance assessments of MR valve were also performed by Grunwald and Olabi [22] through the performance analysis of the annular and orifice type MR valve. The discussions of MR valve type were extended by Ai et al. [23] and Wang et al. [24] through an MR valve design with both annular and radial flow path. In their design, both type of resistance channel were used in an MR valve to increase the on-state resistance force while maintaining valve size and power consumption. In order to make an MR valve more applicable to retrofit general hydraulic applications, Yoo and Wereley [25] introduced the installation of multiple MR valves in H-bridge configuration to actuate a hydraulic cylinder. The work then followed by John et al. [26] with the embedded version of H-bridge MR valve and by Salloom and Samad [27] with the introduction of 4/3 way MR valve design.

1.2 Motivation of Study

MR damper for semi-active vehicle suspension systems are among the most popular and commercially successful MR fluid devices [28–34]. In general, vehicle suspension system can be divided into three categories; passive suspension system, semi-active suspension system, and active suspension system [35]. Passive suspension system is the common suspension system installed in most vehicle nowadays which typically consists of spring and damper in parallel configuration. Semi-active suspension system is similar with passive suspension system but the stiffness of the component (spring and/or damper) can be controlled to suit the desired ride or handling performance [36, 37]. Active suspension system, on the other hand, is the suspension system with the involvement of active actuators such as hydraulic [38], pneumatic [39] or electro-mechanic [40,41], which could provide external force to the suspension. MR dampers are usually implemented as a semi-active device to retrofit hydraulic dampers to enhance passive suspension performance. Enhancement of suspension performance is feasible since the performance limitations of passive suspension system occurred due to a fixed stiffness value of the spring and damper. In this case, MR damper, in contrast to conventional linear hydraulic damper, has the capability to change its damping stiffness by varying the magnetic field strength inside the damper. Together with embedded control system, MR dampers have gained popularity and proved its potential to enhance the performance of suspension systems. Aside of dampers, other types of MR devices have been developed to meet other automotive application demands such as engine vibration suppressors [42–45], seat suspensions [46–49], brakes [50–53] and clutches [54–57].

According to the location of the valve, the MR damper can be divided into two groups, the MR damper with internal valve and the MR damper with bypass valve. The MR damper with internal valve typically has MR valve embedded in the piston of the damper, similarly with the configuration of the valve in a conventional viscous damper. This configuration is the most common valve installation in an MR damper since it is neat and compact. However, the internal valve configuration is not without setback. The disadvantages of internal valve configurations are mainly in the space limitation of MR valve installation, the complexity of wiring and in the risk of thermal build-up from the immersed valve. The MR valve integration to the piston is the main reason why the construction of the MR damper with internal valve can be really neat and compact. However, since the available space inside the cylinder is very limited and the MR valve requires sufficient space for electromagnetic coil and magnetization channel, the performance range of the damper is very narrow. Moreover, since the coil is embedded with the piston, the common way of wiring installation is normally made through the conduit along the rod, which made it prone to leakages and tends to be costly for fabrication. On the other hand, the heat dissipation, as a result of kinetic energy conversion into heat, can be more severe in an MR damper than in a conventional viscous damper because the magnetically altered damping stiffness will definitely increase the heat dissipation. In the case where the MR valve is immersed in the MR fluid, the heat dissipation from the MR valve will have to disperse to the MR fluid first, which responsible in the increase of fluid temperature, before eventually released to the environment. The experimental observation conducted by [58] reported that the temperature rise of MR fluid in an MR damper after 400 s of operation at current input of 2 A and frequency excitation of 6 Hz have caused the damping force to degrade in about 38%. However, the same experiment observed that less degradation can be achieved if the MR damper is properly finned, whereas increase the thermal release to the environment.

The practice in the other type of MR damper, known as the bypass MR damper, is not embedding the valve in its piston since the construction uses no fluid channel in the piston [59]. In the bypass MR damper, the fluids flow between chambers through the bypass channel outside the cylinder where MR valve is installed. Therefore, the valve in the bypass MR damper configuration is easier to be installed and maintained since the construction of the main cylinder is similar with the structure of a conventional hydraulic cylinder. The bypass MR damper is also less prone to over-heat because the valve is already located outside the cylinder. Various types of MR valve also can be implemented in an MR damper with bypass configuration because the valve size is no longer constrained by the cylinder size nor the piston size. However, the existence of bypass channel and MR valve outside the cylinder are obviously making the bypass construction not as neat and compact as the damper with internal valve. The MR damper with bypass configuration is also difficult to be installed in space-constrained applications since the bypass damper requires more room than the damper with internal valve. With these characteristics, the bypass configuration is normally implemented in the large scale MR damper with high energy dissipation [60–62].

Despite the advantages and disadvantages of each MR damper structure, the technological advancement of the MR valve, as the heart of the MR damper performance, is not as extensive as the advancement of the MR damper. Regardless the types of MR damper, most of them are still using the same MR valve concept. The only differences are probably the size, coil configuration and/or MR fluid types. Most of MR dampers are employed with annular type MR valve as one of the most popular types of MR valve [29, 46, 49, 63–68]. The annular MR valve is the first generation of MR valve that utilized the annular channel as the effective area. The effective area is the area where the MR fluids are exposed to magnetic flux perpendicularly to the flow direction. There are several variants of annular MR valve that has been proposed by researchers [16–20, 69], but the main concept is basically similar. The annular MR valve is popular because it is simple to be manufactured and has a high ratio between the on-state and off-state performance. However, the effectiveness of space utilization in the conventional annular MR valve is very low because not all areas of the annular channel can be utilized as the effective area. Therefore, any improvement effort on the annular valve performance will typically tend to increase the valve size either in length, by enlarging the effective area, or in diameter, by enlarging the electromagnetic coil. Thus, in a constrained space device such as in the MR damper with internal valve configuration, the desired performance improvements are sometimes difficult to be achieved.

Due to the limitation of the annular MR valve, another type of valve, known as the radial MR valve, was introduced by [21]. The radial MR valve, as a distinction from annular MR valve, has radial flow channel inside the valve and utilize it as the effective area. The utilization of radial channel as the effective area offers several benefits than the effective area of the annular channel, especially in terms of area efficiency since the radial channel can be made in multi-stage configuration. Therefore, with multi-stage capability of the radial MR valve, the performance improvement of radial valve typically has lower implication to the valve size than the one in the annular MR valve. As a result, the radial valve concept has been installed to serve several concepts of large scale MR dampers [61, 62, 70, 71]. Recently, another concept of MR valve also has been developed by combining both annular and radial valve concept in a single valve [23, 24]. The combination of both annular and radial channel in an MR valve has been proven effective to improve the performance of MR valve. It has been reported by [72] that the MR valve with combination of annular and radial channel has higher achievable pressure drop than annular valve with lower power consumption although at the cost of lower valve ratio. The MR valve with combination of annular and radial channel also has been implemented in MR mount design [42] and MR damper design [73].

From these explanations, it can be observed that the technological advancement of an MR valve has a significant impact to the advancement of other MR devices. Therefore, particular explorations of the MR valve concept are necessary as a basis to provide knowledge on how to improve the performance of MR devices in general. The concept explorations is not limited to the geometrical and design arrangements of the MR valve, but also in terms of behavioral characteristics of the MR valve such as the identification of the MR valve hysteretic behavior. The hysteretic behavior, as well as other complex characteristics, in generally in any MR devices is still considered a challenging problem in terms of the modeling technique and controller design [14, 74]. The hysteresis could be occurred due to magnetic field remnant in steel elements and due to the viscoelastic properties of MR fluid itself. In terms of controllability, hysteresis behavior is a disadvantage since the controller will face difficulties to track the damper behavior. For example, according to Wang and Liao [74], tracking ability of damping force is one of the highly important issues that should be considered in order to get an accurate MR damper controller. However, a controller with such capability will tend to be more complex, require more computational resources, be costly and less robust. Therefore, innovation in the control design is also vital to support the final implementation of MR devices. Innovation of the control algorithm will be more difficult if the model that is used in the controller design phase is not able to simulate the hysteresis phenomenon accurately. A simple and accurate model of an MR valve, in particular, is needed in order to design an appropriate controller with good robustness, stability and reliability. Therefore, the advancement of modeling technique that have the ability to accommodate the hysteretic behavior of MR valve is as important as the advancement of the MR valve concept.

1.3 Research Objectives

This study embarks on the following objectives:

(a) To develop a new concept of MR valve with meandering flow path to improve the achievable pressure drop.

(b) To analyze the effect of gap size selection to the achievable pressure drop of MR valve.

(c) To assess the performance of MR valve using experimental work.

(d) To model the hysteretic behavior of the MR valve.

1.4 Research Scope

In this research, a new concept of MR valve will be investigated. This study focuses on the elaboration of a new concept of MR valve utilizing the combination of multiple annular and radial gaps that formed a meandering flow path. The new concept of MR valve is introduced to provide an adjustable pressure drop with a high on-state limit. In order to examine the capability of the MR valve, the steady-state model of the new MR valve concept is derived and the magnetic circuit performance of the MR valve is simulated using Finite Element Method Magnetics (FEMM) software package. The performance of MR valve, in this study, is only evaluated in terms of the achievable pressure drop as a function of gap size of the flow channel, magnitude of current input charged to the coil, and fluid flow rate. This research is also covering the experimental evaluation of the MR valve using an MR valve testing cell in variable flow rates, to reveal the hysteretic behavior, with constant current inputs. The measured performance of the MR valve is also used to model the hysteretic behavior of the MR valve, which is not covered in the steady-state model. However, the optimization of the concept is not discussed in this research and the demonstration of control application is only performed.

1.5 Significance of Research

The significance of this research is mainly in terms of general advancement of MR devices and applications especially to answer the demand of smart, simple yet high performance and reliable new MR devices. The new concept of MR valve with meandering flow path is expected to provide a new method to improve the design of an MR valve, which will highly influence the design of MR damper as well as other MR based actuators. Moreover, the concept is expected to be performed as a demonstration of a generic MR device that can suit various applications. Therefore, the concept can be anticipated as a modular and re-sizable device so that the range of operation and the capacity can be adjusted. The significances of this research are summarized as follows:

(a) This study demonstrates a new concept of MR valve using a meandering flow path structure.

(b) This research provides knowledge of the effect of gap size selection to the achievable pressure drop of the valve which will be further useful for valve sizing process.

(c) The hysteretic modeling process of the MR valve introduces a new modeling approach of MR valve using modified LuGre hysteresis model.

1.6 Outline of Thesis

This thesis is organized in six chapters. Each respective chapter in this thesis ends with a brief summary outlining the achievements and findings that were established in the chapter. The outline of this thesis is organized as shown:

Chapter 2 covers the theoretical background, which includes the properties and the working modes of MR fluids, the basic knowledge of MR valves, the recent advancement of MR valves, as well as the applications of MR valves.

Chapter 3 explains the new concept of the MR valve with meandering flow path, the design consideration for the performance assessment, the steady-state model derivation, the magnetic simulation as well as the performance prediction of the new MR valve with respect to various dependent variables.

Chapter 4 elaborates the experimental evaluation of the MR valve including the description of the experimental setup, the experimental procedure and the analysis of the experimental results.

Chapter 5 presents the development of two different hysteresis MR valve models, the parameter estimation processes and the performance comparison of these two models.

Chapter 6 concludes the work and presents the achieved contribution of the research as well as recommends open problems for future work.

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