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

ZAHRAH MOHAMAD

And

Sisters

IZYAN IRYANA

NURHIDAYAH

NUR HIDAYU

The source of all the good in me

ACKNOWLEDGEMENT

I am grateful to Almighty Allah for the fulfillment of my desire to finish this thesis. Completing a Ph.D. is truly a marathon event, and I would not have been able to complete this journey without the aid and support of countless people in this three years. My deepest gratitude goes firstly to my main supervisor, Assoc. Prof. Ir. Dr. Saiful Amri Mazlan for his tremendous support during my entire study. His intensive encouragement, enthusiasm, guidance, understanding and patience have made me able to pass through this process easier. I also would like to thank you, my co-supervisor, Dr. Hairi Zamzuri for his advice, interest and support to my work. Over the years, I have enjoyed the scholarship from Malaysia-Japan International Institute of Technology (MJIIT) which supported me while completing my Ph.D. This research would not have been possible without the financial assistance of MJIIT Student Incentives, Universiti Teknologi Malaysia and The Ministry of Higher Education of Malaysia. I express my gratitude to those sponsors.

My sincere thanks also go to Dr. Wira Jazair Yahya, Dr. Izwan Ismail, and Dr. Mohd Azizi Abdul Rahman for their encouragement, suggestion, and insightful comments to make this thesis a successful one. Appreciation is also given to the faculty members and colleagues in the Vehicle System Engineering (VSE) research laboratory, especially, Dr. Fitrian, Dr. Yasser, and Jamal for helping me a lot during my earlier time in the university. Not forget to the other members in VSE laboratory which have helped make my time during this study more fun and interesting. Thanks also to Mr. Hairulail, and the remaining MJIIT staffs that have been supportive to me during my study. Special acknowledgment goes to Prof. Dr. Nor Haniza Sarmin, SPS staffs, and Postgraduate Students Society UTM (PGSS-UTM) members. Their encouragements and moral supports have made this journey more valuable. I regret that I cannot mention all the valuable names here, but I believe and pray that Allah will reward all the good deeds.

Needless to say, this entire exercise would be at most a dream if it was not for my loving family. To my parents, Mohd Yazid Daros and Zahrah Mohamad, education has been as important as food in my development, and they have diligently encouraged my study. Their unlimited love, support, trust and pray have brought me to this level. Finally, to my three sisters; Izyan Iryana, Nur Hidayah, and Nur Hidayu, whom have provided me with an invaluable emotional support.

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. Kesan kusyen yang dihasilkan oleh mod himpitan pula dinilai dengan magnitud daya redaman pada kepelbagaian 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. Kesan kusyen didapati bermula sebaik sahaja arus diinputkan dengan menunjukkan magnitude 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 kesan kusyen yang disebabkan oleh mod himpitan membantu menguatkan daya redaman dan seterusnya membawa kesan 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.

TABLE OF CONTENTS

CHAPTER	TITLE	PAGE
	DECLARATION	ii
	DEDICATION	iii
	ACKNOWLEDGEMENT	iv
	ABSTRACT	vi
	ASBTRAK	vii
	TABLE OF CONTENTS	viii
	LIST OF TABLES	xi
	LIST OF FIGURES	xii
	LIST OF ABBREVIATIONS	xvi
	LIST OF APPENDICES	xviii
1	**INTRODUCTION**	**1**
	1.1 Introduction	1
	1.2 Motivation of Study	2
	1.3 Research Objectives	4
	1.4 Research Scope	5
	1.5 Outline of Thesis	6
2	**LITERATURE REVIEW**	**8**
	2.1 Introduction	8
	2.2 Magnetorheological Fluid	8
	2.2.1 Synthesizing Magnetorheological Fluid	9
	2.2.2 Magnetic Properties of Magnetorheological Fluid	12

	2.2.3	Rheological Properties of Magnetorheological Fluid	13
2.3		Magnetorheological Fluid Working Modes	16
	2.3.1	Flow Mode	16
	2.3.2	Shear Mode	17
	2.3.3	Squeeze Mode	19
2.4		Magnetorheological Fluid Applications	22
2.5		Magnetorheological Damper	23
	2.5.1	Design of Magnetorheological Damper	25
	2.5.2	Working Mechanism	28
	2.5.3	Magnetic Circuit Design	31
	2.5.4	Coil Configurations	32
2.6		Summary of Chapter 2	34
3	**METHODOLOGY**		**37**
3.1		Introduction	37
3.2		Magnetorheological Material	37
3.3		Conceptual Design	39
3.4		Finite Element Method Magnetics	42
	3.4.1	Problem Definition and Creating Model Geometry	43
	3.4.2	Boundary Conditions	44
	3.4.3	Material and Circuit Properties	46
	3.4.4	Meshed Geometry	49
	3.4.5	Finite Element Method Magnetics Analysis	51
3.5		Magnetorheological Damper Design	52
	3.5.1	Selection of Coils	58
	3.5.2	Fabrication of Magnetorheological Damper	60
3.6		Experimental Set-up	62
	3.6.1	Test Procedures	63
3.7		Summary of Chapter 3	65

4	**BEHAVIOR OF MAGNETORHEOLOGICAL FLUID**		**67**
	4.1	Introduction	67
	4.2	Magnetic Circuit Analysis	67
		4.2.1 Effect of Coil	69
		4.2.2 Effect of Piston's Position	72
		4.2.3 Effect of Gap Size	74
		4.2.4 Effect of Applied Current	75
	4.3	Behavior of Damping Force	76
		4.3.1 Effect of Applied Current on the Damping Force	77
		4.3.2 Effect of Piston Stroke Lengths on the Damping Force	80
		4.3.3 Cushion Effect	83
	4.4	Summary of Chapter 4	85
5	**CONCLUSION**		**87**
	5.1	Introduction	87
	5.2	Contribution of the Thesis	91
	5.3	Recommendations for Future Work	92
REFERENCES			**94**
Appendices A-B			109-117

LIST OF TABLES

TABLE NO.	TITLE	PAGE
2.1	Composition of various types of MR fluid	10
2.2	The properties of MR fluids	15
3.1	Physical properties of tested MR fluid	38
3.2	List of parts and materials for MR damper	55
3.3	List of changes in the design concept	55
3.4	Specifications of the copper wire needed to make the coil	60
3.5	Design details and materials for each component of the MR damper	62
3.6	Test parameters for MR damper	64

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Summary of the research process in Chapter 1	7
2.1	The characteristics of MR fluid during the OFF-state (without magnetic field) and ON-state (with magnetic field)	9
2.2	Basic concept of flow mode	16
2.3	Basic concept of shear mode	18
2.4	Basic concept of squeeze mode	19
2.5	Basic concept of compression in squeeze mode	20
2.6	Basic concept of tension in squeeze mode	22
2.7	Section view of commercial MR damper	24
2.8	Design structure of monotube MR damper	25
2.9	Design structure of twin-tube MR damper	26
2.10	Design structure of double-ended MR damper	27
2.11	Schematic of MR damper incorporated with external and internal coils	33
2.12	Summary of the research process in Chapter 2	36

3.1	Magnetic property of MRF-132DG obtained from manufacturer's material datasheet	39
3.2	A sketch of the design concept of mixed mode MR damper	40
3.3	A conceptual design of MR damper	41
3.4	Problem definition in FEMM	44
3.5	Applying boundary conditions in FEMM	46
3.6	Material properties selection for the model of damper	47
3.7	Constructing MRF-132DG material model in FEMM	47
3.8	The *B-H* curve of MRF-132DG in FEMM	48
3.9	The input current in FEMM	49
3.10	Triangulation of Massachusetts	50
3.11	Meshed geometry in FEMM	51
3.12	Magnetic field analysis in MR damper. (a) Simulated magnetic flux density distribution and (b) the magnetic flux lines in MR damper	52
3.13	Schematic of the (a) original design of MR damper and (b) average values of magnetic flux density at shear and squeeze areas	53
3.14	Diagram of the (a) conceptual design of MR damper after modifications and (b) middle of MR damper at the initial design concept	54
3.15	A new design of mixed mode MR damper	58
3.16	Magnetic field intensity for each wire gauge	59
3.17	The schematic of a new design of mixed mode MR damper	60
3.18	The fabrication of mixed mode MR damper	61

3.19	Experimental set-up for MR damper test	63
3.20	Summary of the research process in Chapter 3	66
4.1	Magnetic field distribution in the MR damper at shear and squeeze gaps	68
4.2	The average values of magnetic flux density at the top of cylinder	69
4.3	Simulation analysis on (a) the magnetic flux lines across MR fluid and (b) the average values of magnetic flux density at the shear gap	71
4.4	Simulation analysis on (a) the magnetic flux lines across MR fluid and (b) the average values of magnetic flux density at the squeeze gap	71
4.5	Magnetic flux lines distribution in the MR damper when the position of piston is at the (a) middle, (b) top and (c) bottom of the cylinder	72
4.6	The average values of magnetic flux density at (a) shear and (b) squeeze gaps for a mixed mode MR damper	74
4.7	Effect of gap size on the magnetic flux density	75
4.8	Effect of different applied currents on the average values of magnetic flux density at (a) shear and (b) squeeze gaps	76
4.9	The graph of force versus displacements produced by the mixed mode MR damper	77
4.10	Damping force of MR damper for different applied currents at 15 mm of piston stroke length	78
4.11	Damping force of MR damper for different applied currents at 18 mm of piston stroke length	79

4.12	Damping force of MR damper for different applied currents at 23 mm of piston stroke length	79
4.13	Damping force of MR damper for different applied currents at 26 mm of piston stroke length	80
4.14	The illustration of iron particles movement in the MR damper at OFF-state and ON-state during compression and tension modes.	82
4.15	Effect of piston stroke lengths on the damping force for 0.8 A of applied current	83
4.16	The behavior of cushion effect under different applied currents	84
4.17	Summary of the research process in Chapter 4	86
B1	Exploded view of the MR damper	112
B2	Dimension of the piston and the cylinder of MR damper	113
B3	Dimension of the top cap of MR damper	114
B4	Dimension of the top shaft of MR damper	115
B5	Dimension of the bottom cap of MR damper	116
B6	Dimension of the bottom shaft of MR damper	117

LIST OF ABBREVIATIONS

B	-	Magnetic flux density
H	-	Magnetic field intensity
M	-	Magnetization of the material
m	-	Magnetic dipole moment of particles
a	-	Diameter of the particles
μ	-	Permeability of the material
μ_f	-	Specific permeability of particles
μ_0	-	Permeability of vacuum
μ_p	-	Specific permeability of carrier liquid
$\mu_s M_s$	-	Saturation magnetization of the particles
τ	-	Shear stress
τ_y	-	Yield stress
η	-	Viscosity
ρ	-	Density
ϕ	-	Volume fraction of the suspended solutes or particles
J_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

∇	-	Divergence operator
A	-	Magnetic vector potential
A	-	Ampere
μ_r	-	Relative magnetic permeability
μ_0	-	Permeability of free space
n	-	Direction normal to the boundary
R	-	Outer radius of a sphere problem domain
C	-	Coefficients
N	-	Number of turns in coil
I	-	Current input
L_{coil}	-	Length of coil
MR	-	Magnetorheological
MRF	-	Magnetorheological fluid
FEM	-	Finite Element Method
FEMM	-	Finite Element Method Magnetics
VSM	-	Vibrating Sample Magnetometer
AGM	-	Alternating Gradient Magnetometer
CAD	-	Computer Aided Design
AWG	-	American Wire Gauge
CI	-	Carbonyl iron
CIP	-	Carbonyl iron particle

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Publications	109
B	SolidWorks Drawings	111

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 105-106 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.

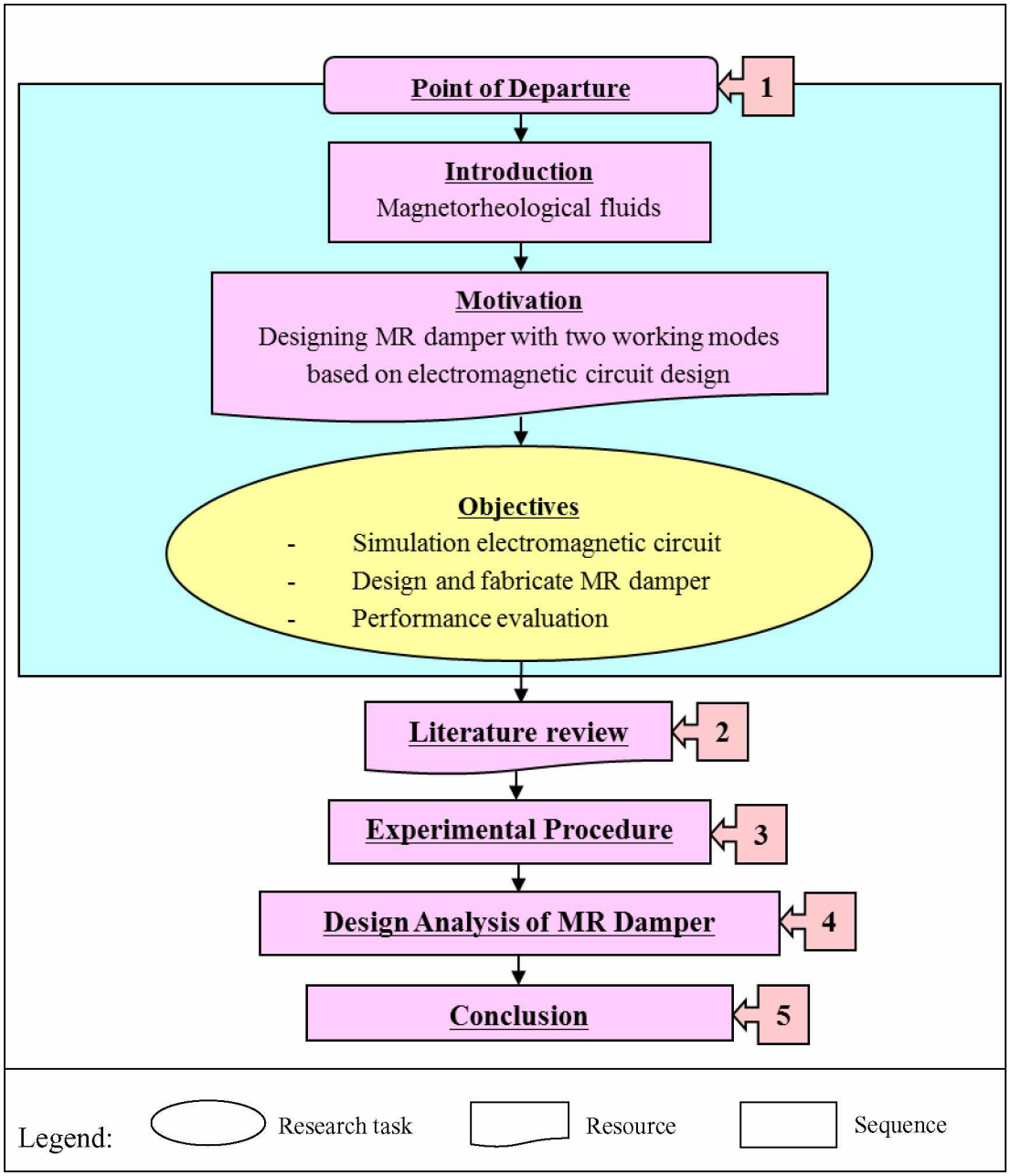

Figure 1.1 Summary of the research process in Chapter 1

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

1. Jolly, M. R., Bender, J. W. and Carlson, J. D. Properties and Applications of Commercial Magnetorheological Fluids. *Journal of Intelligent Material Systems and Structures.* 1999. 10: 5–13.

2. Simon, T. M., Reitich, F., Jolly, M. R., Ito, K. and Banks, H. T. The Effective Magnetic Properties of Magnetorheological Fluids. *Mathematical and Computer Modelling.* 2001. 33(1-3): 273–284.

3. Tao, R. Super-strong Magnetorheological Fluids. *Journal of Physics: Condensed Matter.* 2001. 13: 979–999.

4. Chen, S., Huang, J., Sun, T. and Jian, K. Analysis and Testing of Chain Characteristics and Rheological Properties for Magnetorheological Fluid. *Advances in Materials Science and Engineering.* 2013. 1–6.

5. Batterbee, D. and Sims, N. D. Temperature Sensitive Controller Performance of MR Dampers. *Journal of Intelligent Material Systems and Structures.* 2008. 20: 297–309.

6. Rabinow, J. The Magnetic Fluid Clutch. A*IEE.* 1948. 67: 1308–1315.

7. Wang, H., Bi, C., Kan, J., Gao, C. and Xiao, W. The Mechanical Property of Magnetorheological Fluid Under Compression, Elongation, and Shearing. *Journal of Intelligent Material Systems and Structures.* 2011. 22: 811–816.

8. Bose, H. and Ehrlich, J. Novel Adaptive Damping Systems Based on Magnetorheological Fluids. *Advances in Science and Technology.* 2012. 77: 86–95.

9. El Wahed, A. K., Sproston, J.L. and Schleyer, G. K. Electrorheological and Magnetorheological Fluids in Blast Resistant Design Applications. *Materials & Design.* 2002. 23: 391–404.

10. Olabi, A. G. and Grunwald, A. Design and Application of Magneto-rheological Fluid. *Materials & Design.* 2007. 28: 2658–2664.

11. Mazlan, S. A., Issa, A., Chowdhury, H. A. and Olabi, A. G. Magnetic Circuit Design for the Squeeze Mode Experiments on Magnetorheological Fluids. *Material and Design.* 2009. 30: 1985–1993.

12. El Wahed, A. K. and Mcewan, C. A. Design and Performance Evaluation of Magnetorheological Fluids under Single and Mixed modes. *Journal of Intelligent Material Systems and Structures.* 2011. 22: 631–643.

13. Mughni, M. J., Zeinali, M., Mazlan, S. A., Zamzuri, H. and Rahman, M. A. A. Experiments and Modeling of a New Magnetorheological Cell under Combination of Flow and Shear-flow Modes. *Journal of Non-Newtonian Fluid Mechanics.* 2015. 215: 70–79.

14. See, H., Mackenzie, S. and Chua, B. T. Effect of Compression on the Response of a Magnetorheological Suspension. *Korea - Australia Rheology Journal.* 2006. 18: 121–126.

15. Kuzhir, P., Lopez-Lopez, M. T., Vertelov, G., Pradille, C. and Bossis, G. Shear and Squeeze Rheometry of Suspensions of Magnetic Polymerized Chains. *Rheologica Acta.* 2007. 47: 179–187.

16. Kulkarni, P., Ciocanel, C., Vieira, S. L. and Naganathan, N. Study of the Behavior of MR Fluids in Squeeze, Torsional and Valve Modes. *Journal of Intelligent Material Systems and Structures.* 2003. 14: 99–104.

17. See, H. and Tanner, R. Shear Rate Dependence of the Normal Force of a Magnetorheological Suspension. *Rheologica Acta.* 2003. 42: 166–170.

18. Tang, X., Zhang, X., Tao, R. and Rong, Y. Structure-enhanced Yield Stress of Magnetorheological Fluids. *Journal of Applied Physics.* 2000. 87(5): 2634.

19. Zhang, X. Z., Gong, X. L., Zhang, P. Q. and Wang, Q. M. Study on the Mechanism of the Squeeze-strengthen Effect in Magnetorheological Fluids. *Journal of Applied Physics.* 2004. 96(4): 2359–2364.

20. Spaggiari, A. and Dragoni, E. Combined Squeeze-shear Properties of Magnetorheological Fluids: Effect of Pressure. *Journal of Intelligent Material Systems and Structures*. 2014. 25(9): 1041–1053.

21. Becnel, A. C., Sherman, S. G., Hu, W. and Wereley, N. M. Squeeze Strengthening of Magnetorheological Fluids using Mixed Mode Operation. *Journal of Applied Physics*. 2015. 117: 17C708.

22. Hegger, C. and Maas, J. Investigation of the Squeeze Strengthening Effect in Shear Mode. *Journal of Intelligent Material Systems and Structures*. 2015. DOI:10.1177/1045389X15606998.

23. Bai, X. X., Hu, W. and Werely, M. Magnetorheological Damper Utilizing an Inner Bypass for Ground Vehicle Suspensions. *IEEE Transactions on Magnetics*. 2013. 49(7): 3422–3425.

24. Sohn, J. W., Oh, J. S. and Choi, S. B. Design and novel type of a magnetorheological damper featuring piston bypass hole. *Smart Materials and Structures*. 2015. 24: 035013.

25. Gordaninejad, F. and Breese, D. G. Heating of Magnetorheological Fluid Damper. *Journal of Intelligent Material Systems and Structures*. 1999. 10: 634–645.

26. Wilson, N. L. and Wereley, N. M. Analysis of a Magnetorheological Fluid Damper Incorporating Temperature Dependence. *51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. April 12-15, 2010. Orlando, Florida: American Institute of Aeronatics and Astronautics. 2010. 2993.

27. Wang, D. H. and Wang, T. Principle, design and modeling of an integrated relative displacement self-sensing magnetorheological damper based on electromagnetic induction. *Smart Materials and Structures*. 2009. 18: 095025.

28. Hu, G., Ru, Y. and Li, W. Design and Development of a Novel Displacement Differential Self-induced Magnetorheological Damper. *Journal of Intelligent Material Systems and Structures*. 2014. 26: 527–540.

29. Jolly, M. R., Carlson, J. D. and Munoz, B. C. A Model of the Behaviour of Magnetorheological Materials. *Smart Materials and Structures*. 1996. **5**: 607–614.

30. Ly, H., Reitich, F., Jolly, M., Banks, H. and Ito, K. Simulations of Particle Dynamics in Magnetorheological Fluids. *Journal of Computational Physics*. 1999. 155: 160–177.

31. Ashtiani, M., Hashemabadi, S. H. and Ghaffari, A. A Review on the Magnetorheological Fluid Preparation and Stabilization. *Journal of Magnetism and Magnetic Materials*. 2015. **374**: 716–730.

32. Goncalves, F. D., Ahmadian, M. and Carlson, J. D. Investigating the Magnetorheological Effect at High Flow Velocities. *Smart Materials and Structures*. 2006. 15: 75–85.

33. Dang, A., Ooi, L., Fales, J. and Stroeve, P. Yield Stress Measurements of Magnetorheological Fluids in Tubes. *Industrial & Engineering Chemistry Research*. 2000. 39: 2269–2274.

34. Wang, J. and Meng, G. Magnetorheological Fluid Devices: Principles, Characteristics and Applications in Mechanical Engineering. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*. 2001. 215: 165–174.

35. Ashour, O., Rogers, C. A. and Kordonsky, W. Magnetorheological Fluids: Materials, Characterization, and Devices. *Journal of Intelligent Material Systems and Structures*. 1996. **7**: 123–130.

36. Gorodkin, S. R., James, R. O. and Kordonski, W. I. Magnetic Properties of Carbonyl Iron Particles in Magnetorheological Fluids. *Journal of Physics: Conference Series*. 2009. 149: 012051.

37. Park, J. H. and Park, O. O. Electrorheology and Magnetorheology. *Korea - Australia Rheology Journal*. 2001. 13(1): 13–17.

38. Vekas, L. Ferrofluids and Magnetorheological Fluids. *Advances in Science and Technology*. 2008. 54: 127–136.

39. Shah, K. and Choi, S. B. The Influence of Particle Size on the Rheological Properties of Plate-like Iron Particle based Magnetorheological Fluids. *Smart Materials and Structures.* 2015. 24: 015004.

40. Chiriac, H. and Stoian, G. Influence of Particle Size Distributions on Magnetorheological Fluid Performances. *Journal of Physics: Conference Series.* 2010. 200: 072095.

41. Werely, N. M., Chaudhuri, A., Yoo, J. H., Kotha, S., Suggs, A., Radhakrishnan, R., Love, B. J. and Sudarshan, T. S. Bidisperse Magnetorheological Fluids using Fe Particles at Nanometer and Micron Scale. *Journal of Intelligent Material Systems and Structures.* 2006. 17: 393–401.

42. Phule, P. P. Magnetorheological (MR) Fluids: Principles and Applications. *Smart Materials Bulletin.* 2001. 2001(2): 7–10.

43. Korolev, K. A., Chen, S., Li, Z. and Afsar, M. N. Millimeter-wave Transmittance and Reflectance Measurement on Pure and Diluted Carbonyl Iron. *IEEE Transactions on Instrumentation and Measurement.* 2010. 59(8): 2198–2203.

44. Muhammad, A., Yao, X. L. and Deng, Z. C. Review of Magnetorheological (MR) Fluids and its Applications in Vibration Control. *Journal of Marine Science and Application.* 2006. 5(3): 17–29.

45. Genc, S. and Phule, P. P. Rheological Properties of Magnetorheological Fluids. *Smart Materials and Structures.* 2002. 11: 140–146.

46. Goncalves, F. D., Koo, J. H. and Ahmadian, M. A Review of the State of the Art in Magnetorheological Fluid Technologies - Part I: MR fluid and MR fluid models. *The Shock and Vibration Digest.* 2006. 38(3): 203–219.

47. Fuchs, A., Xin, M., Gordaninejad, F., Wang, X., Hitchcock, G. H., Gecol, H., Evrensel, C. and Korol, G. Development and Characterization of Hydrocarbon Polyol Polyurethane and Silicone Magnetorheological Polymeric Gels. *Journal of Applied Polymer Science.* 2004. 92: 1176–1182.

48. Fuchs, A., Rashid, A., Liu, Y., Kavlicoglu, B., Sahin, H. and Gordaninejad, F. Compressible Magnetorheological Fluids. *Journal of Applied Polymer Science.* 2010. 115: 3348–3356.

49. Carlson, J. D. What Makes a Good MR Fluid? *Journal of Intelligent Material Systems and Structures*. 2002. 13: 431–435.

50. Lim, S. T., Cho, M. S., Jang, I. B., Choi, H. J. and Jhon, M. S. Magnetorheology of Carbonyl-Iron Suspensions With Submicron-Sized Filler. *IEEE Transactions on Magnetics*. 2004. 40(4): 3033–3035.

51. Genc, S. *Synthesis and Properties of Magnetorheological Fluids*. Ph.D. Thesis. University Pittsburgh; 2002.

52. Reinecke, B. N., Shan, J. W., Suabedissen, K. K. and Cherkasova, A. S. On the Anisotropic Thermal Conductivity of Magnetorheological Suspensions. *Journal of Applied Physics*. 2008. 104: 023507.

53. Seong, M. S., Choi, S. B. and Sung, K. G. Control Strategies for Vehicle Suspension System Featuring Magnetorheological (MR) Damper. In: Francisco Beltran-Carbajal. *Vibration Analysis and Control - New Trends and Development*. ISBN 978-953-307-433-7: InTech. 97-114. 2006.

54. Butter, K., Bomans, P. H., Frederik, P. M., Vroege, G. J. and Philipse, A. P. Direct Observation of Dipolar Chains in Ferrofluids in Zero Field using Cryogenic Electron Microscopy. *Journal of Physics: Condensed Matter*. 2003. 15: S1451–S1470.

55. Gans, B. J., Hoekstra, H. and Mellema, J. Non-linear Magnetorheological Behaviour of an Inverse Ferrofluid. *Faraday Discussion*. 1999. 112: 209–224.

56. Carlson, J. D. and Mark, R. J. MR Fuid, Foam and Elastomer Devices. *Mechatronics*. 2000. 10: 555–569.

57. Premalatha, S. E., Chokkalingam, R. and Mahendran, M. Magneto Mechanical Properties of Iron Based MR Fluids. *American Journal of Polymer Science*. 2012. 2(4): 50–55.

58. Nishiyama, H., Fushimi, S. and Nakano, M. Numerical Simulation of MR Fluid Damping Characteristics using a Modified Bingham Model. *Journal of Intelligent Material Systems and Structures*. 2007. 13: 647–653.

59. Carlson, J. D., Catanzarite, D. M. and Clair, K. A. St. Commercial Magneto-rheological Fluid Devices. *International Journal of Modern Physics B*. 1996; 10(23-24): 2857-2865.

60. Kim, K. and Jeon, D. Vibration Suppression in an MR Fluid Damper Suspension System. *Journal of Intelligent Material Systems and Structures.* 1999. 10: 779–786.

61. Mukhlis, R. Z., Mohamed, N. A. N. and Nor, M. J. M. The Design and Simulation of Flow Mode Electrorheological Damper. *Jurnal Teknologi.* 2006. 44: 115–125.

62. Yao, G. Z., Yap, F. F., Chen, G., Li, W. H. and Yeo, S. H. MR Damper and its Application for Semi-active Control of Vehicle Suspension System. *Mechatronics.* 2002. 12: 963–973.

63. Yoo, J. H. and Wereley, N. M. Design of a High-Efficiency Magnetorheological Valve. *Journal of Intelligent Material Systems and Structures.* 2002. 13: 679–685.

64. Rosenfeld, N. C. and Wereley, N. M. Volume-constrained Optimization of Magnetorheological and Electrorheological Valves and Dampers. *Smart Materials and Structures.* 2004. 13: 1303–1313.

65. Nguyen, Q. H., Choi, S. B. and Wereley, N. M. Optimal Design of Magnetorheological Valves via a Finite Element Method Considering Control Energy and a Time Constant. *Smart Materials and Structures.* 2008. 17: 025024.

66. Imaduddin, F., Mazlan, S. A., Zamzuri, H. and Yazid, I. I. M. Design and Performance Analysis of a Compact Magnetorheological Valve with Multiple Annular and Radial Gaps. *Journal of Intelligent Material Systems and Structures.* 2013. 26(9): 1038–1049.

67. Jang, K. I., Min, B. K. and Seok, J. A Behavior Model of a Magnetorheological Fluid in Direct Shear Mode. *Journal of Magnetism and Magnetic Materials.* 2011. 323: 1324–1329.

68. Hu, W. and Wereley, N. M. Behavior of MR Fluids At High Shear Rate. *International Journal of Modern Physics B.* 2011. 25(7): 979.

69. Tse, T., Chang, C. C. and Asce, M. Shear-Mode Rotary Magnetorheological Damper for Small-Scale Structural Control Experiments. *Journal of Structural Engineering.* 2004. 130: 904–911.

70. Wereley, N. M., Cho, J. U., Choi, Y. T. and Choi, S. B. Magnetorheological Dampers in Shear Mode. *Smart Materials and Structures*. 2008. 17: 15022.

71. Ikhouane, F. and Dyke, S. J. Modeling and Identification of a Shear Mode Magnetorheological Damper. *Smart Materials and Structures*. 2007. 16: 605–616.

72. Vieira, S. L., Ciocanel, C., Kulkarni, P., Agrawal, A. and Naganathan, N. Behaviour of MR Fluids in Squeeze Mode. *International Journal of Vehicle Design*. 2003. 33(1-3): 36–49.

73. Mazlan, S. A., Ekreem, N. B. and Olabi, A. G. The Performance of Magnetorheological Fluid in Squeeze Mode. *Smart Materials and Structures*. 2007. 16: 1678–1682.

74. Farjoud, A., Cavey, R., Ahmadian, M. and Craft, M. Magnetorheological Fluid Behavior in Squeeze Mode. *Smart Materials and Structures*. 2009. 18: 95001.

75. Ismail, I., Mazlan, S. A., Zamzuri, H. and Olabi, A. G. Fluid–particle Separation of Magnetorheological Fluid in Squeeze Mode. *Japanese Journal of Applied Physics*. 2012. 51: 067301.

76. Wang, H. Y., Zheng, H. Q., Li, Y. X. and Lu, S. Mechanical Properties of Magnetorheological Fluids under Squeeze-shear Mode. *Proceedings of SPIE*. 2008. 7130: 71302M.

77. Guo, C., Gong, X., Xuan, S., Yan, Q. and Ruan, X. Squeeze Behavior of Magnetorheological Fluids under Constant Volume and Uniform Magnetic Field. *Smart Materials and Structures*. 2013. 22: 045020.

78. Mazlan, S. A., Ekreem, N. B. and Olabi, A. G. Apparent Stress–strain Relationships in Experimental Equipment where Magnetorheological Fluids Operate under Compression Mode. *Journal of Physics D: Applied Physics*. 2008. 41: 095002.

79. Mazlan, S. A., Ekreem, N. B. and Olabi, A. G. An Investigation of the Behaviour of Magnetorheological Fluids in Compression Mode. *Journal of Materials Processing Technology*. 2008. 201: 780–785.

80. Mazlan, S. A., Ismail, I., Zamzuri, H. and Fatah, A. Y. A. Compressive and Tensile Stresses of Magnetorheological Fluids in Squeeze Mode. *International Journal of Applied Electromagnetics and Mechanics*. 2011. 36: 327–337.

81. Wang, H., Bi, C., Zhang, Z., Kan, J. and Gao, C. An investigation of tensile behavior of magnetorheological fluids under different magnetic fields. *Journal of Intelligent Material Systems and Structures*. 2013. 24(5): 541–547.

82. Mazlan, S. A., Issa, A. and Olabi, A. G. Magnetorheological Fluids Behaviour in Tension Loading Mode. *Advanced Materials Research*. 2008. 47-50: 242–245.

83. Park, J. H., Chin, B. D. and Park, O. O. Rheological Properties and Stabilization of Magnetorheological Fluids in a Water-in-Oil Emulsion. *Journal of Colloid and Interface Science*. 2001. 240: 349–354.

84. Pan, H. J, Huang, H. J., Zhang, L. Z., Qi, J. Y. and Cao, S. K. Rheological Properties of Magnetorheological Fluid Prepared by Gelatin- Carbonyl Iron Composite Particles. *Journal of Center South University Technology*. 2005. 12(4): 411–415.

85. Chin, B. D., Park, J. P., Kwon, M. H. and Park, O. O. Rheological Properties and Dispersion Stability of Magnetorheological (MR) Suspensions. *Rheologica Acta*. 2001. 40: 211–219.

86. Rwei, S. P., Lee, H. Y., Yoo, S. D., Wang, L. Y. and Lin, J. G. Magnetorheological Characteristics of Aqueous Suspensions that Contain Fe3O4 Nanoparticles. *Colloid and Polymer Science*. 2005. 283: 1253–1258.

87. Ahn, Y. K., Yang, B. S., Ahmadian, M. and Morishita, S. A Small-sized Variable-damping Mount using Magnetorheological Fluid. *Journal of Intelligent Material Systems and Structures*. 2005. 16: 127–133.

88. Chen, J. Z. and Liao, W. H. Design, Testing and Control of a Magnetorheological Actuator for Assistive Knee Braces. *Smart Materials and Structures*. 2010. 19: 035029.

89. Kikuchi, T., Tanida, S., Otsuki, K., Yasuda, T. and Furusho, J. A Novel Estimating Method of the Gait State and Velocity Control in the Initial Stance Phase for the Intelligent Ankle Foot Orthosis with Compact MR Fluid Brake (i-AFO). *Journal of JSEM.* 2010. 10: 240–246.

90. Liu, B., Li, W. H., Kosasih, P. B. and Zhang, X. Z. Development of an MR-brake-based Haptic Device. *Smart Materials and Structures.* 2006. 15: 1960–1966.

91. Bica, I., Liu, Y. D. and Choi, H. J. Physical Characteristics of Magnetorheological Suspensions and their Applications. *Journal of Industrial and Engineering Chemistry.* 2013. **19**(2): 394-406.

92. Tu, J. W., Liu, J., Qu, W. L., Zhou, Q., Cheng, H. B. and Cheng, X. D. Design and Fabrication of 500-kN Large-Scale MR Damper. *Journal of Intelligent Material Systems and Structures.* 2011. 22: 475–487.

93. Kasprzyk, J., Wyrwal, J. and Krauze, P. Automotive MR Damper Modeling for Semi-active Vibration Control. *2014 IEEE/ASME International Conference on Advanced Intelligent Mechatronics.* July 8-11, 2014. Besangon, France: IEEE. 2014. 500-505.

94. Gordaninejad, F. and Kelso, S. P. Fail-Safe Magnetorheological Fluid Dampers for Off-Highway, High-Payload Vehicles. *Journal of Intelligent Material Systems and Structures.* 2012. 11: 395–406.

95. Choi, S. B., Seong, M. S. and Ha, S. H. Vibration Control of an MR Vehicle Suspension System Considering both Hysteretic Behavior and Parameter Variation. *Smart Materials and Structures.* 2009. 18: 125010.

96. Batterbee, D. C., Sims, N. D., Stanway, R. and Wolejsza, Z. Magnetorheological Landing Gear: 1. A Design Methodology. *Smart Materials and Structures.* 2007. 16: 2429–2440.

97. Saxena, D. and Rathore, H. Vibration Control of MR Damper Landing Gear. *Interantional Journal of Advanced Research in Artificial Intelligence.* 2013. 2(3): 72–76.

98. Li, Z. X., Lv, Y., Xu, L. H., Ding, Y. and Zhao, Q. Experimental Studies on Nonlinear Seismic Control of a Steel–concrete Hybrid Structure using MR Dampers. *Engineering Structures*. 2013. 49: 248–263.

99. Cha, Y. J., Agrawal, K. K. and Dyke, S. J. Time Delay Effects on Large-scale MR Damper based Semi-active Control Strategies. *Smart Materials and Structures*. 2013. 22: 015011.

100. Kikuchi, T., Ikeda, K., Otsuki, K., Kakehashi, T. and Furusho, J. Compact MR Fluid Clutch Device for Human-friendly Actuator. *Journal of Physics: Conference Series*. 2009. 149: 012059.

101. Yang, T., Gao, Y., Zhao, J., Wang, S. and Zhu, Y. A Rotary Magnetorheological Fluid Damper for Pathological Tremor Suppression. *2012 IEEE International Conference on Mechatronics and Automation.* August 5-8, 2012. Changdu, China: IEEE. 2012. 575-580.

102. Xie, H., Li, F. and Kang, G. The Application Research of Six-Axis Force Sensor used by Trans-Femoral Prosthesis. *Advanced Materials Research.* 2013. 683: 741–744.

103. Park, J. and Choi, S. B. A Prosthetic Knee using Magnetorhelogical Fluid Damper for Above-knee Amputees. *Proceeding of SPIE: Active and Passive Smart Structures and Integrated Systems 2015*. 2015. 9431: 943108.

104. Rodriguez, A., Pozo, F., Bahar, A., Acho, L., Vidal, Y. and Rodellar, J. Force-derivative Feedback Semi-active Control of Base-isolated Buildings using Large-scale MR Fluid Dampers. *Structural Control and Health Monitoring.* 2012. 19: 120–145.

105. Zhu, X., Jing, X. and Cheng, L. Magnetorheological Fluid Dampers: A Review on Structure Design and Analysis. *Journal of Intelligent Material Systems and Structures*. 2012. 23(8): 839–873.

106. Zhu, X., Jing, X. and Cheng, L. Optimal Design of Control Valves in Magnetorheological Fluid Dampers using a Nondimensianal Analytical Method. *Journal of Intelligent Material Systems and Structures.* 2012. 24(1): 108-129.

107. Ebrahimi, B. *Development of Hybrid Electromagnetic Dampers for Vehicle Suspension Systems*. Ph.D. Thesis. University of Waterloo; 2009.

108. Yeh, F. K, Huang, J. J. and Huang, C. W. Adaptive-Sliding Mode Semi-Active Bicycle Suspension Fork. *SICE Annual Conference 2010*. August 18-21, 2010. Taipei, Taiwan: SICE. 2010. 3312-3317.

109. Breese, D. G. and Gordaninejad, F. Semi-active, Fail-safe Magnetorheological Fluid Dampers for Mountain Bicycles. *International of Vehicle Design*. 2003. 33(1-3): 128-138.

110. Li, Z. C. and Wang, J. A Gun Recoil System Employing a Magnetorheological Fluid Damper. *Smart Materials and Structure.s* 2012. 21(10): 105003.

111. Hu, H., Wang, J., Qian, S., Li, Y. and Jiang, X. Investigation on Controllability of a Magnetorheological Gun Recoil Damper. *2009 IEEE International Conference on Information and Automation, ICIA 2009*. June 22-25, 2009.Macau, China: IEEE. 2009. 1044-1049.

112. Dyke, S. J., Spencer, Jr. B. F., Sain, M. K. and Carlson, J. D. An Experimental Study of MR Dampers for Seismic Protection. *Smart Materials and Structures*. 1998. **7**: 693–703.

113. Ding, Y., Zhang, L., Zhu, H. T. and Li, Z. X. A New Magnetorheological Damper for Seismic Control. *Smart Materials and Structures*. 2013. 22: 115003.

114. Yang, M. G., Li, C. Y. and Chen, Z. Q. A New Simple Non-linear Hysteretic Model for MR Damper and Verification of Seismic Response Reduction Experiment. *Engineering Structures*. 2013. 52: 434–445.

115. Yang, M. G., Chen, Z. Q. and Hua, X. G. An Experimental Study on using MR Damper to Mitigate Longitudinal Seismic Response of a Suspension Bridge. *Soil Dynamics and Earthquake Engineering*. 2011. 31(8): 1171–1181.

116. Yang, G., Spencer, B. F., Carlson, J. D. and Sain., M. K. Large-scale MR Fluid Dampers: Modeling and Dynamic Performance Considerations. *Engineering Structures*. 2002. 24: 309–323.

117. Yu, M., Dong, X. M., Choi, S. B. and Liao, C. R. Human Simulated Intelligent Control of Vehicle Suspension System with MR Dampers. *Journal of Sound and Vibration*. 2009. 319: 753–767.

118. Sung, K. G. and Choi, S. B. Performance Comparison of MR Dampers with Three Different Working Modes: Shear, Flow and Mixed Mode. *International Journal of Modern Physics B*. 2005. 19(7, 8 & 9): 1556–1562.

119. Choi, S. B., Hong, S. R., Sung, K. G. and Sohn, J. W. Optimal Control of Structural Vibrations using a Mixed-mode Magnetorheological Fluid Mount. *International Journal of Mechanical Sciences*. 2008. 50: 559–568.

120. Sims, N. D., Stanway, R., Johnson, A. R. and Yang, J. S. Vibration Isolation using a Magnetorheological Damper in the Squeeze-flow Mode. *Part of the SPIE Conference on Smart Structures and Integrated Systems*. March 1999. Newport Beach, California: SPIE. 1999. 520-526.

121. Sims, N. D., Stanway, R., Johnson, A. R. and Mellor, P. Design, Testing and Model Validation of an MR Squeeze-flow Vibration Damper. *Proceedings of SPIE Smart Structures and Materials 2001: Damping and Isolation*. 2001. 4331: 111–120.

122. Nguyen, T. M., Ciocanel, C., Elahinia, M. H. A Squeeze-Flow Mode Magnetorheological Mount: Design, Modeling, and Experimental Evaluation. *Journal of Vibration and Acoustics*. 2012. 134(2): 021013.

123. Nam, Y. J. and Park, M. K. Electromagnetic Design of a Magnetorheological Damper. *Journal of Intelligent Material Systems and Structures*. 2009. 20: 181–191.

124. Sassi, S., Cherif, K., Mezghani, L., Thomas, M. and Kotrane, A. An Innovative Magnetorheological Damper for Automotive Suspension: From Design to Experimental Characterization. *Smart Materials and Structures*. 2005. 14(4): 811–822.

125. Zhang, H. H., Liao, C. R., Chen, W. M. and Huang, S. L. A Magnetic Design Method of MR Fluid Dampers and FEM Analysis on Magnetic Saturation. *Journal of Intelligent Material Systems and Structures*. 2006. 17: 813–818.

126. Nguyen, Q. H. and Choi, S. B. Optimal Design of MR Shock Absorber and Application to Vehicle Suspension. *Smart Materials and Structures*. 2009. 18: 035012.

127. Sung, K. G., Han, Y. M. and Choi, S. B. Geometric Optimization of Controllable Magnetorheological Shock Absorber for Commercial Passenger Vehicle. *Proceedings of SPIE.* 2008. 6928: 69280Q.

128. Nam, Y. J. and Park, M. K. Performance Evaluation of Two Different Bypass-type MR Shock Dampers. *Journal of Intelligent Material Systems and Structures.* 2007. 18: 707–717.

129. Salloom, M. Y. and Samad, Z. Finite Element Modeling and Simulation of Proposed Design Magnetorheological Valve. *International Journal of Advanced Manufacturing Technology.* 2011. 54: 421–429.

130. Yu, G., Du, C. and Li, Z. Optimum Design of a Magnetic Circuit in a Magneto-Rheological Damper. *Applied Mechanics and Materials.* 2011. 130-134: 1400–1403.

131. Du, C., Wan, F. and Yu, G. A Magnetic Flux Leakage Study of a Self-decoupling Magnetorheological Damper. *Smart Materials and Structures.* 2011. 20: 065019.

132. Xu, Z. D., Sha, L. F., Zhang, X. C. and Ye, H. H. Design, Performance Test and Analysis on Magnetorheological Damper for Earthquake Mitigation. *Structural Control and Health Monitoring.* 2013. 20: 956–970.

133. Kelso, S. P. Experimental Characterization of Commercially Practical Magnetorheological Fluid Damper Technology. *SPIE Conference on Smart Structures and Materials Industrial and Commercial Applications of Smart Structures Technologies.* March, 2001.San Diego, CA: SPIE. 2001. 4332-34.

134. Hitchcock, G. H., Wang, X., and Gordaninejad, F. A New Bypass Magnetorheological Fluid Damper. *Journal of Vibration and Acoustics.* 2007. 129: 641–647.

135. Grunwald, A. and Olabi, A. G. Design of Magnetorheological (MR) valve. *Sensor and Actuators A: Physical.* 2008. 148(1): 211–223.

136. Farjoud, A. and Bagherpour, E. A. Electromagnet Design for Magnetorheological Devices. *Journal of Intelligent Material Systems and Structures.* 2014. 27(1): 51–70.

137. Kim, K. J., Lee, C. W. and Koo, J. H. Design and Modeling of Semi-active Film Dampers using Magneto-rheological Fluids. *Smart Materials and Structures.* 2008. 17: 035006.

138. Mazlan, S. A. *The Behavior of Magnetorheological Fluids in Squeeze Mode.* Ph.D. Thesis. Dublin City University; 2008.

139. MRF-132DG Magneto-Rheological Fluid. LORD Corporation; 2011. www.lord.com.

140. Gavin, H., Hoagg, J. and Dobossy, M. Optimal Design of MR Dampers. *Proceedings of U.S.-Japan Workshop on Smart Structures for Improved Seismic Performance in Urban Regions*. August 14, 2001. Seattle, WA: 2001. 225-236.

141. Chowdhury, H. A. A *Finite Element Approach for the Implementation of Magnetostrictive Material Terfenol-D in Automotive CNG Fuel Injection Actuation.* Ph.D. Thesis. Dublin City University; 2008.

142. Meeker, D. Improvised Open Boundary Conditions for Magnetic Finite Elements. *IEEE Transactions on Magnetics* 2013. 49(10): 5243–5247.

143. Bose, H. and Ehrlich, J. Magnetorheological Dampers with Various Designs of Hybrid Magnetic Circuits. *Journal of Intelligent Material Systems and Structures.* 2012. 23(9): 979–987.