

### THE BEHAVIOUR OF MAGNETORHEOLOGICAL

### FLUIDS IN SQUEEZE MODE

by

#### SAIFUL AMRI BIN MAZLAN

B.ENG., M.ENG., P.ENG., MIEM, MIEI

A thesis submitted for the degree of Doctor of Philosophy

School of Mechanical and Manufacturing Engineering Faculty of Engineering and Computing Dublin City University

August 2008

Supervisor

Dr. Abdul Ghani Olabi

### Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading the award of Doctor of Philosophy is entirely my own work and has not been taken from the work of others and to the extent that such work has been cited and acknowledged within the text of my work.

SAIFUL AMRI MAZLAN

Student ID Number: 54168511 Date: 8 August 2008

# Publications

This work has been disseminated through the following publications.

#### **Selected Peer Reviewed Journals:**

- **S.A. Mazlan**, A. Issa and A.G. Olabi, Magnetorheological Fluids Behaviour in Tension Loading Mode, Advanced Materials Research, Vols. 47-50, 2008, 242-245.
- **S.A. Mazlan**, N.B. Ekreem and A.G. Olabi, An Investigation of the Behaviour of Magnetorheological Fluids in Compression Mode, Journal of Materials Processing Technology, Vol. 241, Nos. 1-3, 2008, 780-785.
- S.A. Mazlan, N.B. Ekreem and A.G. Olabi, Apparent Stress-Strain Relationships in Experimental Equipment where Magnetorheological Fluids Operate under Compression Mode, Journal of Physics D: Applied Physics, Vol. 41, No. 9, 2008, 095002.
- S.A. Mazlan, N.B. Ekreem and A.G. Olabi, The Performance of a Magnetorheological Fluid in Squeeze Mode, Smart Materials and Structures, Vol. 16, No. 5, 2007, 1678-1682.

#### **Under Review:**

- S.A. Mazlan, A. Issa, H.A. Chowdhury and A.G. Olabi, Tensile Stress-Strain Relationships of Magnetorheological Fluids under Various Factors, Submitted to Journal of Solid State Phenomenon.
- **S.A. Mazlan**, A. Issa, H.A. Chowdhury and A.G. Olabi, Magnetic Circuit Design for the Squeeze Mode Experiments on Magnetorheological Fluids, Submitted to Journal of Materials and Design.

#### **Conferences:**

- S.A. Mazlan, A. Issa, H.A. Chowdhury and A.G. Olabi, Tensile Stress-Strain Relationships of Magnetorheological Fluids under Various Factors, presenting in the European Materials Research Society (E-MRS) Fall Meeting, Warsaw University of Technology, Poland, September 15-19, 2008.
- **S.A. Mazlan**, A. Issa and A.G. Olabi, Magnetorheological Fluids Behaviour in Tension Loading Mode, presenting in the International Conference on Multifunctional Materials and Structures, Hong Kong, China, July 28-31, 2008.

- S.A. Mazlan, N.B. Ekreem and A.G. Olabi, An Investigation of the Magnetorheological Fluids in Compression Mode, in Proceedings of the 10<sup>th</sup> International Conference on Advances in Materials and Processing Technologies, Daejeon, Korea, Edited by Y. –T. Im, ISBN 978-89-89453-13-0 93560, October 7-11, 2007, 262.
- S.A. Mazlan and A.G. Olabi, Investigation of the Performance of Magnetorheological Fluid in Squeeze Mode, in Proceedings of the 24<sup>th</sup> International Manufacturing Conference, Waterford, Ireland, Edited by J. Phelan, ISBN 0-9556468-0-5, August 29-31, Vol. 2, 2007, 847-854.
- S.A. Mazlan, N.B. Ekreem and A.G. Olabi, Mechanical Properties of Magnetorheological Fluids under Compression Mode, in Proceedings of the Smart Structures and Materials, III ECCOMAS Thematic Conference, Gdansk, Poland, Edited by W. Ostachowicz, J. Holnicki-Szulc and C. M. Soares, ISBN 978-83-88237-03-4, July 9-11, 2007, 40.
- S.A. Mazlan, N.B. Ekreem and A.G. Olabi, Magnetorheological Fluid in Squeeze Mode under Different Instantaneous Magnetic Fields, Presented in the 10<sup>th</sup> Joint MMM/Intermag Conference, Baltimore, USA, January 7-11, 2007.

#### **Posters:**

• **S.A. Mazlan** and A.G. Olabi, Mechanical Property of a Magnetorheological Fluid in Squeeze Mode, 1<sup>st</sup> Mechanical and Manufacturing Engineering Symposium, DCU, Dublin, Ireland, December 20, 2006.

### Dedication

### TO MY BELOVED WIFE (AZLINA MASDAR)

&

CHILDREN (Amira Nabila Putri, Amir Asyraf Azraei And Amira Daniea)

The source of all the good in me

### Acknowledgments

I am grateful to Almighty Allah for the fulfilment 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 over the past three years. I must first express my gratitude towards my supervisor, Dr. Abdul Ghani Olabi, whose expertise, understanding and patience, added considerably to my graduate experience. Over the years, I have enjoyed the aid of scholarship which supported me while completing my PhD. This research would not have been possible without the financial assistance of Skim Latihan Akademik Bumiputera (SLAB), The Ministry of Higher Education of Malaysia, Technology University of Malaysia and National Defence University of Malaysia. I express my gratitude to those sponsors.

I must also acknowledge Dr. Ahmed Issa and Andrew Clarke for their suggestions, encouragement, editing assistance and provision of the font materials evaluated in this study. Appreciation also goes out to Michael May, Liam Domican, Alan Meehan, Jim Barry, Chris Crouch, Keith Hickey and the remaining department's technical staff whose expertise in various engineering fields facilitated the smooth running of this project. I also thank some of my fellow PhD students and friends; Mohamad, Husam, Habibullah, Essam, Ayad, Helen, Hemant and especially my best friend Nasser Ekreem. They have each helped make my time in the PhD programme more fun and interesting. I apologize for the so many names not included here, this only means that you are closer to my heart.

Needless to say, this entire exercise would be at most a dream if it was not for my loving family. To my parents, Datuk Mazlan Abdullah and Datin Azizah Hussin, education has been as important as food in my development, and my father has diligently encouraged my study. My two brothers; Ir. Mufadzir Huzaireen and Khairul Rizal, and my five sisters; Mazillah Azleen, Dr. Sadanah Aqashiah, Erita Mazwin, Elis Mardzianah and Fairuz Shahila, have provided me with an invaluable emotional support. Finally, I dearly thank my wife Dr. Azlina Masdar, whose love and caring made this entire endeavour worthwhile.

### Abstract

Magnetorheological (MR) fluids possess rheological properties, which can be changed in a controlled way. These rheological changes are reversible and dependent on the strength of an excitation magnetic field. MR fluids have potentially beneficial applications when placed in various applied loading (shear, valve and squeeze) modes. The squeeze mode is a geometric arrangement where an MR fluid is sandwiched between two flat parallel solid surfaces facing each other. The distance between these two parallel surfaces is called the gap size. These surfaces are either pushed towards or pulled apart from each other by orthogonal magnetic-induced forces. In this study, a test rig was designed and built to perform the experiments with three different types of MR fluids. One type of water-based and two types of hydrocarbon-based MR fluids were activated by a magnetic field generated by a coil using different magnitudes of DC electrical current. To finalize the design, a Finite Element Method Magnetics (FEMM) was used to predict the magnetic field strength throughout the MR fluids. For each trial, combination of three process parameters were experimented in both compression and tension modes on each type of MR fluid. The three process parameters were the electric current applied to the coil, the initial gap size and the compressive or tensile speed. In every test, the speed and the current in the coil were kept constant, while the instantaneous compressive and tensile forces were recorded. Experimental results showed that MR fluids have distinct unique behaviour during the compression and tension processes. The behaviour of MR fluids was dependent on the relative movement between the solid magnetic particles and the carrier fluid in both squeeze modes. A high ratio of solid particles to carrier liquid in the MR fluid is an indication of high magnetic properties. The water-based MR fluid had a relatively large solids-to-liquid ratio. At a given applied current, significant increases in compressive and tensile stresses were obtained in this fluid type. On the other hand, the hydrocarbon-based MR fluids had relatively lower solids-to-liquid ratios, whereby, less significant increases in compressive and tensile stresses were obtained. The magnetic field strength was proportional to the applied current. Consequently, the MR effect, in terms of resulting stresses, was directly proportional to the current. When plotting stress against strain for each experiment, the slopes of the curves were found to be larger in general when the initial gap sizes were smaller. This was due to higher magnetic fields generated in smaller initial gap sizes. However, the stress-strain relationships were slightly affected by changing the compressive or tensile speeds. In general, the compressive stresses were much higher than the tensile stresses for the same experimental parameters throughout this study.

# Table of Contents

Declaration	ii
Publications	iii
Dedication	v
Acknowledgements	vi
Abstract	vii
List of Tables	xi
List of Figures	xii
Nomenclature	xxi

#### **CHAPTER 1: INTRODUCTION**

1.0	Introduction	1
1.1	Motivation of study	1
1.2	Purpose of study	4
1.3	Outline of thesis	4

#### **CHAPTER 2: FIELD RESPONSIVE FLUIDS**

2.0	Introduction					
2.1	Smart materials					
2.2	Field responsive fluids	8				
	2.2.1 Magnetorheological fluids	10				
	2.2.2 Electrorheological fluids	12				
	2.2.3 Ferrofluids	14				
2.3	Origin of magnetism	14				
2.4	Magnetic materials					
	2.4.1 Hysteresis loop	18				
	2.4.2 Hard magnetic materials	21				
	2.4.3 Soft magnetic materials	21				
2.5	Concept of electromagnetism	22				
	2.5.1 Magnetic properties	24				
2.6	Summary of chapter 2	25				

#### **CHAPTER 3: MAGNETORHEOLOGICAL FLUIDS**

3.0 3.1 3.2	<ul> <li>Introduction</li> <li>Composition of MR fluids</li> <li>Magnetic properties of MR fluids</li> <li>Fundamentals of rheological properties</li> </ul>				
5.5	3.3.1 3.3.2 3.3.3 3.3.4	Basic principles of MR fluids         Rheology of MR fluids         Off- and on-state rheology         Volume fraction and particle size factors	31 35 37 38 39		
3.4	MR fl	uid modes of operation and its applications	41		
	3.4.1 3.4.2 3.4.3 3.4.4	Valve mode	43 46 49 55		
3.5	Summ	ary of chapter 3	57		
CHA	PTER	4: EXPERIMENTAL PROCEDURES			
4.0 4.1	Introd MR fl	uctionuid materials	59 59		
	4.1.1 4.1.2 4.1.3	Physical properties of tested MR fluids Magnetic properties of tested MR fluids Remixing method	60 62 63		
4.2	Exper	mental design	64		
		0			
	4.2.1 4.2.2 4.2.3 4.2.4	Simulation of the magnetic circuit Design of test rig Selection of coil dimension and material Fabrication of the test rig	65 67 72 74		
4.3	4.2.1 4.2.2 4.2.3 4.2.4 Experi	Simulation of the magnetic circuit Design of test rig Selection of coil dimension and material Fabrication of the test rig mental set-up	65 67 72 74 77		
4.3	4.2.1 4.2.2 4.2.3 4.2.4 Expert 4.3.1	Simulation of the magnetic circuit Design of test rig Selection of coil dimension and material Fabrication of the test rig mental set-up Test procedures	65 67 72 74 77 79		

#### **CHAPTER 5: BEHAVIOUR OF MR FLUIDS**

5.0	Introd	uction	97				
5.1	Compression behaviour of MD fluids						
5.2	Comp		99				
	5.2.1	Comparison of compression behaviour of MR fluids	104				
	5.2.2	Compression benaviour of hydrocarbon-based MR fluids	105				
5.3	Tensio	on behaviour of MR fluids	107				
	5.3.1	Comparison of tension behaviour of MR fluids	111				
5.4	Summ	nary of chapter 5	112				
CHA	PTER	6: EFFECTS OF VARIOUS FACTORS					
6.0	Introd	uction	114				
6.1	Effect	of applied current	114				
	6.1.1	Effect of applied current under compression	114				
	6.1.2	Effect of applied current under tension	119				
6.2	Effect	of initial gap size	121				
	6.2.1	Effect of initial gap size under compression	122				
	6.2.2	Effect of initial gap size under tension	127				
6.3	Effect	of compressive/tensile speed	131				
	6.3.1	Effect of compressive speed	131				
	6.3.2	Effect of tensile speed	133				
6.4	Gener	al discussion	135				
	6.4.1	Comparisons between compressive and tensile stresses	139				
	6.4.2	Combinations of compressive and tensile stresses	142				
6.5	Summ	nary of chapter 6	144				
CHA	PTER	7: CONCLUSIONS					
7.0	Concl	usions	146				
7.1	Contri	ibutions of the thesis	150				
7.2	Recon	nmendations for future work	151				
Refe	rences .		153				
Appe	endices						
	Apper	ndix A : CAD drawings	167				
	Apper	Indix       B : Detailed compression mode results         Indix       C : Detailed tension mode results	172				
	мррег	iuix C: Detailed tension mode results	190				

## List of Tables

Table 2.1	:	Classification of smart materials and their response	8
Table 2.2	:	Comparison the properties of MR fluids, ER fluids and ferrofluids	9
Table 2.3	:	Different types of magnetic behaviour	16
Table 2.4	:	Comparison of magnetic properties between soft and hard magnetic materials	20
Table 4.1	:	Physical properties of tested MR fluids	61
Table 4.2	:	List of changes in the design concept	69
Table 4.3	:	Numbers of turns of the coil and maximum values of the applied current	72
Table 4.4	:	Specifications of copper wire used to make the coil	73
Table 4.5	:	Design details and material for each component of the test rig	75
Table 4.6	:	Conversions of gap height to gap volume	79
Table 5.1	:	Comparison values of the tensile stress and strain of MR fluids	111
Table 6.1	:	Experimental values of the mechanical properties of MR fluids	139
Table 6.2	:	Parameter values obtained from equation 6-5	141

# List of Figures

#### FIGURE OF CHAPTER 1

Figure 1.1	:	Summary of the research process in chapter 1	6

#### **FIGURES OF CHAPTER 2**

Figure 2.1	:	Magnetic flux density versus magnetic field strength	18
Figure 2.2	:	Hysteresis loops for soft and hard magnetic materials	20
Figure 2.3	:	Schematic of a basic solenoid coil wound around air	23
Figure 2.4	:	Summary of the research process in chapter 2	26

#### **FIGURES OF CHAPTER 3**

Figure 3.1	:	Schematic representation of the affine deformation of a chain of spheres	30
Figure 3.2	:	Classification types of the behaviour of the fluids	34
Figure 3.3	:	Fluid element under a shear force	35
Figure 3.4	:	Diagrams of application ideas. (a) Energy dissipating or braking device, (b) 3-dimensional graphic device, (c) adjusting device or pointer device and (d) dashpot or shock absorber	42
Figure 3.5	:	MR fluid used to make a mould, (a) screw was inserted into the mould, (b) moulds after the screw was unscrewed and (c) cavity was filled by molten material	43
Figure 3.6	:	Basic concept of valve mode	44
Figure 3.7	:	Velocity profile of the fluid flow in valve mode	44
Figure 3.8	:	Schematic of an MR fluid seismic damper	46
Figure 3.9	:	Basic concept of shear mode	47
Figure 3.10	:	Schematic of a cylindrical MR clutch	48
Figure 3.11	:	Schematic of an MR haptic device	51
Figure 3.12	:	Basic concept of compression in squeeze mode	52
Figure 3.13	:	Basic concept of tension in squeeze mode	54
Figure 3.14	:	Schematic of dampers in three different modes. (a) Shear mode, (b) valve mode and (c) mixed mode which combines the valve and shear modes of operation	56
Figure 3.15	:	Summary of the research process in chapter 3	58

#### **FIGURES OF CHAPTER 4**

Figure 4.1	:	Typical magnetic properties of tested MR fluids	63
Figure 4.2	:	Overhead rotary mixer used to mix MR fluids in this work	64
Figure 4.3	:	Middle half of the test rig of the initial design concept	68
Figure 4.4	:	Sketch of a new configuration of material of support cylinder	71
Figure 4.5	:	Number of coil's turns and current as functions of wire gauge	73
Figure 4.6	:	Test rig assembly	75
Figure 4.7	:	Cross-sectional view and dimensions of the lower part	76
Figure 4.8	:	Schematic diagram of experimental set-up	78
Figure 4.9	:	A syringe used to quantify the amount of MR fluids	79
Figure 4.10	:	Procedures of the tests	80
Figure 4.11	:	Sketch of the test rig showing the black centred lines in the middle half of the test rig and red centred line between the upper and lower cylinders	81
Figure 4.12	:	Input parameters in the FEMM software package	82
Figure 4.13	:	Simulated magnetic flux density distribution (a) in the test rig and (b) in the area of the gap between the upper and lower cylinders	83
Figure 4.14	:	Simulated magnetic flux density distribution, (a) in MRF-241ES, (b) in MRF-132DG and (c) in MRF-122-2ED	84
Figure 4.15	:	Simulated magnetic flux lines across the (a) air gap, (b) MRF-241ES, (c) MRF-132DG and (d) MRF-122-2ED	85
Figure 4.16	:	Simulated magnetic flux density distribution inside the air gap and MR fluids from centre line to the edge between the upper and the lower cylinders. (a) Normal magnetic flux density (B.n) and (b) Tangential magnetic flux density (B.t)	86
Figure 4.17	:	Simulated magnetic flux lines towards the edge of the test rig	87
Figure 4.18	:	Simulated tangential magnetic flux density in the opposite direction	88
Figure 4.19	:	Simulated magnetic flux density versus applied current for initial gap sizes of (a) 2.0, (b) 1.6, (c) 1.2, (d) 0.8 and (e) 0.4 mm	89
Figure 4.20	:	Simulated magnetic flux density versus initial gap size for different values of applied current for (a) Air, (b) MRF-241ES, (c) MRF-231DG and (d) MRF-122-2ED	90

Figure 4.21	:	Simulated magnetic flux density versus initial gap size for the applied currents of (a) 1.6, (b) 1.2, (c) 0.8 and (d) 0.4 Amps	91
Figure 4.22	:	Simulated magnetic flux density versus current for different values of the initial gap sizes for (a) Air, (b) MRF-241ES, (c) MRF-231DG and (d) MRF-122-2ED	92
Figure 4.23	:	The 5000 series hand-held gaussmeter (F.W Bell)	93
Figure 4.24	:	Comparison of magnetic field strength between direct measurement and simulation result	94
Figure 4.25	:	Summary of the research process in chapter 4	96

#### **FIGURES OF CHAPTER 5**

Figure 5.1	:	Compressive stress versus compressive strain of the MR fluids	99
Figure 5.2	:	Compression process regions for (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED	100
Figure 5.3	:	Schematic of the arrangement of magnetic particles (a) under normal condition without magnetic field, (b) when magnetic field is applied, and at the (c) first region, (d) second region and (e) third region	101
Figure 5.4	:	Magnetic induction curves of MRF-241ES for two different iron volume percents	102
Figure 5.5	:	In the data, already given in figure 4.1, was scaled to show details in the range of values of compressive stress between 0.40 and 0.59 MPa	106
Figure 5.6	:	The compressive stress versus time data for the (a) MRF-132DG and (b) MRF-122-2ED	106
Figure 5.7	:	Tensile stress versus tensile strain relationships for the MR fluids	108
Figure 5.8	:	The three regions of tension process in (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED	109
Figure 5.9	:	Schematic of the aggregation of MR fluids under elongation (a) with magnetic field applied, and at the (b) first region, (c) second region and (d) third region	110
Figure 5.10	:	Summary of the research process in chapter 5	113

#### FIGURES OF CHAPTER 6

Figure 6.1 : Compressive stress versus compressive strain under different applied currents for (a) MRF-241ES, (c) MRF-132DG and (e) MRF-122-2ED, and a zoom in when the curves became plateau for (b) MRF-241ES, (d) MRF-132DG and (f) MRF-122-2ED ..... 116

Figure 6.2	:	Initial gap size as a function of compressive stress at different applied currents ranging from 0.4 to 1.6 Amps of (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED	117
Figure 6.3	:	Tensile stress versus tensile strain under different applied currents at initial gap size of 2.0 mm for (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED	120
Figure 6.4	:	Effect of the initial gap size under compression tests and a zoom in when the curves became plateau of (a) and (b) MRF-241ES, (c) and (d) MRF-132DG, and (e) and (f) MRF-122-2ED	123
Figure 6.5	:	Compressive stress versus displacement of MRF-241ES under a constant compressive speed of 1.5 mm/min and applied current of (a) and (b) 1.6, (c) and (d) 1.2, (e) and (f) 0.8, and (g) and (h) 0.4 Amps	125
Figure 6.6	:	Stress-strain curves of MRF-241ES corresponding to, (a) current- to-gap size ratio is equal to 0.8 Amps/mm, (b) zoom in on (a), (c) current-to-gap size ratio is equal to 0.4 Amps/mm, and (d) zoom in on (c)	126
Figure 6.7	:	Effect of the initial gap size under constant tensile speed of 1.5 mm/min for (a) MRF-241ES at applied current of 1.2 Amps, (b) MRF-241ES at applied current of 0.8 Amps, (c) MRF-132DG at applied current of 1.2 Amps, (d) MRF-132DG at applied current of 0.8 Amps, (e) MRF-122-2ED at applied current of 1.2 Amps and (f) MRF-122-2ED at applied current of 0.8 Amps	128
Figure 6.8	:	Tensile stress versus displacement under a constant tensile speed of 1.5 mm/min of (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED	130
Figure 6.9	:	Stress-strain relationships under different compressive speeds at 1.2 Amps of applied current of (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED	132
Figure 6.10	:	Effect of the tensile speed under a constant current of 1.2 Amps of (a) MRF-241ES, (c) MRF-132DG and (e) MRF-122-2ED at initial gap size of 2.0 mm, and (b) MRF-241ES, (d) MRF-132DG and (f) MRF-122-2ED at initial gap size of 1.0 mm	134
Figure 6.11	:	The adjusted or shifted curves of compressive stress versus compressive strain at the initial gap size of 2.0 mm for (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED	136
Figure 6.12	:	The adjusted or shifted curves of compressive stress versus compressive strain at the initial gap size of 1.0 mm for (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED	137
Figure 6.13	:	Compressive and tensile stresses versus magnetic flux density at different initial gap sizes of (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED	140
Figure 6.14	:	Combination of compressive and tensile stresses of MRF-241ES at (a) 2.0 mm and (b) 1.0 mm of initial gap size	142

Figure 6.15	:	Combination of compressive and tensile stresses of MRF-132DG at (a) 2.0 mm and (b) 1.0 mm of initial gap size	142
Figure 6.16	:	Combination of compressive and tensile stresses of MRF-122- 2ED at (a) 2.0 mm and (b) 1.0 mm of initial gap size	143
Figure 6.17	:	Summary of the research process in chapter 6	145

#### FIGURES OF APPENDIX A

Figure A1	: Upper cylinder	. 167
Figure A2	: Lower cylinder	. 168
Figure A3	: Upper ring	. 169
Figure A4	: Lower ring	170
Figure A5	: Support cylinder	171

#### FIGURES OF APPENDIX B

Figure B1	:	Stress-strain relationship of <b>MRF-241ES</b> under compression mode at <b>2.0</b> mm initial gap size, <b>0.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	172
Figure B2	:	Stress-strain relationship of <b>MRF-241ES</b> under compression mode at <b>2.0</b> mm initial gap size, <b>1.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	173
Figure B3	:	Stress-strain relationship of <b>MRF-241ES</b> under compression mode at <b>2.0</b> mm initial gap size, <b>1.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	174
Figure B4	:	Stress-strain relationship of <b>MRF-241ES</b> under compression mode at <b>2.0</b> mm initial gap size, <b>2.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	175
Figure B5	:	Stress-strain relationship of <b>MRF-241ES</b> under compression mode at <b>1.0</b> mm initial gap size, <b>0.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	176
Figure B6	:	Stress-strain relationship of <b>MRF-241ES</b> under compression mode at <b>1.0</b> mm initial gap size, <b>1.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	177

Figure B7	:	Stress-strain relationship of <b>MRF-241ES</b> under compression mode at <b>1.0</b> mm initial gap size, <b>1.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	178
Figure B8	:	Stress-strain relationship of <b>MRF-241ES</b> under compression mode at <b>1.0</b> mm initial gap size, <b>2.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	179
Figure B9	:	Stress-strain relationship of <b>MRF-132DG</b> under compression mode at <b>2.0</b> mm initial gap size, <b>0.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	180
Figure B10	:	Stress-strain relationship of <b>MRF-132DG</b> under compression mode at <b>2.0</b> mm initial gap size, <b>1.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	181
Figure B11	:	Stress-strain relationship of <b>MRF-132DG</b> under compression mode at <b>2.0</b> mm initial gap size, <b>1.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	182
Figure B12	:	Stress-strain relationship of <b>MRF-132DG</b> under compression mode at <b>2.0</b> mm initial gap size, <b>2.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	183
Figure B13	:	Stress-strain relationship of <b>MRF-132DG</b> under compression mode at <b>1.0</b> mm initial gap size, <b>0.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	184
Figure B14	:	Stress-strain relationship of <b>MRF-132DG</b> under compression mode at <b>1.0</b> mm initial gap size, <b>1.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	185
Figure B15	:	Stress-strain relationship of <b>MRF-132DG</b> under compression mode at <b>1.0</b> mm initial gap size, <b>1.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	186
Figure B16	:	Stress-strain relationship of <b>MRF-132DG</b> under compression mode at <b>1.0</b> mm initial gap size, <b>2.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	187
Figure B17	:	Stress-strain relationship of <b>MRF-122-2ED</b> under compression mode at <b>2.0</b> mm initial gap size, <b>0.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	188

Figure B18	:	Stress-strain relationship of <b>MRF-122-2ED</b> under compression mode at <b>2.0</b> mm initial gap size, <b>1.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	189
Figure B19	:	Stress-strain relationship of <b>MRF-122-2ED</b> under compression mode at <b>2.0</b> mm initial gap size, <b>1.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	190
Figure B20	:	Stress-strain relationship of <b>MRF-122-2ED</b> under compression mode at <b>2.0</b> mm initial gap size, <b>2.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	191
Figure B21	:	Stress-strain relationship of <b>MRF-122-2ED</b> under compression mode at <b>1.0</b> mm initial gap size, <b>0.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	192
Figure B22	:	Stress-strain relationship of <b>MRF-122-2ED</b> under compression mode at <b>1.0</b> mm initial gap size, <b>1.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	193
Figure B23	:	Stress-strain relationship of <b>MRF-122-2ED</b> under compression mode at <b>1.0</b> mm initial gap size, <b>1.5</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	194
Figure B24	:	Stress-strain relationship of <b>MRF-122-2ED</b> under compression mode at <b>1.0</b> mm initial gap size, <b>2.0</b> mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	195

#### FIGURES OF APPENDIX C

Figure C1	:	Stress-strain relationship of <b>MRF-241ES</b> under tension mode at <b>2.0</b> mm initial gap size, <b>0.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	196
Figure C2	:	Stress-strain relationship of <b>MRF-241ES</b> under tension mode at <b>2.0</b> mm initial gap size, <b>1.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	197
Figure C3	:	Stress-strain relationship of <b>MRF-241ES</b> under tension mode at <b>2.0</b> mm initial gap size, <b>1.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	198

Figure C4	:	Stress-strain relationship of <b>MRF-241ES</b> under tension mode at <b>2.0</b> mm initial gap size, <b>2.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	199
Figure C5	:	Stress-strain relationship of <b>MRF-241ES</b> under tension mode at <b>1.0</b> mm initial gap size, <b>0.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	200
Figure C6	:	Stress-strain relationship of <b>MRF-241ES</b> under tension mode at <b>1.0</b> mm initial gap size, <b>1.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	201
Figure C7	:	Stress-strain relationship of <b>MRF-241ES</b> under tension mode at <b>1.0</b> mm initial gap size, <b>1.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	202
Figure C8	:	Stress-strain relationship of <b>MRF-241ES</b> under tension mode at <b>1.0</b> mm initial gap size, <b>2.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	203
Figure C9	:	Stress-strain relationship of <b>MRF-132DG</b> under tension mode at <b>2.0</b> mm initial gap size, <b>0.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	204
Figure C10	:	Stress-strain relationship of <b>MRF-132DG</b> under tension mode at <b>2.0</b> mm initial gap size, <b>1.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	205
Figure C11	:	Stress-strain relationship of <b>MRF-132DG</b> under tension mode at <b>2.0</b> mm initial gap size, <b>1.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	206
Figure C12	:	Stress-strain relationship of <b>MRF-132DG</b> under tension mode at <b>2.0</b> mm initial gap size, <b>2.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	207
Figure C13	:	Stress-strain relationship of <b>MRF-132DG</b> under tension mode at <b>1.0</b> mm initial gap size, <b>0.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	208
Figure C14	:	Stress-strain relationship of <b>MRF-132DG</b> under tension mode at <b>1.0</b> mm initial gap size, <b>1.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	209

Figure C15	:	Stress-strain relationship of <b>MRF-132DG</b> under tension mode at <b>1.0</b> mm initial gap size, <b>1.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	210
Figure C16	:	Stress-strain relationship of <b>MRF-132DG</b> under tension mode at <b>1.0</b> mm initial gap size, <b>2.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	211
Figure C17	:	Stress-strain relationship of <b>MRF-122-2ED</b> under tension mode at <b>2.0</b> mm initial gap size, <b>0.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	212
Figure C18	:	Stress-strain relationship of <b>MRF-122-2ED</b> under tension mode at <b>2.0</b> mm initial gap size, <b>1.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	213
Figure C19	:	Stress-strain relationship of <b>MRF-122-2ED</b> under tension mode at <b>2.0</b> mm initial gap size, <b>1.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	214
Figure C20	:	Stress-strain relationship of <b>MRF-122-2ED</b> under tension mode at <b>2.0</b> mm initial gap size, <b>2.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	215
Figure C21	:	Stress-strain relationship of <b>MRF-122-2ED</b> under tension mode at <b>1.0</b> mm initial gap size, <b>0.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	216
Figure C22	:	Stress-strain relationship of <b>MRF-122-2ED</b> under tension mode at <b>1.0</b> mm initial gap size, <b>1.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	217
Figure C23	:	Stress-strain relationship of <b>MRF-122-2ED</b> under tension mode at <b>1.0</b> mm initial gap size, <b>1.5</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	218
Figure C24	:	Stress-strain relationship of <b>MRF-122-2ED</b> under tension mode at <b>1.0</b> mm initial gap size, <b>2.0</b> mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps	219

## Nomenclature

$\eta$	:	Viscosity
$\eta_r$	:	Relative viscosity of the suspension
V	:	Kinematics viscosity
В	:	Magnetic flux density
$B_r$	:	Magnetic remanence
Η	:	Magnetic field intensity
$H_c$	:	Coercive force
Xm	:	Magnetic susceptibility
$F_{ij}$	:	Magnetic force tensor acts on particle $i$ from $j$
т	:	Magnetic dipole moment of particles
Α	:	Magnetic vector potential
μ	:	Permeability of the material
$\mu_0$	:	Permeability of a vacuum
$\mu_r$	:	Relative permeability
$\mu_{f}$	:	Specific permeability of particles
$\mu_p$	:	Specific permeability of carrier liquid
М	:	Magnetization of the material
$\mu_s M_s$	:	Saturation magnetization of the particles
$J_s$	:	Saturation polarization of the particles
Ι	:	Current
$I_m$	:	Maximum current supplied to the coil
J	:	Current density
l	:	Length of the solenoid
h	:	Height of the gap
$L_a$	:	Active length of the flow channel
$A_w$	:	Surface area of the uncoated wire
r	:	Radius of the wire
R	:	Outer radius of a sphere problem domain
V	:	Volume
Ν	:	Number of turns
F	:	Force

Р	:	Pressure
$\Delta P$	:	Pressure drop
$\nabla$	:	Divergence operator
r <sub>ij</sub>	:	Position of particles <i>i</i> from <i>j</i>
a	:	Diameter of the particles
b	:	Mid annulus circumference of the valve
d	:	Gap distance
$A_p$	:	Effective area of the flow channel
$\overline{\delta}$	:	Nondimensional plug thickness
$\phi$	:	Volume fraction of the suspended solutes or particles
$\phi_{max}$	:	Maximum concentration of the particles
К	:	Correction factor
τ	:	Shear stress
$ au_y$	:	Yield stress
$\sigma_{y}$	:	Maximum value of compressive or tensile stress at the first region
$\sigma_{min}$	:	Value of compressive or tensile stress at zero magnetic field strength
γ	:	Shear strain
γ̈́	:	Shear strain rate
γ1	:	Compressive strain at the first region
$\gamma_2$	:	Compressive strain at the second region
γ3	:	Compressive strain at the third region
γ1,max	:	Maximum value of compressive strain at the first region
γ3,min	:	Minimum value of compressive strain at the third region
и	:	Velocity of the particles
$v_p$	:	Cylinder head velocity
G	:	Complex material modulus
$G_1$	:	Compressive modulus at the first region
$G_3$	:	Compressive modulus at the third region
ρ	:	Density of the fluid
W	:	Weight percentage

# CHAPTER 1

# INTRODUCTION

#### 1.0 Introduction

Controllable fluids are materials that respond to an external excitation field. When exposed to an electric or magnetic field, their rheological behaviour exhibits remarkable changes. These smart materials are commonly referred to as Magnetorheological (MR) fluids, Electrorheological (ER) fluids and ferrofluids. Amongst these smart fluids, MR fluids gain more attention since they can produce the highest stress, which can be applied into many applications [1, 2]. An MR fluid is a suspension of micron-sized magnetically soft particles in a carrier liquid, which can exhibit dramatic changes in rheological properties. The change from a free-flowing liquid state to a solid-like state is reversible and is dependent on the presence of a magnetic field. Iron powder is the most popular material used as particle inclusion due to its high saturation magnetization. Under the influence of a magnetic field, these iron particles are arranged to form very strong chains of "fluxes" with the pole of one particle being attracted to the opposite pole of another particle [3]. Once aligned in this manner, the particles are restrained from moving away from their respective flux lines and act as a barrier preventing the flow of the carrier fluid.

MR fluids can be operated in three working modes depending on the type of deformation employed such as shear mode, valve mode and squeeze mode [2, 4, 5]. In the case of the shear mode, the MR fluid is located between surfaces moving in relation to each other with the magnetic field flowing perpendicularly to the direction of motion of these shear surfaces. In the valve mode, the MR fluid is forced to flow directly between static plates, while in the squeeze mode, the MR fluid is squeezed by a normal pressure in the direction of the magnetic field under dynamic or static (compression or tension) loadings. Details regarding these working modes are explained in the next chapter.

#### **1.1** Motivation of study

Many potential applications of MR fluids have been suggested in the literature. Applications have been demonstrated in the automotive industry where benefits could be achieved in parts such as clutches, brakes, dampers and actuators [2, 6, 7]. Most of the researchers in the field assume a geometrical arrangement referred to as shear mode in their design, but it was found that the magnitudes of the stress in systems with 'shear mode' geometry are too low to be of value in the potential applications listed above. Concurrent with the extensive investigation of the shear strength of the MR fluids, researchers started to search for other techniques to take advantage of utilizing MR fluids to achieve higher forces. Therefore, the squeeze mode appeared to be one of the most interesting modes to be investigated. The geometrical arrangement designated squeeze mode can produce compressive and tensile stresses which are much higher and this has generated new interest in this approach.

The values of compressive stress, obtained with MR fluids, are similar to those reported in experimental studies using ER fluids [8-10]. Tian et al. [8] studied the performance of ER fluid under different working modes. It was reported that the compressive stress was the greatest among other stresses, whilst tensile yield stress was higher than shear yield stress. These results agreed well with computer simulation on the employment of single chain or a column of Body Centred Tetragonal (BCT) unit cells structure. Compressive loading was found to transfer the largest force from plate to plate with computer simulation modelling [9]. Monkman [10] has considered the compressive effect for different type of ER fluids and observed that the hardness modulus of the fluids increased as the electrode gap size was reduced. Additionally, Tian et al. [11] have investigated a stepwise compression of ER fluids that contained zeolites and silicones in squeeze mode. In order to understand the tensile stress, Tian et al. [12] introduced a normalized method to differentiate the tensile behaviour of the ER fluids under various applied electric field strengths. Other co-workers [13] reported that the tensile behaviour of ER fluids was proportional to the electric field for several values of electric field power depending on the range of the applied voltages. Under squeeze mode, many factors contribute to variable stresses such as ratio of solid suspension to carrier liquid [10], initial gap distances [14] and external field strength [3, 15, 16]. In another study done by Choi et al. [17] on poly(methylaniline) based ER fluid, with the factors previously mentioned, it was found that compressive speed also affected the compressive and tensile stresses. Furthermore, the suspension particle size can cause a significant effect on the yield stress. Generally, a higher stress, can be obtained with coarser particles sizes [18].

Despite the fact that MR fluids have been investigated repeatedly with the squeeze mode geometry, controlling vibration of rotor systems was dealt with in many of the studies. Forte et al. [19], Ahn et al. [20] and Carmignani et al. [21] developed an MR squeeze film damper system for rotor applications. The performance of the squeeze film damper in dynamic behaviour in relation to the magnetic field strength was studied. Forte et al. [19] have carried out a preliminary test to obtain the optimum conditions for each steady rotational speed of MR squeeze film damper. Later, Carmignani et al. [21], continued to work on the effectiveness in dampening the rotor vibrations and controlling its dynamic characteristics. Furthermore, Wang et al. [22] investigated the dynamic performance of a similar system, and in a later study, Wang et al. [23] analyzed the mechanical properties of the film and the unbalanced response characteristics of the MR squeeze film in the damper-rigid rotor system.

In another experimental investigation done by Vieira et al. [24], the forcedisplacement curve was greatly affected by the magnetic field strength, frequency and displacement factors in squeeze mode under oscillatory conditions. In terms of the forces produced by squeeze mode; fluid film force and magnetic pull force are also affected by the dynamic performance of an MR fluid squeeze film damper [22]. Even though tension and compression behaviour of the MR fluids were observed during these experimental studies, individual investigation on these behaviour still needs to be performed. A thorough study of the stress-strain relationships in compression and tension of MR fluids under squeeze mode is still not complete. In consequence of the potential commercial impact of the MR fluids, it is essential to understand the behaviour of MR fluid under squeeze mode in order to determine the desirable or achievable stresses. Therefore, a systematic and thorough further study of MR fluid in squeeze mode with various factors needs to be conducted.

#### **1.2** Purpose of study

MR fluids show excellent properties as a result of rapid, dramatic and reversible change of the consistency in magnetic field. The preference for either type of fluid or working mode depends on the requirements of the sought application. Thus, investigation of the behaviour of MR fluids in tension and compression condition are interesting for both academic researchers and engineers. The potentials of an MR fluid can only be fully exploited if the property profile and the design of the device are accommodated with each other. Therefore, the main objective of this study is to investigate the behaviour of MR fluids in squeeze mode. More specifically, the aims of this study can be summarized as follows:

- A. To design and build a test rig in order to carry out the compression and tension tests under squeeze mode.
- B. To simulate a magnetic field generated by a coil to achieve the required magnetic field strength.
- C. To study the behaviour of MR fluids under compression and tension in terms of stress-strain relationship.
- D. To investigate the influence on the stress-strain curve due to different factors such as, type of carrier liquid, applied current, initial gap size and compressive speed.
- E. To compare between compressive and tensile stresses of the MR fluids.

#### **1.3** Outline of thesis

This thesis is organized in five chapters. A brief and comprehensive overview of the main points of the research process is shown in figure 1.1. The thesis contains an introductory chapter which gives a brief introduction on MR fluids and their behaviour under the influence of magnetic fields to the readers who are not already familiar with the subject. This chapter also talks about previous research findings leading to the objectives of this study. Each chapter in this thesis ends with a brief summary outlining the achievements and findings that were established in the chapter. The remainder of this thesis is organized as follows:

- Chapter 2: Field responsive fluids that undergo significant responses leading to consequent rheological changes upon the influence of an external field are reviewed in this chapter.
- Chapter 3: The theoretical background which covers basic principles and rheological properties of MR fluids is described. Major significance is given to the individual working modes and their applications.
- Chapter 4: The simulation and experimental procedure related to the test rig design is covered in order to obtain the best magnetic field strength generated by a coil for optimum performance in squeeze mode.
- Chapter 5: This chapter is provided with results and discussions on the behaviour of MR fluids under compressive and tensile loadings.
- Chapter 6: This chapter is furnished with results and discussions of each factor that contributes to the effects on the performance of MR fluids.
- Chapter 7: This chapter is presented with conclusions and highlights of the study contribution, and is concluded with recommendations for future research work.



Figure 1.1: Summary of the research process in chapter 1.

# CHAPTER 2

# FIELD RESPONSIVE FLUIDS

#### 2.0 Introduction

Smart materials, such as rheological materials exhibit a perceptible change of a certain physical behaviour in reaction to external stimuli. In this chapter, a brief description about smart materials, their properties and some of the theory of the magnetism are discussed.

#### 2.1 Smart materials

In the earlier development, most eras of technological development have been connected to utilize and alter the use of materials such as the stone, bronze and iron ages. Until relatively recent years, the vigorous technological change in many respects has switched towards information technology. These changes are generously demonstrated by the ability of microprocessors to control daily domestic appliances. However, the generation of the information technology has stimulated material sciences and led to a new family of engineered materials and structures. Smart materials are materials that have multiple properties (chemical, electrical, magnetic, mechanical and thermal), or can transform energy (photovoltaic, thermo-electric, piezoelectric, photoluminescent, and electrostrictive) which can be altered or tuned using external fields [25]. In general, smart materials can be divided into many categories based on their stimulus and response as shown in table 2.1.

Stimulus	Material Class	Response
Temperature	Shape Memory Alloys [26]	Mechanical strain
remperature	Pyroelectrics [27]	Electric polarization
Electric Current	Piezoelectrics [28, 29]	Mechanical strain
	Electroluminescent Materials [30]	Light emission
Electric Field	Electrochromic Materials [31]	Colour change
	Electrorheological Materials [1, 32]	Rheology change
	Electrostrictors [33]	Mechanical strain
Electric Field / pH	Electroactive Polymers [34]	Mechanical strain
	Magnetorheological Materials [4, 35]	Rheology change
Magnetic Field	Ferrofluids [36]	Rheology change
	Magnetostrictors [37, 38]	Mechanical strain

**Table 2.1:** Classification of the smart materials and their response.

MR materials are field responsive rheology under smart materials, where their properties may be controlled by the execution of an external magnetic field. The materials are currently enjoying renewed interest within the technical community in terms of the fundamental and applied research. Usually, MR materials comprise of MR fluids, foams and elastomers [39]. The focus on MR fluids makes possible numerous applications in the automotive, aerospace and other sectors of technology [40], and has attracted much interest of many researchers in recent years [41-44].

#### 2.2 Field responsive fluids

Field responsive fluids are materials that undergo significant responses leading to consequent rheological changes upon the influence of an external field. There are two main classes of smart fluids; MR fluids and ER fluids under the influence of applied magnetic and electric fields, respectively. The fluids comprise a carrier liquid, such as a dielectric medium, including mineral oil or hydrocarbon oil, and solid particles. MR

fluids require the use of solid particles that are magnetizable, and ER fluids make use of solid particles responsive to an electric field. In addition, ferrofluids (magnetic liquid) also can be categorized as smart materials. In the presence of a magnetic field, colloidal magnetic fluids retain their liquid properties. They do not generally exhibit the ability to form particle chains or develop a yield stress. However, ferrofluids experience a body force on the entire fluid, and this force causes the fluids to be attracted to regions of high magnetic field strength. Table 2.2 shows the comparison of some of the properties between them. In a general manner, MR and ER fluids demonstrate specific advantages or disadvantages which can be considered as complementary rather than competitive. They have their own markets and applications in different fields [45, 46]. For instance, one of the advantages of MR fluids is higher stresses that they can withstand, while the major advantage of ER fluids is a smaller size of the systems that they can be developed with them.

No.	Items	MR fluids	ER fluids	Ferrofluids
		[18, 42, 47]	[48]	[49]
1	Particulate material	Ferromagnetic,	Polymers,	Magnetite,
		ferrimagnetic, etc	Zeolites, etc	hematite, etc
2	Particle size	0.1 – 10 μm	$0.1 - 10 \ \mu m$	< 10 nm
3	Carrier fluid	Water, synthetic oils,	Oils, dielectric	Aqueous
		non-polar and polar	gel and other	paramagnetic
		liquids, etc	polymers	salt solution
4	Density (g/cc)	3-5	1 -2	1-2
5	Off viscosity	0.1 to 0.3	0.1 to 0.3	0.002-0.05
	(Pa.s <sup>-1</sup> @ 25 °C)			
6	Required field	~3 kOe	~ 3 kV/mm	~ 1 kOe
7	Yield strength	100 kPa	10 kPa	$\frac{\Delta \eta(B)}{\approx 2}$
	(Field)			$\eta(0) \sim 2$
8	Device excitation	Electromagnets and /	High Voltage	Permanent
		or permanent magnet		magnet

**Table 2.2:** Comparison the properties of MR fluids, ER fluids and ferrofluids.

One benefit of these materials is that electromechanical actuators can be appropriately designed and fabricated. The utilization of MR or ER fluids can work to rapidly respond in active interface between sensors or controls and mechanical outputs. The fluids can be employed in vibration isolation systems as an example of precision surface shaping/polishing machines, mechanical clutches, brakes damping devices, building seismic isolators, torque/tension controllers, gripping/latching devices and fluid flow controllers [50].

#### 2.2.1 Magnetorheological fluids

MR fluids can be described as magnetic field responsive fluids which are part of a group of relatives known as smart or actively controllable fluids. The discovery of MR fluids is credited to Jacob Rabinow at the US National Bureau of Standard in 1948 [51]. MR fluids consist of magnetically permeable micron-sized particles dispersed throughout the carrier medium either a polar or non-polar fluid, which then influence the viscosity of the MR fluids. On the other hand, MR fluids are controllable fluids that exhibit dramatic reversible change in rheological properties (elasticity, plasticity or viscosity) either in solid-like state or free-flowing liquid state depending on the presence or absence of a magnetic field. In the presence of an applied magnetic field, the suspended particles appear to align or cluster and the fluid drastically thickens or gels. The flow resistance (apparent viscosity) of the fluid is intensified by the particle chain. When the magnetic field is removed, the particles are returned to their original condition, which lowers the viscosity of the fluid. The fluid structure is dependent on many factors such as volume fraction, magnetic field strength and carrier fluid. The fluid structure is also responsible for a rapid formation and is reversible either in solid-like state or free-flowing liquid state. The changes of solid-liquid state or the consistency or yield strength of the MR fluid can be precisely and proportionally controlled by altering the strength of the applied magnetic field. These characteristics provide simple, quiet and rapid response interfaces between electronic control and mechanical systems.

Most of the researchers used carbonyl iron as particles scatter in oil medium, for instance silicone oil [18, 22, 52, 53], hydrocarbon oil [54], mineral oil [55-57] and hydraulic oil [58]. The material also can be produced at a relatively lower cost as compared to MR fluids that include hydrophobic-oil type fluids as a carrier fluid. Iron powder is the most popular material used as particle due to its high saturation magnetization about 2.1 T [59]. Those particles are arranged in a proper order from one pole to another pole of a magnet to form very strong chains or fluxes [3]. Initially, in the absence of the magnetic field, the iron particles in the space between two walls move unrestrained. In the presence of the magnetic field, the iron particles are constructed into a uniform polarity and connected to the walls [60]. Once aligned in this manner, the iron particles are refrained from moving out of their respective flux lines and act as a barrier to an external force. The yield stress, in this case, symbolizes the maximum of the stress-strain relationship, and the chains will break when the stress has reached its maximum which allows the fluid to flow even if the magnetic field is still applied [61].

MR and ER fluids use feedback information such as rapid response interfaces between electric controls and mechanical systems to vigorously change the material behaviour. By changing the material behaviour, the performance of the devices is intensified to a certain level that unattainable using conventional materials and devices. MR fluids can be considered as unique smart materials because they produce milliseconds response time [39, 62]. The fluids may be used in both small and large displacement devices in order to generate very large forces and torques without reliance on the velocity of the working systems. The performance of the fluids depends on the fluids' structure in connection with many factors such as volume fraction, carrier fluid and particle size [49]. The development and success of MR fluids in recent years are mainly due to the rapid research devoted to improving the technology into one that is commercially viable. Research studies done by industries such as Lord Corporation and Liquids Research Limited and all over the world have contributed to the MR technologies in order to be used in a wide variety of applications [47, 63].

#### 2.2.2 Electrorheological fluids

One of the attractive field-responsive fluids, similar to MR fluid, is ER fluid which also exhibit rheological changes or ability to alter their flow under the influence of an applied electric field. In the earlier era, ER fluids have long been known as electroviscous fluids [64], where rheological effects were used to depict the changes observed in the mechanical properties of the fluid due to electrostatic stress. Nevertheless, the initial discovery of electrorheological fluids is credited to the American inventor Willis M. Winslow [65] who, in the 1947 described the effects of ER fluids in his patent. He also discussed in details the ER effects (also known as Winslow effect) in his work with regard to the mechanism of induced fibration [66]. Subsequent studies on the ER fluids and their effect gained much more attention. The ER effect was ascribed to Klass and Martinek [67] regarding the study on electroviscous properties of suspensions, where a large change in electroviscosity as a function of many parameters was found.

ER fluids comprise of electrical polarizable particles dispersed in carrier fluid (electrically insulating oil) with complement of additives and/or surfactants [68, 69]. Basically, an ER fluid consists of particles containing mobile charge carriers such as polyacene quinines, polymeric electrolytes of Bayer, carbonaceous fluid of Bridgestone, zeolites and polyelectrolytes [70]. For a certain particle like silica, in order to increase the performance of ER effect, polyelectrolytes are added for the purpose of absorbing water onto the particulate material. This process increases the electrostatic force of attraction between the particles, where the effect decreases as the amount of water absorbed decreases [71, 72]. Therefore, at the initial stage, ER fluids had not created much interest until Block and Kelly [73] discovered water-free ER fluids. These materials are classified as intrinsically polarizable materials. For instance ferroelectric, inorganic, semiconductor polymer, metal, coated conductor and liquid crystal materials are water-free ER materials, which perform as a function of bulk polarization or interfacial polarization [74]. Furthermore, particle shape was also found to affect the performance of ER fluids [75].
The working mechanism of MR fluids is assumed to be similar to that of ER fluids except the MR fluids are limited by magnetic saturation while ER fluids are limited by dielectric strength [66]. When an electric field is applied, the particles inside the ER fluid become polarized and have a higher dielectric constant than its surrounding carrier fluids. At the greatest field concentration, the number of polarized particles is increased by the movement of the mobile charges to those areas. This results in inducement of dipoles moments that attract one another and endure particles alignment to minimize the dipole-dipole interaction energy in the field direction [40]. These particle chains restrict the movement of the fluid.

In comparison, MR fluids are found to be superior to ER fluids in terms of yield stress, current consumption and stability [42]. In addition, the amount of active fluids required in the MR fluids in order to execute mechanical performance is less than the requirement of ER fluids. Even though ER and MR fluids require almost the same magnitude of power, MR fluids need only small voltages and high currents, while ER fluids demand high voltages and low currents. Furthermore, MR fluids have an advantage over ER fluids in the sense of the influence of contaminants or impurities. ER fluids are very sensitive to this factor but MR fluids are not [39]. Thus, the extremely high voltage requirements and inability to withstand contamination of ER fluids make them unpractical for most of commercial applications.

In contrast, ER fluids have a distinctive feature where they show higher response characteristics as compared to MR fluids. For instance, Choi et al. [76] have done comparison of the field controlled characteristics between ER and MR clutches. They found that shorter time is needed to track the desirable trajectory in the ER clutch to the desired set-torque. In another study, El Wahed et al. [77] discovered that ER devices appeared to provide more viable means (in terms of input displacement and transmitted force) of achieving fixing relaxation subjected to various magnitudes of impact loading.

## 2.2.3 Ferrofluids

Another category of field responsive fluids is ferrofluids which are different from the usual MR fluids. Ferrofluids consist of colloidal suspension of monodomain ultrafine magnetic particles (typically less than 10 nm), dispersed in either aqueous or nonaqueous liquids [78-80]. Basically, particle types of superparamagnetic materials such as iron oxides, Mn-Zn Ferrites, Ferrum and Cobalt is chosen together with a carrier fluid, such as water, oil or diester, to produce a stable colloidal suspension. When an external magnetic field is applied, dipolar interactions are induced within the particles causing them to align in the field direction. Forces exerted from the magnetic field are transmitted through viscous friction to the ferrofluids, which leads to various interesting phenomena. However, ferrofluids do not exhibit yield stress (like MR fluids), but, instead they have field dependent viscosity [81].

In contrast, MR fluids have larger particles and react differently as compared to ferrofluids under the same influence of the magnetic field [82]. MR fluids can change their viscosity with the formation of a chain structure and solidify when a magnetic field is applied. However, ferrofluids commonly keep their viscosity with high magnetic fields without forming any chain. However, since ferrofluids are synthesized by colloidal magnetic particles, they are more stable compared to MR fluids, which are based on non-colloidal magnetic particles. Practical applications of this property include automotive, mechanical engineering, optics, electronic devices, biomedical and heat dissipation [78, 79].

#### 2.3 Origin of magnetism

There are three types of magnets such as permanent magnet, temporary magnet and electromagnet that could attract other pieces of iron or steel. A permanent magnet is connected with the motion and interaction of its electrons, and has a high coercivity to retain magnetism for a long time. The coercivity can be described as the intensity of the magnetic field required to reduce the magnetization of that material to zero after the magnetization of the sample has reached saturation [83]. A temporary magnet has a low coercivity which is readily magnetized but retains only a very small field. They easily become magnetized under the influence of an external field. Electromagnets can be produced by wrapping a coil of wire around soft iron core. The magnetic field is created only during the time of current flow through the coil. The strength of these magnets is indicated by the magnetic moment, as a result on the atomic scale from the orbital motion of the electrons around the nucleus. The source of electromagnetic moment is indicated by a quantum mechanical property (spin dipole magnetic moment). The overall magnetic moment of the atom is referred to as the net sum of all the magnetic moments of the individual electrons. The net of magnetic moment is due to the tendency of the magnetic dipoles to oppose each other to reduce the net energy. Some pairs of the electrons in an atom are either adding or cancelling each other, resulting in different forms of magnetism [84].

The behaviour of magnetic materials can be classified as diamagnetic, paramagnetic, ferromagnetic, anti-ferromagnetic and ferrimagnetic as shown in table 2.3. Magnetic susceptibility (in table 2.3) is the degree of magnetization of a material in response to an applied magnetic field. At room temperature, both diamagnetic and paramagnetic materials do not exhibit any hysteresis where the magnetism of these materials is very weak. Hysteresis is a property of a system that does not instantly follow the forces applied to it. Instead the system reacts slowly or does not return completely to its original state depending on its immediate history. Diamagnetism exhibits a very small negative magnetization in a material that consists of atoms with almost no net magnetic moment. Magnetic permeability is the ability of a substance to acquire a high magnetization in relatively weak magnetic fields. The relative permeability can also be referred to as the ratio of the permeability of a magnetic material to the permeability of vacuum. Thus, the relative permeability in the diamagnetism is slightly less than zero when it reacts with an external magnetic field. On the contrary, a paramagnetic material with disorder of the atomic moment generates no net magnetization. This material has a relative permeability that is slightly greater than one [83].

Type of Magnetism	Magnetic Behaviour	Magnetic Susceptibility	Examples [85]
Diamagnetic		Small and negative	Copper, silver, gold and alumina
Paramagnetic		Small and positive	Aluminium, titanium and alloys of copper
Ferromagnetic		Very large and positive, function of applied field, microstructure dependent	Iron, nickel and cobalt
Anti- ferromagnetic		Small and positive	Manganese, chromium, MnO and NiO
Ferrimagnetic		Large and positive, function of applied field, microstructure dependent	Ferrites

 Table 2.3: Different types of magnetic behaviour.

Ferromagnetic is a material with high magnetic permeability, capable of becoming highly magnetic and have the ability to retain a permanent magnetic moment. The elementary magnetic dipoles inside the domains are all oriented parallel to each other. Domains can be classified as regions in the material in which all of the dipoles are aligned. However, when the domains are all oriented in an anti-parallel direction to each other, the material is said to be anti-ferromagnetic and appears to be nonmagnetic. Whereas, if the domains of a specific type of anti-ferromagnetic in which the net domain of the system is not equal to zero, such material is said to be ferrimagnetic [86]. This happens due to the spin in each direction not being equal.

## 2.4 Magnetic materials

Ferromagnetic and ferrimagnetic are two types of materials that are widely used in magnetic components. They have different coercivity depending on their sizes or domains. The coercivity increases when the amount of particles of the magnetic materials increases. Therefore materials with a few or no domains have a high coercivity whilst those with many domains have low coercivity. The energy of the domains on either side of the walls (an interface separating magnetic domains) will increase with the application of a very low magnetic field. This low magnetic field produces zero coercivity where there is nothing to impede its motion. Under the pressure of the applied magnetic field, magnetization reversal occurs either by coherent rotation of the magnetic moments in the domain or by nucleation and growth of reverse domains. The coercivity of a crystal structure in a permanent magnet is usually very small. A crystal structure (also known as a lattice) is a set of atoms arranged in a particular way. However, due to imperfections in the structure such as inclusion [87] and dislocation [88], the crystal coercivity increases. These factors act as a barrier to the movement of domain boundaries.

Inclusions are small "holes" in the medium, usually formed by the entrapment of a foreign material. The inclusions are either nonmagnetic or having much smaller magnetization than their surroundings. Such inclusions impede the process of magnetization, having magnetic poles induced on their surface causing a reduction in the surface energy of the domain walls. On the other hand, a dislocation in the crystal lattice interacts with the domain walls. In some cases, the easy axes on two sides of the dislocation may be aligned differently. (In iron, the easy axes are all mutually perpendicular). If the dislocation is severe, the exchange interaction between atoms on the two sides of the wall may become negligible and a domain wall might not be able to cross the boundary. Generally, if a material is easily magnetized and demagnetized, it can be referred to as a soft magnetic material, whereas, if it is difficult to demagnetize, it can be referred to as a hard magnetic material. Apart from coercivity, there are few other factors that can differentiate between soft and hard magnetic materials such as hysteresis loop, saturation magnetization, permeability and remanence.

#### 2.4.1 Hysteresis loop

A hysteresis loop carries a lot of information on the magnetic properties of a material and can be represented by the relationship between magnetic flux density B and magnetic field intensity H and is normally called the B-H curve [86]. A material with a wide hysteresis loop has low permeability and high remanence, coercivity, reluctance and residual magnetism. On the contrary, a material with a narrower loop has the opposite characteristics. An example of a hysteresis loop for a ferromagnetic material is shown in figure 2.1.



Figure 2.1: Magnetic flux density versus magnetic field strength [86].

The ferromagnetic hysteresis loop is generated by measuring the magnetic flux B as the magnetizing force H is changed. Initially, magnetization for an unmagnetized

ferromagnetic material will follow the dashed line, in figure 2.1, until it reaches magnetic saturation. Points *S* and *S'* represent the saturation values at positive and negative sides, respectively. When the value of *H* is reduced to zero, the curve moves from point *S* to point  $B_r$  instead of return back to its original point. At this point, some of the magnetic flux density still exists and this residual field  $B_r$  is called the magnetic remanence. When the value of *H* is placed in the negative side or as *H* is reversed, the curve further moves to point  $-H_c$  (coercivity or coercive force) at zero value of *B*. With further increase of *H* in the negative direction, the material will become magnetically saturated reaching the point *S'* as the magnetizing force is increased in the negative direction.

On the other hand, when the value of *H* is increased back to zero, the curve moves from point *S*' to point  $-B_r$ , which has the same value of  $B_r$  in the other direction. This is because they have the same amount of the residual magnetism. The curve moves to  $H_c$  when *H* is given a positive value at zero value of *B*. Further increases of *H* will result the curve to move back to point *S*, where the curve completes the loop [89].

Figure 2.2 shows typical hysteresis loops for hard and soft magnetic materials. The shape and size of the hysteresis loop greatly depends on the type of the material. The loop will be narrow if the material is easily magnetized. On the other side, the loop will be wide if the material does not get magnetized easily. In addition, different types of magnetic materials will saturate at different values of magnetic flux density, which is affecting the height of the loop. The loop area also depends upon the maximum flux density that is established in the material.



Figure 2.2: Hysteresis loops for soft and hard magnetic materials. [90].

**Table 2.4:** Comparison magnetic properties between soft and hard magnetic materials.

Magnetic Property	Soft Magnetic Material	Hard Magnetic Material
Hysteresis loop	Narrow	Large area
Remanence	High	High
Coercivity	Low	High
Saturation flux density	High	Good

Table 2.4 gives the magnetic properties of hard and soft magnetic materials. The permanent magnets are made from hard magnetic materials such as steel, cobalt steel and carbon steel. The magnet is quite strong since these materials have high remanence. They are difficult to be demagnetized by removing the magnetic fields due to their high coercivity. The electromagnets or temporary magnets are made from soft magnetic materials such as soft iron. They can be easily demagnetized and produce strong magnets since these materials have low coercivity and high saturation flux density, respectively. For instance, transformer cores are made from soft magnetic materials since they have narrow hysteresis loop (smaller hysteresis loop area). When a transformer is in use, its core is taken through many cycles of magnetization. The energy

lost as heat in reversing the magnetization of the material (hysteresis loss) is proportional to the area of the hysteresis loop.

#### 2.4.2 Hard magnetic materials

Hard magnets, also referred to as permanent magnets, are magnetically saturated materials. As a result, once magnetized, these materials have a very large intrinsic coercivity and become permanent magnets [86]. At the atomic level, ferromagnetic materials exhibit a long-range ordering phenomenon which causes unpaired-electron spins to line up parallel to each other in a domain. A strong magnetic field exists within the domain, but as an entire material it has a small magnetic field because the domains are randomly oriented with respect to one another. An external magnetic field can cause the magnetic domains to line up with each other. As a result, the material is said to be magnetized.

One of the important factors in permanent magnets is called magnetic remanence of the material. This phenomenon occurs when the applied magnetic field is removed where a fraction of the saturation magnetization still remains [83]. A certain level of energy is required in order to force the domains back to the original condition. Normally, hard magnetic materials are used in the production of permanent magnets. The properties of ferromagnetic materials make them applicable to be utilized as a magnetic memory. Some of the compositions of the ferromagnetic materials will retain an imposed magnetization indefinitely such that the criteria of permanent magnets can be fulfilled.

# 2.4.3 Soft magnetic materials

Soft magnetic materials require a very small magnetizing field to become magnetized. For instance, a magnetic field is created when a current is passed through a wire wound around a soft magnetic core. They have a low coercivity and once the magnetizing field is removed, the flux density essentially goes to zero. Alternating current (AC) or direct current (DC) electrical circuits can be used in order to generate a magnetic field or to create a force. Permeability is the main consideration for the material selection in the DC application, whereas the saturation magnetization may then be significant. This would be the case, for example, in shielding applications where the flux must be channelled through the material, and can also be utilized to amplify the flux generated by an electric current [83]. Energy loss is the most critical factor in the system for AC applications as the material is cycled around its hysteresis loop. The energy loss can originate from three different sources such as hysteresis loss, eddy current loss and anomalous loss (magnetic losses in soft magnetic material) [86]. Hysteresis losses can be reduced by the reduction of intrinsic coercivity with a consequent reduction in the area within the hysteresis loop. An eddy current is a swirling current set up in a conductor in response to a changing magnetic field. Eddy current losses can be reduced by decreasing the electrical conductivity of the material. Because of the skin effect at a higher frequency which can influence the overall conductivity, it also can be reduced by laminating the material. Finally, anomalous losses can be reduced by having a completely homogeneous material, so that there is no obstruction to the motion of the domain walls [91].

#### 2.5 Concept of electromagnetism

Electromagnetism can be described as relationship between electricity and magnetism. A changing magnetic field produces an electrostatic force. Similarly, changing electric field generates a magnetostatic field. The magnetic field is generated by the motion of electric charges such as electric current, to cause a magnetic force associated with magnets. A type of a helical coil or solenoid can be used in order to produce an electromagnetic field. Figure 2.3 shows the basic solenoid where a wire is wound around an air core.



Figure 2.3: Schematic of a basic solenoid coil wound around air.

Kraus [89] recommended that the magnetic flux density B at the centre of the coil (maximum value) can be calculated as

$$B = \frac{\mu NI}{\sqrt{4r^2 + l^2}} \tag{2-1}$$

where *B* is the magnetic flux density or magnetic inductance (tesla, T or Weber/m<sup>2</sup>, Wb/m<sup>2</sup>),  $\mu$  is the permeability of the material in the field (N/m<sup>2</sup>), *N* is the number of turns on the excitation coil (turn, t or can be considered as unitless), *I* is the current enclosed in the coil in each turn (A), *r* is the radius of the wire (m) and *l* is the length of the solenoid (m). At the one end of the coil, the magnetic flux density becomes

$$B = \frac{\mu NI}{2\sqrt{r^2 + l^2}} \tag{2-2}$$

If the length of the solenoid is much greater than its radius  $(l \gg r)$ , equations (2-1) reduces to

$$B = \frac{\mu NI}{l} \tag{2-3}$$

and equation (2-2) reduces to

$$B = \frac{\mu NI}{2l} \tag{2-4}$$

#### 2.5.1 Magnetic properties

Magnetic field intensity H is the amount of magnetizing force which is proportional to the length of a coil l and the amount of electrical current passing through the coil I (refer to figure 2.3). According to Ampere's law, the line integral of H around a single closed path is equal to the current enclosed is denoted by [89]

$$\oint H \cdot dL = I \tag{2-5}$$

where *H* is the magnetic field intensity  $(Am^{-1})$  and *dL* is the infinitesimal element of path length (m). An analogous relation with static electric field and the relation of magnetomotive force, equation (2-5) can also be written as

$$\oint H \cdot dL = I = F \tag{2-6}$$

where F is the magnetomotive force (mmf) is equal to the current enclosed (ampereturn, At).

If the path of integration in equation (2-6) consists of a number of turns of wire each with a current in the same direction, equation (2-6) may be written as

$$\oint H \cdot dL = F = NI \tag{2-7}$$

In other word, if the magnetic field is generated by a cylindrical coil, then

$$H = \frac{NI}{l} \tag{2-8}$$

In this case, the unit of H can be written as either ampere-turns per metre (At/m) or simply ampere per metre (A/m).

In a vacuum, magnetic flux density B represents the magnitude of the internal field strength within a substance that is subjected to an H field [86] and is given by,

$$B = \mu_0 H \tag{2-9}$$

where,  $\mu_0$  is the permeability of a vacuum =  $4\pi \times 10^{-7} \approx 1.257 \times 10^{-6}$  T.m/A. If there is a material, other than vacuum, in the middle of the magnetic fields, the magnetic flux density now is [83]:

$$B = \mu H \tag{2-10}$$

Relative permeability  $\mu_r$  (unitless) is used to measure the degree to which the material can be magnetized, where

$$\mu_r = \frac{\mu}{\mu_0} \tag{2-11}$$

Magnetization M is a property of some materials that describes the level of magnetic field affect is given by [86],

$$B = \mu_0 H + \mu_0 M \tag{2-12}$$

where, *M* is the magnetization of a material (magnetic moment per unit volume,  $A.m^2/kg$  or Wb.m/kg).

In general, a material becomes magnetized in response to an external field H and can be measured through susceptibility and permeability. Hence, M can be expressed as

$$M = \chi_m H \tag{2-13}$$

where  $\chi_m$  is the magnetic susceptibility (unitless). Magnetic susceptibility is the degree of magnetization of a material in response to an applied magnetic field. Both relative permeability and magnetic susceptibility are related as follows:

$$\mu_r = 1 + \chi_m \tag{2-14}$$

#### 2.6 Summary of chapter 2

A brief and comprehensive overview of the main points of a body of the research process is shown in figure 2.4. The general knowledge about smart materials, their properties and some of the theory of the magnetism are discussed in great details. The basic fundamentals of the smart materials lead to the focus subject on MR fluids in chapter 3.



Figure 2.4: Summary of the research process in chapter 2.

# CHAPTER 3

# Magnetorheological Fluids

#### 3.0 Introduction

Pertaining to the technological challenges, it can be expected that the continuing development of the technology based on smart fluids will create a large number of new electromechanical devices in the near future. This chapter reviews the details of MR fluids in terms of rheological properties and basic principles when magnetic field is applied. Finally, a substantial amount of potential applications are listed depending on their working modes followed by a brief summary of the chapter.

#### **3.1** Composition of MR fluids

As mentioned in section 2.2.1, MR fluids consist of non-colloidal suspensions, magnetically soft ferromagnetic, ferrimagnetic or paramagnetic elements and compounds in a non-magnetic medium. However, MR fluids consist of suitable magnetizable particles (iron, iron alloys, iron oxides, iron nitride, iron carbide, carbonyl iron, nickel and cobalt) [46, 92]. A preferred magnetic responsive particle that is commonly used to prepare MR fluids is carbonyl iron. The possible maximum yield stress induced by MR effect is mainly determined by the lowest coercivity and the highest magnitude of saturation magnetization of the dispersed particles. Therefore, soft magnetic phase for most of the practical MR fluids composition [93]. Other than carbonyl iron, Fe-Co alloys and Fe-Ni alloys can also be used as MR materials, whereby, Fe contributes to the high saturation magnetization. However some of the ferrimagnetic materials such as Mn-Zn ferrite, Ni-Zn ferrite and ceramic ferrites have low saturation magnetizations and are therefore suitable to be applied in low yield stress applications [46].

Iron powder magnet can be prepared by hydrogen reduction of ferric oxide [94] or by Chemical Vapour Deposition (CVD) from iron pentacarbonyl,  $Fe(CO)_5$  [18, 40]. Once the particles are magnetized, the oriented domains can grow with the magnetization persisted and simultaneously increased permeability. Saturation magnetization of the iron can be obtained when all of the domains are properly oriented.

The domain walls can easily move, ideally making the magnetization a single-valued function of the magnetizing field, so that there is no hysteresis loss when the field reverses repeatedly. The particle size should be meticulously selected, so that it can exhibit multi-domain characteristics when subjected to an external magnetic field. MR particles are typically in the range of 0.1 to 10  $\mu$ m [18, 95], which are about 1000 times bigger than those particles in the ferrofluids [42]. In the MR fluids, magnetic particles within a certain size distribution can give a maximum volume fraction without causing unacceptable increasing in zero-field viscosity. For instance, fluid composition that consists of 50 % volume of carbonyl iron powder was used in the application of electromechanically controllable torque-applying device. An MR material was utilized thus providing a drive connection between two independently rotating components [96].

The carrier liquid forms the continuous phase of the MR fluids. Examples of appropriate fluids include silicone oils, mineral oils, paraffin oils, silicone copolymers, white oils, hydraulic oils, transformer oils, halogenated organic liquids, diesters, polyoxyalkylenes, fluorinated silicones, cyanoalkyl siloxanes, glycols, water and synthetic hydrocarbon oils [40, 92]. A combination of these fluids may also be used as the carrier component of the MR fluids. In the earlier patents, inventors were using magnetizable particles dispersed in a light weight hydrocarbon oil [97], either a liquid, coolant, antioxidant gas or a semi-solid grease [98] and either a silicone oil or a chlorinated or fluorinated suspension fluid [99]. However, when the particles settled down, the field-induced particle chains formed incompletely at best in which MR response was critically degraded. Later, in order to prevent further sedimentation, new compositions of MR fluids with consideration on viscoplastic [55] and viscoelastic continuous phases [52] were formulated, so that the stability could be improved immensely. In addition, a composite MR fluid has been prepared by Pan et al. [100] with a combination of iron particles powder, gelatine and carrier fluids. They showed that the MR effects were superior under low magnetic field strength, and had a better stability compared to pure iron carbonyl powder alone.

Surfactants, nanoparticles, nanomagnetizable or coating magnetizable particles can be added to reduce the sedimentation of the heavy particles in the liquid phase [56, 93]. The sedimentation phenomenon can cause a shear-thinning behaviour of the suspension [59]. With further sedimentation, with MR fluids under the influence of high stress and high shear rate over a long period of time, the fluid will thicken (in-usethickening) [45, 101]. Sedimentation phenomenon will reduce the MR effect where the particles in the MR fluids are settled down and form a hard "*cake*" that consists of firmly bound primary particles due to incomplete chain formation [53]. MR particles such as carbonyl iron can be described as the particle erosions and similar to onion like structure where they can be easily peeled by jolt or frictions. Anti-settling agent such as organoclay can provide soft sedimentation. When the composition of MR fluids has relatively low viscosity, it does not settle hard and can easily re-disperse [92]. Coating of the polymer layer also influences magnetic properties of the particles and cause them to easily re-disperse after the magnetic field is removed [102]. However, specific properties of MR fluids such as shear and yield stresses under the same conditions were enormously degraded inevitably by addition of the coating layer. This is due to the shielding of the polymer layer that affects the magnetic properties of the particles [102, 103]. In addition, some additives can improve the secondary properties like oxidation stability or abrasion resistance.

#### **3.2** Magnetic properties of MR fluids

The static magnetic properties of MR fluids are important to design any MR fluid-based devices and can be characterized by *B-H* and *M-H* hysteresis. Through the magnetic properties, the dependence of the MR fluid response on the applied current in the device can be predicted. There are many methods to measure the hysteresis loops for the fluid under different fields such as vibrating sample magnetometer (VSM) [18, 104], alternating gradient magnetometer (AGM) [80] and other induction techniques.

Under the influence of the magnetic field, a standard model for the structure is used to predict the behaviour of the particle of MR fluid [61]. The model is based on a cubic network of infinite chains of the particles arranged in a line with respect to the direction of the magnetic field as shown in figure 3.1. The chains are considered to deform with the same distance between any pair of neighbours in the chains and increase at the same rate with the strain when the MR fluid is strained. This model is seems quite simple since the chains, in actual case, are formed into some more compact aggregates of spheres in which can be constituted in the form of cylinders. Under shear stress, these aggregates might deform and eventually break. Even though the particles develop into different complicated structures under different conditions [85], the standard model still can be used in order to give a valid prediction of the yield stress [61].



**Figure 3.1:** Schematic representation of the affine deformation of a chain of spheres [61].

The equation of motion of each particle under a magnetic field is required in order to evaluate the bulk property of MR fluids. At a very low magnetic field, the magnetic force tensor  $F_{ij}$  is obtained as point-dipole similar to the pair interaction, the magnetic dipole moment induced by other particles and surrounding walls for an unmagnetized and isolated sphere under a uniform magnetic field is given by [60]:

$$F_{ij} = \frac{3}{4\pi\mu_f \mu_0} \left\{ m^2 \frac{r_{ij}}{r_{ij}^5} - 5(m \cdot r_{ij})^2 \frac{r_{ij}}{r_{ij}^7} + 2(m \cdot r_{ij})m \frac{1}{r_{ij}^5} \right\}$$
(3-1)

where  $F_{ij}$  is the magnetic force tensor acts on particle *i* from *j*,  $\mu_f$  is the specific permeability of particles,  $\mu_0$  is the vacuum permeability, *m* is magnetic dipole moment of particles and  $r_{ij}$  is position from *j* to *i*. The magnetic dipole moment induced in particles within MR fluid is given by [105],

$$m = 4\pi\mu_f \,\mu_0 \beta a^3 H \tag{3-2}$$

where *H* is the uniform magnetic field, *a* is the diameter of the particles and  $\beta$  is given by,

$$\beta = \frac{\mu_p - \mu_f}{\mu_p - 2\mu_f} \tag{3-3}$$

where  $\mu_{\rm p}$  is the specific permeability of carrier liquid.

At high magnetic fields, the magnitude of the moment can be considered as independent point dipoles when magnetization of the particle reaches saturation. Magnetic moment is given by [80].

$$m = \frac{4}{3}\pi a^3 \mu_s M_s \tag{3-4}$$

where  $\mu_s M_s$  is the saturation magnetization of the particle, which is about 1.7 x 10<sup>6</sup> A/m for bulk iron and 0.48 x 10<sup>6</sup> A/m for the magnetite.

# **3.3** Fundamentals of rheological properties

Rheology is defined as a study of the flow properties [106] and the behaviour of materials [107] or the response of materials to applied stress [108]. Rheology is an interdisciplinary field and is used to describe the properties of a wide variety of materials such as oil, food, ink, polymers, clay, concrete, asphalt and others. A rheometer is the instrument used to measure a material's rheological properties for which the equipment uses the working principal of a viscometer. There are many types of rheometers with very versatile control such as the stress and/or strain rheometers and capillary rheometers. The measurement of rheological properties of suspension, colloidal dispersion and emulsion provides critical information for product and process performance in many industrial applications. The materials must be stable in order to be performed properly or to process efficiently [106]. These are often complex formulation of solvents (or fluids); suspended particles of varying sizes and shapes, and various additives used that affect stability.

Many factors affect the stability such as hydrodynamic forces, Brownian motion, strength of the antiparticles interaction, volume fraction, electrostatic forces, size and shape of particles, and steric repulsion. These factors are responsible for the unique rheological properties of MR fluids. For instance, a quick formation of a network in response to an external field creates a rapid liquid-to-solid transition [109]. Measuring the rheology of a formulation gives an indication on the colloidal state and the interactions that are occurring. Rheology-based measurements can help predict which formulation might exhibit flocculation, coagulation or coalescence, resulting in undesired effects such as settling, creaming, separation and others. Flocculation is referred to the process by which particles are caused to stick together in floc (formation of loose or open aggregates), while coagulation is a process in which dispersed colloidal particles agglomerate (formation of compact aggregates) and coalescence is the disappearance of the boundary between two particles in contact, or is the process by which particles merge and pull each other to make the slightest contact. Rheology measurements and parameters can be used to determine the processing behaviour of non-Newtonian materials, viscoelastic behaviour as a function of time, the degree of stability of a formulation at rest condition or during transport, and zero shear viscosity or the maximum viscosity of the fluid phase to prevent sedimentation.

The viscosity equation on the basis of a hydrodynamic theory for dilute dispersions of spherical particles has been developed by Einstein about 100 years ago [110]. The equation has been derived as

$$\eta_r = 1 + 2.5\phi \tag{3-5}$$

where  $\eta_r$  is the relative viscosity of the suspension and  $\phi$  is the volume fraction of the suspended solutes or particles assumed to be spherical. The addition of the solid particles to a liquid will increase the amount of particles and consequently increases the volume fraction of the particles. Therefore, as the volume fraction of particles increases, there will be an increase in the fluid's viscosity. Shook [111] has suggested that the maximum concentration of the particles  $\phi_{max}$  should be incorporated in the relationship between viscosity and concentration as

$$\eta_r = \frac{\phi_{\max}}{(1 - \phi)^{2.5\phi_{\max}}}$$
(3-6)

However, these equations do not depend on the particle size but instead depend on the particle shape and solid concentration. Thus, Toda and Furuse [112] extended the equation in order to satisfy the viscosity behaviour of concentrated dispersion for small and large particles, given by,

$$\eta_r = \frac{1 - 0.5\phi}{(1 - \phi)^3} \tag{3-7}$$

and 
$$\eta_r = \frac{1 + 0.5\kappa\phi - \phi}{(1 - \kappa\phi)^2 (1 - \phi)},$$
 (3-8)

respectively, where  $\kappa$  is the correction factor that may depend on the size and concentration of the particles. If the value of  $\kappa$  is equal to one, then the size effect is neglected and equation (3-8) is transformed into equation (3-7).

The viscosity of the fluid can be increased with additional amounts of the solid particles. However, at the same time, the fluid behaviour will change and diverge from a Newtonian fluid. A fluid is known to be Newtonian when the stress at any point is proportional to the applied strain rate at that point. Shear stress  $\tau$  increases with the shear rate  $\frac{du}{dy}$  which often can be represented by the relationship

$$\tau = \tau_y + \eta \left(\frac{du}{dy}\right)^n \tag{3-9}$$

where  $\tau_y$ ,  $\eta$  and *n* are constants.  $\tau_y$  is the yield stress and  $\eta$  is the dynamic viscosity.

Newtonian fluids occur when the fluids show no yield stress or  $\tau_y$  is equal to zero and *n* is equal to one. The viscosity of a Newtonian fluid is independent of time and shear rate. In addition, the deviation of the behaviour of Newtonian fluid is known as a non-Newtonian fluid which the viscosity change is dependent on the applied shear rate. As shown in figure 3.2, the behaviour of the fluids can be classified into Newtonian fluids and non-Newtonian fluids such as plastic, Bingham plastic, pseudo-plastic and dilatant fluids [113]. Fluids are said to be plastic when the shear stress must reach a certain minimum value before it begins to flow. If n, in equation 3-9, is equal to one, the material is known as a Bingham plastic. For the pseudo-plastic or shear-thinning fluid, the dynamic viscosity decreases as the shear rate increases. On the other hand, a shear-thickening or dilatant fluid exhibits the converse property of pseudo-plastic for which the dynamic viscosity increases as the shear rate increases. If P, in equation 3-9, is equal to 0, the shear thickening fluid is represented by n > 1 and shear thinning fluid by n < 1.



Figure 3.2: Classification types of the behaviour of the fluids [113].

Additional non-Newtonian behaviour or time dependent properties are rheopecty and thixotropy [114]. In principle, shear thickening proceeds from the rheopecty and shear thinning proceeds from the thixotropy. As stress is applied, the apparent viscosity increases with the duration of the stress, the fluid is then called rheopectic. If the apparent viscosity decreases with the duration of stress, the fluid is then called thixotropic. Rheopectic behaviour occurs as a result of temporary aggregation due to interaction between the particles rather than breakdown due to collision of the attractive particles. On the other hand, the decrease in the viscosity of the thixotropic fluid occurs because of the breakdown of the microstructure and behaves like a liquid. These timedependent behaviour are reversible, which is, when the stress is removed the structure that was disturbed by shearing builds up in the thixotropic material and breaks down in the rheopectic material. Thus, the material settles back into its original consistency.

#### **3.3.1** Basic principles of MR fluids

MR fluids respond to the external field, where the particles are held together to form chains parallel to the applied field. The interaction between the particles impedes to a certain level of the shear stress without breaking and simultaneously increases the viscosity of the fluids [115]. In many cases, the effect of MR fluids is described by Bingham Plastic model [58]. A modified or extended Bingham model, or a combination of Bingham model with other models such as viscous and coulomb friction have also been used to describe the behaviour of MR fluid [116, 117]. In the absence of an external field, MR fluids behave like a normal fluid which is known as Newtonian fluid. Rheological studies have revealed the concept of dynamic yield stress. Rheology is primarily concerned about the study of the relationship between the shear stress and shear strain for solid materials and liquids. Figure 3.3 shows the basic concept of shear stress when a force is applied onto a fluid element.



Figure 3.3: Fluid element under a shear force [118].

When a shearing force F is applied at the top area of the element, shear stress can be calculated by the ratio of force over effective area which is equal to the force per unit area.

shear stress, 
$$\tau = \frac{F}{Area}$$
 (3-10)

where  $Area = \delta_x \times \delta_z$ .

Shear strain is the deformation caused by the shear stress and can be measured by the size of the angle  $\phi$ . The value of  $\phi$  is constant for a fixed value of shear stress in a solid state. However in a fluid state, the value of  $\phi$  increases as the shear stress is applied depending on the duration of time.

For a small particle to move from point E to point E', a distance x due to shear stress, the small deformation can be written as:

shear strain, 
$$\gamma = \frac{x}{y}$$
 (3-11)  
rate of the shear strain,  $\dot{\gamma} = \frac{\gamma}{t} = \frac{x}{ty} = \frac{x}{t} \frac{1}{y}$ 
$$= \frac{u}{y}$$
(3-12)

where  $\frac{x}{t} = u$  is the velocity of the particle at E. Shear stress is proportional to the rate of shear strain, therefore:

$$\tau = cons \times \tan t \times \frac{u}{y} \tag{3-13}$$

The term  $\frac{u}{y}$  is the change in velocity with y, or the velocity gradient, and may be written in the differential form  $\frac{du}{dy}$ . The constant of proportionality is known as the dynamic viscosity  $\eta$  of the fluid, giving

$$\tau = \eta \frac{du}{dy} \quad or \quad \eta \dot{\gamma} \tag{3-14}$$

Equation (3-14) can be recognized as a Newtonian fluid's equation.

For a non-Newtonian fluid with shear stress  $\tau$  above the yield stress  $\tau_y$ , the equation can be represented by Bingham plastic's equation as:

$$\tau = \tau_{y} + \eta \dot{\gamma}, \qquad \tau > \tau_{y} \tag{3-15}$$

Below the yield stress, material behaves viscoelastically as denoted by:

$$\tau = G\gamma, \qquad \tau < \tau_{y} \tag{3-16}$$

where *G* is the complex material modulus. If the shear stress  $\tau$  and shear strain rate  $\dot{\gamma}$  are known, the kinematic viscosity *v* can be calculated from,

$$v = \frac{\eta}{\rho} \tag{3-17}$$

where  $\rho$  is the density of the fluid and  $\eta$  is the dynamic viscosity.

#### 3.3.2 Rheology of MR fluids

MR fluid is a suspension of magnetically soft micron-sized particles in a carrier liquid. MR fluids demonstrate an ability to change their viscosity in milliseconds by several orders of magnitude under the influence of an applied magnetic field. There are many factors that influence the rheological properties of controllable MR fluids such as concentration and density of particles, particle size and shape distribution, properties of the carrier fluid [119], additional additives, applied field and temperature. The relationships of all these factors are very complex and are important in establishing methodology to improve efficiency of these fluids for suitable applications. Excellent MR fluids must have low viscosity and coercivity of particles without the influence of an external magnetic field. Gross [97] in his invention related to the valve for magnetic fluids, found that the advantage of large particle sizes or heavy suspensions can increase

the size of the gap which also increases the flow of the fluid. Conversely, the large particles of the magnetically active phase of MR fluids lead to a strong tendency for particles to settle out of the liquid phase [102].

Some of the techniques are typically necessary in order to increase the yield stress; either by increasing the volume fraction of MR particles or by increasing the strength of the applied magnetic field. However, neither of these techniques is desirable since a higher volume fraction of the MR particles can add significant weight to the MR devices as well as increases the overall off-state viscosity of the material. In that connection, restricting the size and geometry of the MR device capable of utilizing that material, and a higher magnetic field significantly increases the power requirement of the device. To overcome this difficulty, Carlson [120] in his patent introduced alloy-particles material that was used as a solid particle instead of the common carbonyl iron. This MR fluid independently increases the yield stress without requiring increment of either the volume fraction of particles or magnetic field strength.

#### 3.3.3 Off- and on-state rheology

The novelty of MR fluids is to minimize the off-state viscosity of the fluid, while the on-state yield stress of the fluid is maximized [121]. Both off-state viscosity and the on-state yield stress are very important in order to achieve a maximum MR effect. Turnup ratio refers to the differences between off-state viscosity and on-state yield stress. Turn-up ratio can also be defined as the ratio of the force output (on-state controlled by yield stress) generated by the magnetically activated MR fluid divided by the force output (off-state controlled by viscosity) for the same fluid in the off-state. As mentioned earlier, the increases in the volume fraction of the particle can increase the yield stress and viscosity of the MR fluids. In any event, the on- and off-states of MR fluids have been linked together in the sense that any attempt to maximize the on-state yield stress by increasing the solid volume fraction will carry a great penalty in turn-up ratio because the viscosity in the off-state will increase at the same time [49]. Thus, in order to obtain a suitably high yield stress, one must tolerate a relatively high viscosity when the material is in the turned off condition. In other words, the influence of materials that contain particles of a single particle size mode could result in a crucial turn-up ratio. Therefore, it is necessary to maximize the turn-up ratio. For instance, a mixture of two different particle sizes or bimodal, can contribute to a significant improvement in turn-up ratio [121].

Viscosity of the controllable fluids at zero magnetic fields is generally in the range of 0.1 kPa to 1.0 kPa [102], depending on the function of carrier liquid, additives, surfactants [93], particle loading and particle size distribution [121]. Under field responsive effect, the applied field induces a dipole moment in the same direction of the magnetic field in each particle causing the formation of chains. Those chain formations are responsible for the increase in yield stresses by the order of at least 100 times when subjected to a magnetic field [102]. A high magnetic field turns the magnetically soft particles into solid within milliseconds and substantially uniformly redisperses in the solvent after the magnetic field is removed. Foister [121] has found that at the off-state condition, the blend of large and small particles did not change the viscosity, whereas it provided an increase in yield stress. Furthermore, the size distribution of particles may affect the off-state viscosity and also on-state yield stress, since particles of different sizes may have different magnetic properties. Alternatively, by using volume fraction of a bimodal particle population with suitable fraction of the small particles, it is possible to obtain a high turn-up ratio [122].

# 3.3.4 Volume fraction and particle size factors

Few studies on the field-induced structures have determined the fundamental properties of the MR fluids. Researchers characterized the structures of self-assembly MR fluids depending on the cell thickness and the volume fraction of particles [81, 123, 124]. The magnetic flux density increases as the volume fraction of particles of the fluid increases [2], and as a result, the yield stress also increases. In order to predict this result, a mathematical model based on the theory of homogenization has been proposed by Simon et al. [125]. However, the authors did not consider the particle shapes and the microstructure of the fluid. Liu et al. [81] observed that the structure of MR fluid with low volume fraction can be characterized by uniformly spaced columns after the fluid

undergoes phase transition, changing from a liquid to solid. Even though they used 0.5  $\mu$ m particles sizes, their finding was concurred with Lemaire et al. [82], where the shape of the aggregate changes from an ellipsoid to a cylinder for bigger particle sizes 100 - 400  $\mu$ m at a higher volume fraction. In another experimental work, Carletto and Bossis [123] have observed the formation of a periodic planar structure in the plane of rotation of the field between parallel walls. They also showed that the shape of the domain depends on the geometry of the cell. The structures become complex (either the pattern forms like individual chains, walls or a mixture of chains and walls) and highly dependent on the cell thickness [124]. Oi et al. [104] reported that the uniform structures formed by the aligned magnetic rods exhibited larger magnetic anisotropy of particulate magnetic materials compared to microsphere shaped particles. The roll-slip behaviour has been observed by Davis et al. [126]. The authors showed the influence of surface roughness on reducing the effective viscosity, as they reduced the viscous dissipation of flowing suspensions.

At a high volume fraction, colloidal particles experience hydrodynamic interactions with each other and with the walls of the container. The friction, due to this phenomenon at about half of the concentration, would become significant in increasing the viscosity. Other than that, particle size distribution [122], particle shape [50, 104] and surface roughness [126] also have strong effects on viscosity. Moreover, bigger particle sizes give more yield stress where they consume more magnetization than fine particles [18]. Existing particles for MR fluids typically have spherical shapes. According to Starkovich and Shtarkman [50], particles with uncommon shapes such as cubic or cylindrical shapes give at least 10 times higher yield stress than the conventional shapes. This phenomenon is due to the increase of packing density, improved field homogeneity and larger interaction (contact area). This yields the necessary forces between the particles even at the level of small intensity of the magnetic fields. Furthermore, those shapes contribute to a larger magnetic anisotropy as compared with the spherical shape [104].

In general, magnetic characteristics (such as permeability) of the MR fluids only depend on the volume fraction but not on the type of particle size distribution [49]. Therefore, it is possible to reduce the off-state viscosity by utilizing a suitable fraction of

the small particles in order to obtain a desired yield stress based on the volume fraction of bimodal particle population. A combination of small and big particles (bimodal) strongly affects the viscosity and can be controlled within a wide range by controlling the respective fractions of the small and large particles in the bimodal size distribution families. In accord with Zaman and Dutcher [122], for a fixed size of large particles, as the size ratio is increased a minimum viscosity occurs at a higher volume ratio of the small particles in the system. Small particles act to fill up the voids in between the large particles, producing more efficient packing structure of small particles and forms distinct chains [58]. Furthermore, the introduction of the fine particles can greatly reduce the settling rate of the MR fluid. A ratio of particle sizes of at least five times larger can raise the on-state yield stress without affecting the off-state viscosity for a fixed volume fraction of solid [121].

#### **3.4** MR fluid modes of operation and its applications

In general, MR fluid devices use one of the three basic modes of operation of MR fluids or any combination of them depending on the function of the system. These series of actions are known as valve mode, shear mode, and squeeze mode [4, 39, 117]. Before designing any MR fluid device, the rheological, magnetic properties, the circuit and the working mode of the MR fluid should be considered. Rabinow [98] reported initial ideas of potential applications of MR fluids, such as dashpots or shock absorbers, energy-absorbing devices, three-dimensional graphs and mould making. In energy dissipating or braking devices as shown in figure 3.4 (a), the MR fluid was used to give a sufficient resistance which can be adjusted by the electric current to control the rotation. Figure 3.4 (b) shows the 3-dimensional graphic application where the position of the pins can be adjusted by the MR fluid. This concept also applies to the adjusting device or pointer device (figure 3.4 (c)). Other than that, the widest applications are in the damper area such as dashpots or shock absorbers (figure 3.4 (d)). A piston in this device moves through the fluid in the housing cylinder where there is enough space between the piston and the wall of the cylinder for the passage of the fluid.



Figure 3.4: Diagrams of application ideas. (a) Energy dissipating or braking device, (b)3-dimensional graphic device, (c) adjusting device or pointer device and (d) dashpot or shock absorber [98].

MR fluid as a moulding medium as depicted from figure 3.5 is another highlyapplicable idea by Rabinow [98]. For example, a screw can be reproduced by inserting it into the MR fluid. A magnetic field is then used to produce a sufficient intensity passed through the MR fluid hence the viscosity of the fluid can be controlled. After the MR fluid is considered to have solidified, the screw is unscrewed from the MR fluid, leaving a cavity. A suitable material such as molten wax or plaster of Paris, is then poured into the cavity. Following solidification of that material, another replica is produced by either bringing the MR fluid back to its normal viscosity under zero magnetic field or unscrewing the replica. This concept also suitable for other methods of casting for example the lost wax method or to cast complicated shapes by using split moulds. However, this idea is not suitable for casting a magnetic material since the magnetic field creates an interaction between the MR fluid and the magnetic material. As a result, the magnetic material is difficult to remove in the presence of magnetic field.



**Figure 3.5:** MR fluid used to make a mould, (a) screw was inserted into the mould, (b) moulds after the screw was unscrewed and (c) cavity was filled by molten material [98].

#### 3.4.1 Valve mode

Valve mode, shown schematically in figure 3.6, is one of the operating modes in the MR devices where the flow of the MR fluid between motionless plates or an orifice is created by a pressure drop. The magnetic field, which is applied perpendicular to the direction of the flow, is used to change the viscosity of the MR fluid in order to control the flow. Therefore, the increase in yield stress or viscosity alters the velocity profile of the fluid in the gap between two plates. A typical velocity profile for Bingham-plastic of the valve mode is illustrated in figure 3.7. The velocity profile contains a pre-yield region, where the velocity gradient is zero across the plug region.



Figure 3.6: Basic concept of valve mode.



Figure 3.7: Velocity profile of the fluid flow in valve mode.

The value of the pressure drop  $\Delta P$  (Pa) can be represented by the following relation [7]

$$\Delta P = \frac{F}{A_p} = \frac{12\eta L_a A_p v_p}{bd^3 \left(1 - \overline{\delta}\right)^2 \left(1 + \frac{\overline{\delta}}{2}\right)}$$
(3-18)

where *F* is the applied force (N),  $A_p$  is the effective area of the flow channel (m<sup>2</sup>),  $\eta$  is the differential post yield viscosity (Pa.s),  $L_a$  is the active length of the flow channel (m),  $v_p$  is the cylinder head velocity (ms<sup>-1</sup>), *b* is the mid annulus circumference of the MR

valve (m), d is the gap distance (m), and  $\overline{\delta}$  is the nondimensional plug thickness, equivalent to  $\delta/d$ . Parameters d and  $\delta$  are shown in figure 3.7. If the value of  $\overline{\delta}$  is equal to zero, the flow can be considered as a Newtonian flow.

High stress can be achieved by the optimization of the valve design with maximum magnetic field strength. Yoo and Wereley [7] achieved a maximum magnetic flux density at the gap with an optimized design based on a constraint on the outer diameter limitation. They showed the importance of the material selection for the magnetic circuit to generate a magnetic field. In another study, Rosenfeld and Wereley [127] optimized a magnetic valve design within a constrained cylindrical volume. A comparison between MR and ER valves that were almost qualitatively identical in their development or production of a field-controllable yield stress and valve design has been carried out. Those optimized MR valves provided a greater range of controllable damping which makes MR technology more attractive for volume constrained conditions. Furthermore, Kulkarni et al. [16] have found that the pressure drop values in a linear damper with valve mode are higher than the stress values obtained for the squeeze film damper. However, the differences are mainly due to the damper design characteristics and partly are due to the MR fluid characteristics [16]. A proper comparison can be achieved if the authors used the same type and volume of the MR fluid.

A high resistance produced by the valve mode can be used in many applications such as dampers, valves and actuators [43, 127-129]. Even though magnetic valves controlling the flow of magnetic fluids have been invented at an earlier time [97, 99], different forms of valve mode, such as MR dampers, could be applied in knee prosthesis, vibration dampers, active engine mounts, propshaft mounts and seismic dampers for civil industry [130]. The applications of MR fluids bring additional functionality whilst keeping the design simplicity. For example, figure 3.8 shows a seismic damper in a simple design in which the outer cylindrical housing constitutes a part of the magnetic circuit. MR fluid is forced to flow through the annular space by movement of the piston. The effective fluid orifice is the entire annular space between the piston outside diameter and the inside of the damper cylinder housing. An electromagnetic coil is wound on the piston to produce a magnetic field to act on the fluid.



Figure 3.8: Schematic of an MR fluid seismic damper [2].

#### 3.4.2 Shear mode

The second working mode for controllable fluid devices is the direct shear mode. An MR fluid is situated between two surfaces, whereby only one surface slides or rotates in relation to the other, with a magnetic field applied perpendicularly to the direction of motion of these shear surfaces. Shear mode as shown in figure 3.9, is useful due to the characteristics of the shear stress versus shear rate which can be controlled by the magnetic field strength. In order to optimize the magnetic field generated by a coil, Sasssi et al. [131] developed a new approach in the coils arrangement and showed that the damping coefficient could be increased by up to three times in the MR damper. When the magnetic field is applied, the behaviour of the MR fluid is often represented by a Bingham plastic fluid of equation (3-15) to describe the constitutive relation of the fluid and the device.



Figure 3.9: Basic concept of shear mode.

The direct shear mode has been studied thoroughly especially in the MR damper technology. Masri et al. [132] proposed a curve fitting technique for representing the nonlinear restoring force of an ER device in order to characterize the ER material behaviour under static and dynamic loading over a wide range of electric fields. Spencer et al. [133] developed a phenomenological model which is based on the improved Bouc-Wen hysteresis model to represent MR dampers. Moreover, Dominguez et al. [134] integrated the current excitation as a variable to gain a better characterization of the hysteresis phenomenon. However, this model is over parameterized and is difficult in comparing different identification techniques for the same device due to non-uniqueness in the determination of the model parameters. Therefore, Ikhouane and Dyke [135] suggested a friction Dahl model for a frictional device whose friction parameters change with the voltage to characterize the dynamics of an MR damper. In terms of the behaviour of the damper under conditions of high-velocity and high field input, Lee et al. [136] recommended the Herschel-Bulkley shear model to analyze the performance of impact damper systems.

In an actuator system, An and Kwon [137] used a modified nonlinear model, which considered a magnetic hysteresis of ferromagnetic material (Hodgdon model) and a nonlinear Bingham model to obtain a torque estimator. The authors managed to estimate the undesirable hysteretic nonlinearity to produce the optimum design of the actuator. Furthermore, Neelakantan et al. [138] incorporated a volume fraction profile of
particles with an analytical technique for calculating the torque transmitted in clutches experiencing particle centrifuging. The effect of centrifuging at high rotational speeds and the subsequent sealing problems associated with it can be mitigated by the proposed model. In connection with a brake system, Huang et al. [6] utilized Bingham model as a basis to analyze the torque transferred by the MR fluid within the brake.

Extraordinary features of the direct shear mode like simplicity, fast response, simple interface between electrical power input and mechanical power output using magnetic fields, and controllability are features that make MR fluid technology suitable for many applications such as dampers, brakes, clutches and polishing devices [6, 138-140]. For instance, figure 3.10 shows a cylindrical MR fluid clutch where the input shaft is linked to the outer cylinder and the output shaft is linked to a rotary piston [138]. The MR fluid is restrained in a small ring-shaped gap between the outer cylinder and the rotary piston. The coil is resided in the piston to generate a magnetic field. As a result, the torque transmitted across the clutch will increase and can be adjusted by controlling the strength of magnetic field.



Figure 3.10: Schematic of a cylindrical MR clutch [138].

#### 3.4.3 Squeeze mode

The third working mode of MR fluids is the squeeze mode. This mode has not been widely investigated. Squeeze mode operates when a force is applied to the plates in the same direction of a magnetic field to reduce or expand the distance between the parallel plates causing a squeeze flow. In squeeze mode, the MR fluid is subjected to dynamic (alternate between tension and compression) or static (individual tension or compression) loadings. As the magnetic field charges the particles, the particle chains formed between the walls become rigid with rapid changes in viscosity. The displacements engaged in squeeze mode are relatively very small (few millimetres) but require large forces.

The squeeze mode was disclosed by Stanway et al. [141] in 1992. They studied the usage of ER fluids in squeeze mode and found that the yield stress produced under DC excitation could be several times greater than the shear mode. The same outcome was later confirmed by Monkman [10] for fluids under compressive stress. Consequently, systematic investigations have been carried out by many researchers to evaluate the mechanical and electrical properties of ER fluids in squeeze flow. Despite the fact that the Bingham plastic model was used to describe the behaviour of ER fluid in shear mode, Nilsson and Ohlson [15] have not recommended to utilize that model in squeeze mode. Bingham parameters tested from shear mode are not well-founded for the calculation of the squeeze mode behaviour. Sproston et al. [142] characterized the performance of ER fluids in dynamic squeeze mode using a bi-viscous model under a constant potential difference or by a constant field. Later on, Sproston and El Wahed [143] utilized the model to assess the fluid's response to a step-change in the applied field and the influence of the size of solid phase. Even though the model was useful to predict the peak values of the input and transmitted forces [144], a more refined model is needed, according to authors, to predict the detailed temporal variations. Therefore, a new approach of modified bi-viscous model was developed by El Wahed et al. in order to model the behaviour of an ER squeeze mode cell under dynamic conditions [145, 146]. Furthermore, Yang and Zhu [147] extended this latter model by incorporating Navier slip condition to obtain the radial velocity, pressure gradient, pressure and squeeze force.

The behaviour of MR fluids in squeeze mode under oscillatory conditions was investigated by Vieira et al. [24]. They found that the damping performance of an MR damper can be obtained by increasing the magnetic field strength or the displacement amplitude. Changing the frequency of the system also contributed to various behaviours of MR fluids. Forte et al. [19] optimized the design of a MR damper for rotor applications and showed that the damping characteristics of rotor vibrations can be controlled by varying the current in the magnetic coils. Later on, they improved both the design and the model through a more practical design process [21]. Moreover, Wang et al. [22] investigated and subsequently analyzed the mechanical properties of squeeze film and the unbalanced response characteristics of a MR fluid squeeze film damper. The squeeze mode of a MR damper has significant advantages such as simple structure, clear effectiveness and quick response [23]. In another study done on a flexible rotor system, the whirling amplitude was reduced by monitoring the rotating speed [20].

The stress produced by the squeeze mode is the highest stress amongst other modes and can be used in damping vibrations with low amplitudes and high dynamic forces [22, 32]. In vibration isolation of structural system, the unwanted vibration in a relatively high frequency range can be attenuated by activating the ER mount [148]. Examples for vibration control are isolation engine mount [149], turbomachinery [150] and squeeze film damper [151]. Another interesting application on the squeeze mode is related to haptic devices where the user can feel the resistance forces by touching and moving a tool. Figure 3.11 [152] shows a prototype of Haptic Black Box II (HBB-II), that contains a number of pistons (act as fast actuators), in which works with a MR fluid. The prototype is designated as a box where the operator can insert his/her bare hand into a latex glove, and interacts with a virtual object by freely moving the hand without mechanical constraints. The pistons can be individually raised and lowered against the finger tip in order to approximate the virtual object. The force, then, will convey information about the shape and surface texture of an object. In this way, sensory receptors on the whole operator's hand would be excited, rather than restricting to just one or few fingertips or phalanges.



Figure 3.11: Schematic of an MR haptic device [152].

## a. Compression

Compression is one of the mechanisms in the squeeze mode as shown in figure 3.12. The geometric arrangement for compression is accomplished by two flat parallel solid surfaces facing each other. The two surfaces are pushed towards each other by an external force, operating at right angles to both surfaces. The liquid in the gap between them is initially free to move away from this increasingly small gap, by flowing parallel to the surfaces, and collecting in a region beyond the gap. Under the presence of a magnetic field, a magnetic dipole moment of the micron-sized particles is induced, so that dipole interactions occur between the particles. The particles form chains and coordinate according to the flux paths [3]. Consequently, this formation resists and restricts the fluid movement from repositioning out of their respective flux paths.



Figure 3.12: Basic concept of compression in squeeze mode

There are few experimental investigations under compressive loading compared to studies on the other modes of ER fluid. Monkman [10] has performed experimental trials to show the effects of applied compressive force on the depth of a layer of ER fluid. Three types of ER fluid were used in his study; one type was a silicone-based ER fluid and two types of hydrocarbon-based ER fluids. The results showed that, the effects of an external field in any event at a higher field, as the distance between the plates closes the applied stress of the ER fluids increases. A description based on the mechanics of particle chains has been recommended to be responsible for the gap size effect on the compression of ER fluids rather than delineated by the Bingham model and the continuous media theory [14]. The effect of an external field on the compressive stress was also applied to the magnetostrictive polymer composite gels [153]. In another study done by Choi et al. [17] on poly(methylaniline) based ER fluid, confirmed that compressive speed was also one of the factors.

An investigation the properties of ER fluids which dealt with a solid-like material under slow compression and tension was conducted by Tian et al. [8]. Stress-strain relationship of ER fluids based on zeolite and silicone oil was obtained under compressive and tensile loadings. Under the same electric field strength, compressive stress was the highest stress and followed by the tensile and shear stresses. Compression of ER fluids can be described by the mechanics of compressing a continuous fluid at the

presence of an external field. While at higher external field strength, structure strengthening of ER fluids should be taken into account [11]. In order to provide a practical knowledge to design and control ER actuators involving voltage on/off adjustment corresponding to different external conditions, transient behaviour of a compressed ER fluid have been experimentally investigated by Tian et al. [154]. They illustrated that the amplitude of the applied voltage had small effect on the ascending time. However, the compressive speed and compressive strain position have influenced greatly the ascending time of the transient compressive stress. The compressive stress increases quicker at a higher speed and a smaller gap size. Meng and Filisko [155] explored the contribution of the electrode sizes to the compression of ER fluids. Their results showed that for the same field intensity, the bigger diameter of electrode size originated in a greater mean pressure than the smaller diameter of electrode size. They also showed that the continuum non-Newtonian squeeze-flow theory was only capable of describing the behaviour at the very beginning stage of compression. See et al. [156] discovered that the compressive modulus of a MR fluid (ratio of compressive stress to compressive strain) had no significant difference at 0.05 of strain value in comparison between one-step and slow compressions.

In terms of theoretical works, Lukkarinen and Kaski [9] studied the mechanical properties of ER suspensions with consideration given to the microscopic behaviour using computer simulations. They used an electrostatic point-dipole model to compare the behaviour of ER fluids under compression and shear strains. The authors found that the difference in maximum forces between sheared and compressed systems are about tenfold. Furthermore, the maximum force on the moving plate to be strongly compression-rate dependent. In another study done by Lukkarinen and Kaski [157], the model was embodied with or without multipolar corrections and the interaction with the base fluid due to viscous laminar flow which is described by the Stokes drag. Compressive stress was observed to be the highest stress among other stresses (tensile and shear), and the ratio of maximum stresses between shear and compressive loadings was quite large and increased with the loading rate. The effect of multipolar corrections was significant on the maximum forces of the grown structures (a single chain or a column of Body Centred Tetragonal (BCT) structure) under tension loading.

#### b. Tension

Another mechanism in the squeeze mode is tension as shown in figure 3.13. Tension in a squeeze mode is as an operational mode where two flat parallel surfaces, standing opposite to each other, are pulled apart from each other by an external force, acting along the path of the magnetic flux lines. Yield stress produced by tension mode is greater by three to four times than shear yield stress, but lower than compressive stress under the same magnetic field strength [8]. In simulation studies done by Lukkarinen and Kaski [157], different types of particle configurations under tension, compression and shear loading were studied. For a single chain and a column of BCT unit cells, they observed that both structures under tension loading appeared stronger than those under shear loading. However, in contrast, thick structure of BCT under tension loading seemed to be weaker than under shear loading. This is probably because of the odd behaviour of the structure during tension, where at the beginning of straining, the forces were obviously negative and the system was very week.



Figure 3.13: Basic concept of tension in squeeze mode

A tensile behaviour study under DC current electric fields has been carried out by Tian et al. [13]. They reported that the tensile behaviour can be divided into five categories depending on the pattern of the stress-strain curves. Different tension types were described by the structural strengthening and the competition between particle chains and the electrodes, and the interaction of particle chain strength. Tian and Zou [12] proposed a normalized method for comparing tensile behaviour of ER fluids. Both tensile stress and electric field were normalized in order to achieve the approximated tensile behaviour of the ER fluids under different conditions. Then, these results were compared with each other to address the electric field effect and the particle structure effect on the tension loading. Under high voltages, the structure effect has been found to be stronger than that under low voltages.

# **3.4.4** Combination of modes

Some of the applications of field responsive fluids take advantage of the combination of two modes for a greater strength and functionality. For instance, dampers can be constructed in three different modes as shown in figure 3.14 [158]. In a general manner, shear mode exhibits Couette flow through the annular bypass, while a valve flow is characterized by Poiseiulle flow through the annular bypass. The combination of them often gives higher yield stress as compared to stress produced by individual operation modes. Kamath et al. [159] have shown in their analysis and testing of Bingham plastic behaviour that mixed (valve and shear) mode dashpot dampers have higher passive damping than flow mode dampers. The mixed mode damper has a secondary effect of viscous drag as a result of the motion of piston head, instead of relying on the pressure gradient developed by the piston head to push the fluid through the gap created by the fixed electrodes. Wereley and Pang [158] have developed nonlinear quasi-steady ER and MR damper models using idealized Bingham plastic shear flow mechanism to characterize the equivalent viscous damping constant of the dampers. Plug thickness is the strongest variable that contributed to the damper behaviour for both flow and mixed modes.



(c)

**Figure 3.14:** Schematic of dampers in three different modes. (a) Shear mode, (b) valve mode and (c) mixed mode which combines the valve and shear modes of operation

[158].

In another experimental study done by Kulkarni et al. [16], the performance of the combination of squeeze and shear modes of MR fluids in dynamic loading was investigated. Even though squeeze mode can produce the highest strength among all modes, the addition of squeeze mode to shear mode did not always give a better strength than the shear mode alone. However, Tang et al. [160] demonstrated that the yield shear stress can be significantly improved by compressing the MR fluid along the magnetic field direction before the shear process is performed. With regards to this result, Tao [161] concluded that the weak points of the MR microstructure under a shear force occurred at the chains' ends. Therefore, a compression-aggregation process can enhance the robust thick columns with strong ends. He also verified this thought with scanning electronic micrographic images for a structure change. Zhang et al. [162] studied the mechanism of the squeeze-strengthen effect in MR fluids. They proposed a semiempirical model by considering the local field theory and the friction between magnetizable particles. In order to achieve the true yield stress of MR fluids, they suggested a ferromagnetic material to be used as a test piece rather than a non-ferromagnetic material. This is because of the existence of the wall effect between the test piece and fluid.

#### 3.5 Summary of chapter 3

A brief and comprehensive overview of the main points of a body of the research process is shown in figure 3.15. Chapter 2 addressed the question of how MR fluids behave under individual static loadings in squeeze mode. Instead of MR fluids, experimental investigations on ER fluids under compression or tension loading are quite thorough and systematic. Even though ER fluids can be considered as MR fluids analogue, some of the researchers found that the behaviour of both fluids is not always the same. Furthermore these types of field responsive fluids are difficult to compare directly because of their reaction to different stimulus. The achievement of producing high stress in squeeze mode attracted extensive interest and makes it worthy of investigation. Therefore, a thorough study on the stress-strain relationship of MR fluids in compression and tension need to be scrutinized. In order to perform experimental trials on MR fluids under squeeze mode, design of the test rig will be based on the previous work which were carried out on the ER fluids as will be presented in chapter 3. A simulation software package will be used to predict the magnetic field through the gap in between the two cylinders of the test rig as also will be demonstrated in chapter 3.



Figure 3.15: Summary of the research process in chapter 3.

# CHAPTER 4

# EXPERIMENTAL PROCEDURES

## 4.0 Introduction

Better understanding of MR fluid characteristics is important for focussing such engineering issues as optimizing apparatus geometry and magnetic field distribution, and developing predictive capabilities for design and control strategies. In this chapter, a method to investigate the behaviour of MR fluid in several carrier liquids in order to optimize the function of the fluid in squeeze mode was carried out. Detailed description of a magnetic circuit design and a test rig were presented. Simulation results in connection with magnetic field strength which was done by Finite Element Method Magnetics (FEMM) software package were also described. Finally, procedures of the experimental set-up were described according to each testing, and overall processes were summarized at the end of this chapter.

#### 4.1 MR fluid materials

In this study, three different types of commercially available MR fluids produced by Lord Corporation were chosen to characterize the compressive/tensile stress under various conditions. These materials were namely MRF-241ES, MRF-132DG and MRF-122-2ED, and they were selected in order to produce consistency in the results. MRF-241ES was a water-based MR fluid, which was developed for general use in sealed systems of controllable, energy-dissipating applications such as shocks, dampers and brakes. MRF-132DG and MRF-122-2ED were hydrocarbon-based MR fluids, which were formulated for general use in controllable, energy-dissipating applications such as shocks, dampers and brakes. The MR fluids have a lot of advantages such as fast response time, high yield stress, low off-state viscosity, high resistance to hard settling, easy remixing and were non abrasive [47]. Fast response time was regarded to instant and reversible responds to changes in a magnetic field. Dynamic yield strength allows for a wide range of controllability, where high yield strength could be achieved in the presence of a magnetic field and very low yield strength could be produced in the absence of a magnetic field. In order to fulfil the requirements of demanding applications such as automotive shock absorbers, temperature resistance performs

59

consistently throughout a broad temperature range. Non-abrasive components were formulated and used to not abrade the apparatus in which the MR fluid was used.

The selection of the carrier liquid determines the temperature ranges in which the MR fluid could be utilized. Even though silicone oil was the most frequently used as a carrier liquid, hydrocarbon oil has some advantages due to its low viscosity, better lubrication properties and suitability for high shear-rate applications. Moreover, a hydrocarbon oil-based MR fluid has lower zero field viscosity, which was about 0.6 times less than the silicone oil-based MR fluid [72]. On the other hand, a water-based MR fluid could minimize waste disposal problems and allows the particles to be easily recycled from the material [163].

#### 4.1.1 Physical properties of tested MR fluids

Typical physical properties of MR fluid materials that are used in this study are listed in table 4.1 [47]. MR fluids have a high tolerance of common impurities or less sensitive to contaminants such as water. They were stable over a broad temperature range; -10°C to 70°C for water-based MR fluids and -40°C to 150°C for hydrocarbon-based MR fluids, but limited by the volatility properties of the carrier fluid rather than the details of the polarization mechanism. The fluids also have the advantages of using low voltage power supplies in the range of 2 to 25 V, with current range between 1 to 2 Amps and power ratings between 2-50 watts [39].

The density range of the soft magnetic particles dispersed in the carrier liquid was between 2.32 - 3.92 g/cm<sup>3</sup>. This property gives a great restriction in terms of the agglomeration and sedimentation because of the higher density of particles compared to the carrier liquids. In a previous study, instead of carbonyl iron, Pu and Jiang [164] used other materials such as Carbon NanoTube (CNT)/Fe<sub>3</sub>O<sub>4</sub> nanocomposites to reduce the density to about 1.8 g/cm<sup>3</sup> and exhibit high sedimentation stability. Furthermore, using surface chemistry by addition of surfactants and additives, MR fluids were also stable against particle-liquid separation [165]. This was because the magnetic polarization mechanism was slightly or considerably not affected by those coated layers and

additives. According to Kormann et al. [166] in their patent, the coated particles with polyelectrolyte had viscosity of less than 10 Pa.s at shear rates of  $10 \text{ s}^{-1}$  and gave MR effects at 10 kPa in an environment of magnetic field of 100 kA/m. On account of volume fraction, most of the MR fluids contain 20 - 40% by volume, or about 80% by weight of comparatively pure and soft iron particles such as carbonyl iron [39].

Property	Values / limits					
Codes of MR fluids	MRF-241ES		MRF-132DG		MRF-122-2ED	
Base Fluid	Water		Hydrocarbon		Hydrocarbon	
Operating Temperature	-10°C to 70°C		-40°C to 130°C		-40°C to 130°C	
Density Range	$3.80 \text{ to } 3.92 \text{ g/cm}^3$		2.98 to 3.18 g/cm <sup>3</sup>		2.32 to 2.44 g/cm <sup>3</sup>	
Colour	Dark Gray		Dark Gray		Dark Gray	
Solids Percentage Weight	85%		80.98%		72%	
	°C	Unit volume per °C	°C	Unit volume per °C	°C	Unit volume per °C
Coefficient of			0 to 50	0.55 x 10 <sup>-3</sup>	0 to 50	0.65 x 10 <sup>-3</sup>
Thermal Expansion	0 to 70	0.223 x 10 <sup>-3</sup>	50 to 100	0.66 x 10 <sup>-3</sup>	50 to 100	0.71 x 10 <sup>-3</sup>
			100 to 150	0.67 x 10 <sup>-3</sup>	100 to 150	0.79 x 10 <sup>-3</sup>
Specific Heat @ 25°C	0.94J/g°C		0.79 J/g°C		0.94 J/g°C	
Thermal Conductivity @ 25°C	0.85 – 3.77 W/m°C		0.25 – 1.06 W/m°C		0.21 – 0.81 W/m°C	
Flash Point	> 93°C		>150°C		> 150°C	

**Table 4.1:** Physical properties of tested MR fluids.

In terms of the MR fluids supplied by Lord Corporation, settling was not significant as the fluids have the capability to remix in the apparatus/device. This property was called redispersability and it depended on the geometry of the apparatus and fluid properties. For example, a number of tests were conducted and results have shown that MR fluids in the device will return to their original condition even after one year of settling with as little as one stroke [47]. Therefore, any apparatus could be designed to have essentially no settling, which was demanded by applications where the apparatus was not active for a long period of time, such as in seismic damage mitigation or automotive crash energy absorption. In any event, a small amount of settling was typically an acceptable trade-off for other desirable properties.

# 4.1.2 Magnetic properties of tested MR fluids

Figure 4.1 shows the magnetic induction curves or *B-H* curves, of three commercial MR fluid materials. MR fluids exhibit approximately linear magnetic properties up to 200 kA/m of applied field intensity. The magnetic flux density of MRF-241ES demonstrates greater values over those of the other MR fluids. The magnetic properties of MR fluids vary significantly due to a higher particle density in MRF-241ES (3.80 to 3.92 g/cm<sup>3</sup>) than MRF-132DG (2.98 to 3.18 g/cm<sup>3</sup>) and MRF-122-2ED (2.32 to 2.44 g/cm<sup>3</sup>). According to Jolly et al. [95], the intrinsic induction or polarization density of an MR fluid at complete saturation was equal to  $\phi \times J_s$  Tesla, where  $\phi$  is the volume percent of particles in the fluid (unitless) and  $J_s$  is the saturation polarization of the particles' material (Tesla). For instance, an MR fluid containing 35% iron and  $J_s$  equal 2.1 Tesla, was expected to saturate at about  $0.35 \times 2.1 = 0.735$  Tesla.



Magnetic field intensity (kA/m)

Figure 4.1: Typical magnetic properties of tested MR fluids [47].

## 4.1.3 Remixing method

All the MR fluids have to remix prior to filling to ensure a homogeneous fluid was placed into the test rig. MR fluids produced by Lord Corporation were formulated for minimal settling and easy redispersion when operating in an apparatus. Studies have shown once inside a properly designed device, MR fluids will typically be fully mixed after the first cycle [47]. Generally, MR fluids were optimized for low fluid viscosity in the non-magnetic state, which might result in the formation of a clear layer between the iron particles and the carrier fluid in the as-shipped state.

In this work, MR fluids were remixed by using a electronic overhead stirrer model EUROSTAR digital supplied by IKA<sup>®</sup>Werke GmbH & Co. KG together with 4bladed propeller stirrer made from stainless steel (non-magnetic materials) [167], shown in figure 4.2. The propeller of choice was a low-shear, axial-flow impeller in order to minimally shear the fluid. MR fluids were mixed at approximately 350 rpm until they were uniform throughout the containers. No separation was observed between particles and the carrier fluid under common flow conditions. A degree of separation may eventually have occurred under static conditions, but low-shear agitation (shaking or remixing) prior to use would easily redisperse the particles into a homogeneous state.



Figure 4.2: Overhead rotary mixer used to mix MR fluids in this work.

# 4.2 Experimental design

The basic concept of the test rig was to perform compression and tension tests on the MR fluids placed between two parallel cylinders (upper and lower cylinders). The best values of the magnetic field strength generated by the test rig, design and materials selection were carried out by FEMM [168]. A selection range of the coil size/design within the test rig was obtained based on the given dimensions of the lower cylinder. The same FEMM software package helped finalizing the coil selection in order to produce the best range of magnetic field strength.

## 4.2.1 Simulation of the magnetic circuit

The main objective of the magnetic circuit was to produce the correct magnetic flux density across the MR fluid. From the electromagnetic point of view, the test rig could be treated as a circuit concentrating the magnetic field generated by a coil and guiding it from the core to and across the fluid. FEMM simulation software package was used to analyze and optimize the design of the magnetic circuit.

An axisymmetric model was employed in the FEMM software package for the magnetostatic problems in 2-Dimensional spaces [168]. The magnetostatic problems are problems in which the fields are time-invariant. In this case, the magnetic field intensity H must comply with

$$J = \nabla \times H \tag{4-1}$$

where  $\nabla$  is the divergence operator (1/m) and *J* is the current density (Amps/m<sup>2</sup>). In another case, according to Gauss's law for magnetism, in the absence of magnetic monopoles, the magnetic flux density *B* must comply with

$$0 = \nabla \cdot B \tag{4-2}$$

where *B* is the magnetic flux density (Tesla).

Equations 4-1 and 4-2 are subject to a constitutive relationship between magnetic flux density B and magnetic field intensity H for each material; same as in equation (2-10):

$$B = \mu H$$

If a material is nonlinear, for instance saturating iron or alnico magnets, the permeability  $\mu$  is actually a function of magnetic flux density *B*,

$$\mu = \frac{B}{H(B)} \tag{4-3}$$

After nonlinear materials have reached the saturation points, the values of magnetic flux density will remain the same as magnetic field intensity increases.

FEMM goes about finding a field that satisfies equations (4-1), (4-2) and (2-10) via a magnetic vector potential approach [168]. The magnetic flux density is written in terms of the vector potential A (magnetic vector potential) as [169]

$$B = \nabla \times A \tag{4-4}$$

Now, this definition of B always satisfies (4-2). Then, equation (4-1) can be rewritten as:

$$J = \nabla \times \left(\frac{1}{\mu(B)}\right) \nabla \times A \tag{4-5}$$

For a linear isotropic material (and assuming the Coulomb gauge  $\nabla A = 0$ ), equation (4-5) reduces to [169]

$$J = -\frac{1}{\mu} \nabla^2 A \tag{4-6}$$

In practice, FEMM uses equation (4-5) so that magnetostatic problems with a nonlinear *B*-*H* relationship can be solved.

A is a vector with three components in the 3-Dimensional case. However, in 2dimensional planar and axisymmetric cases, only one component was left in one direction while the other two components are zero. There was an advantage in using vector potential formulation because all the conditions can be fulfilled and combined into a single equation. If A is found, B and H can then be calculated by differentiating A.

For boundary conditions in the FEMM software package, a *Robin* boundary condition was selected where this boundary was sort of a mix between *Dirichlet* and *Neumann*, prescribing a relationship between the value of A and its normal derivative at the boundary [168]. A *Dirichlet* boundary condition was applicable if the value of vector potential A was explicitly defined on the boundary, for example A = 0 along a boundary to keep the magnetic flux from crossing the boundary, while a *Neumann* boundary condition specified the normal derivative of potential along the boundary. The homogeneous *Neumann* boundary condition  $\partial A/\partial n = 0$  was defined along a boundary to force the flux to pass the boundary condition at exactly 90° angle to the boundary and applicable for a very high permeability metal. Therefore, by using the *Robin* boundary

condition, the magnetic field produced by the coil could be modelled in an unbounded space while still only modelling a finite region of that space. For an asymptotic boundary condition, the coefficients in a boundary condition can be represented by

$$\frac{1}{\mu_r \mu_0} \frac{\partial A}{\partial n} + C_0 A + C_1 = 0 \tag{4-7}$$

where  $\mu_r$  is the relative magnetic permeability of the region adjacent to the boundary,  $\mu_0$  is the permeability of free space and *n* represents the direction normal to the boundary.

Coefficients  $C_0$  and  $C_1$  are specified by

$$C_0 = \frac{1}{\mu_r \mu_0 R}$$
(4-8)

$$C_1 = 0 \tag{4-9}$$

where *R* is the outer radius of a sphere problem domain.

#### 4.2.2 Design of test rig

A design concept of the experimental set-up similar to that used for studying ER fluid by Tian et al. [14] was utilized in this study. In order to execute experimental trials on the MR fluids, the external field had to be changed from an electric field to a magnetic field. Therefore, a new test rig needed to be designed to accommodate these differences. Basically, the test rig consisted of two parts; upper and lower cylinders. A measured amount of the MR fluid was sandwiched in between the two cylinders, so that the upper cylinder could move towards or pulls against the lower cylinder, and simultaneously compressed or decompressed the MR fluid. An axial-symmetrical model was selected in the FEMM software package. A sketch of the initial design concept with coordinates is shown in figure 4.3.



Figure 4.3: Middle half of the test rig of the initial design concept.

At the beginning of the design, the test rig consisted of six parts where part A was the upper cylinder, part B was the lower cylinder, part C was the coil, part D was the support cylinder, part E was the plate and part F was the lower ring. Part A, B, E and F were made from magnetic materials, while parts D and C were made from non-magnetic materials and copper wire, respectively. The inner diameter of the support cylinder (part D) used to contain the MR fluid was a little larger than the outer diameter of the upper cylinder (part A), so that the gap region remained flooded by the MR fluid throughout the compression, which was applicable to perform the tension test. A number of design changes were simulated in the FEMM software package and are listed in table 4.2. An analysis and optimization of the magnetic behaviour of similar devices was

carried out using FEMM [170-172]. This software package was related to the type of materials for each component of the test rig, type of coil, number of turns of the coils wrapping around the core and values of the electric current that runs in the coils. These parameters were important to produce the best value for the magnetic field intensity H, which was correlated with the magnetic flux density B.

In these changes, the number of turns of the coil, the initial gap size and the current value supplied to the coil were kept constant. The average values of magnetic flux density were taken at the middle between the two cylinders, which was indicated by red centred line in figure 4.3 and table 4.2.

Design change	Sketch of test rig	Magnetic flux density (Tesla) versus length taken from middle half of the test rig
<ul> <li><u>Number 1</u></li> <li>First idea of the test rig.</li> <li>Average value of magnetic flux density is about 0.063 Tesla.</li> </ul>		0.07 0.06 0.04 0.04 0.01 0.01 0.01 0.01 0.01 0.01
<ul> <li>Number 2</li> <li>From design number 1.</li> <li>Change material of the lower ring from magnetic (steel) to non-magnetic (stainless steel) materials.</li> <li>Average value of magnetic flux density is about 0.053 Tesla.</li> <li>Smaller value than design number 1.</li> </ul>		0.05 0.07 0.07 0.07 0.07 0.07 0.07 0.07

Table 4.2: List of changes in the design concept.





Based on simulation results, the test rig (design number 7) was expected to produce the highest values of the magnetic flux density. Magnetic materials were useful to make upper cylinder (part A), lower cylinder (part B), plate (part E) and lower ring (part F), while non-magnetic materials were preferred to make support cylinder (part D). The introduction of non-magnetic material as a plate produced uneven distribution of the magnetic flux density. This condition also applied to the support cylinder. However, if magnetic materials were used as a support cylinder, the tested MR fluids would stick to the surface of support cylinder, which were not return back to its original place during and after the experiments. Therefore, it was better to make the support cylinder with two different materials; magnetic material at bottom area of the plate and non-magnetic material at the other parts as shown in figure 4.4.



Figure 4.4: Sketch of a new configuration of material of support cylinder.

#### 4.2.3 Selection of coil dimension and material

The following parameters were used for the geometry of the coil; the dimensions of inner diameter, outer diameter and width of the coil were equal to 60, 92 and 100 mm, respectively. These dimensions were selected based on the various values of magnetic flux density could be achieved by varying the applied current, and furthermore, ease of manufacture and assembly. These parameters were limited the area in which the copper wire can be wound. Current density was limited to 4 Amm<sup>-2</sup> in connection with the appropriate wire diameter [131]. Therefore, the maximum current density is given by

$$J = \frac{I_m}{A_w} \tag{4-10}$$

where J is the current density (Amps/mm<sup>2</sup>),  $I_m$  is the maximum current supplied to the coil (Amps) and  $A_w$  is the surface area of the uncoated wire (mm<sup>2</sup>). For instance, 24SWG copper wires has a diameter of 0.56 mm, thus, the maximum current value allowed in this wire was 1.0 Amps. Furthermore, the wire can be wound around the specified core's dimensions with 160 turns in each layer of the width of coil, 25 layers between inner and outer diameters of the coil, and gave the total number of turns of 4000 turns. Other outcomes using various types of wires are shown in table 4.3.

Wire gauge	Diameter (mm)	Diameter of coated wire (mm)	No. of turns (each layer)	No. of layer	No. of turns	Max. Current (Amps)
18SWG	1.22	1.28	77	12	924	4.7
20SWG	0.91	0.98	102	16	1632	2.6
22SWG	0.71	0.78	128	20	2560	1.6
24SWG	0.56	0.62	160	25	4000	1.0
26SWG	0.46	0.52	191	30	5730	0.7
28SWG	0.38	0.44	226	36	8136	0.4
30SWG	0.31	0.38	263	42	11046	0.3

**Table 4.3:** Numbers of turns of the coil and maximum values of the applied current.

Figure 4.5 shows the range of some parameters to be compromised in order to achieve the desired results.



**Figure 4.5:** Number of coil's turns and current as functions of wire gauge. Curve A is a function of number of turns and wire gauge and curve B is a function of current and wire gauge.

In this study, copper wire type 22SWG was chosen to be wound around the lower cylinder. The specifications of this copper wire [173] are shown in table 4.4. 22SWG copper wire was coated and insulated with polyurethane. It was used normally as a fuse wire for a current limit of 28 Amps [174]. The selected wire was also utilized by Bakir [175] to make a solenoid where that wire was easily wound around the core and had a current carrying capability to generate a very high static magnetic field strength.

Table 4.4: Specifications of copper wire used to make the coil [173].

Coil type	Resistivity	Diameter	Diameter including	Temperature
	(nΩm)	(mm)	insulating layer (mm)	index
22SWG	16.8	0.71	0.776	200 °C

#### 4.2.4 Fabrication of the test rig

After the most adequate design of the test rig was predicted by FEMM (section 4.2.2), the next step was to implement and design the test rig using Pro-Engineer<sup>®</sup> version 2001. Some modifications have been made to the original concept of the test rig because of the manufacturing processes and material limitations. The test rig assembly shown in figure 4.6 was designed to allow different initial gaps before the test can be performed in the compression and tension modes.

In the final design, the test rig consisted of seven parts. The materials of the test rig could be divided into three categories; magnetic materials, non-magnetic materials and a coil. The detail list of each part is shown in table 4.5. Some advantages of this test rig included a small required volume of tested samples, the ability to vary the working gap height, and the simplicity and ease of use. The upper cylinder, lower cylinder, lower ring and lower base were made from magnetic materials, while upper ring and support cylinder were made from non-magnetic material. A length of copper wire type 22SWG having a resistance of 29 ohms was wound around the lower cylinder forming 2750 turns to generate a magnetic field. The support cylinder was attached on the top of the lower cylinder and acted as a container so as to refrain the MR fluid during the testing. An upper cylinder and a lower base made from low carbon steel (type 1020) were available in the institute's workshop and were partly used in this study.



Figure 4.6: Test rig assembly.

Table 4.5: Design details and material for each component of	of the	test rig.
--	--------	-----------

Appendix No.	Part Name	Type of material	Material	Туре
A1	Upper Cylinder	Magnetic	Low Carbon Steel	1020
A2	Lower Cylinder	Magnetic	Low Carbon Steel	1020
A3	Upper Ring	Non-magnetic	Stainless Steel	304
A4	Lower Ring	Magnetic	Low Carbon Steel	1020
A5	Support Cylinder	Non-magnetic	Stainless Steel	304
-	Coil	Non-magnetic	Copper wire	22SWG
-	Lower Base	Magnetic	Low Carbon Steel	1020

A computer numerical control (CNC) lathe machine and a laser cutter were used in order to achieve the desirable dimensions of the parts according to the drawings. All the manufacturing processes were done in the engineering workshop at Dublin City University. For the first step of sub assembly, the upper ring was placed between the bottom of the support cylinder and the top of the lower cylinder. Then the support cylinder was screwed to a threaded part on the top of lower cylinder. After that, the lower ring was attached to the bottom of the lower cylinder. The lower ring and the lower cylinder were then jointed with the lower base using a bolt. These two rings act as a stopper during and after the coil wounding around the lower cylinder. A cross sectional view of the sub assembly drawing for the lower part (without the coil) is shown in figure 4.7.



Figure 4.7: Cross-sectional view and dimensions of the lower part.

# 4.3 Experimental set-up

A schematic diagram of the experimental set-up is shown in figure 4.8. The experimental-set up consisted of five main components, namely the Instron Machine, the test rig, the MR fluids, the power supply and the control computer. The test rig was placed in the testing area of the Instron Universal Electromechanical Testing (UTS) machine (model 4202) [176]. This UTS machine has a load weighting system accuracy at digital readout accessory or analog output for error about  $\pm 1\%$  of reading to 1/50 of load cell capacity, or  $\pm 1$  count of the display. The communication with the machine was achieved via a built-in data acquisition board in the computer. The Instron machine was operated in the vertical direction to obtain displacements and forces under compression and tension modes. A measured amount of the MR fluids was filled in the gap between the upper and the lower cylinders. The current was supplied by the Xantrex<sub>TM</sub> XFR 150v [177], 18 Amps DC power supply with  $\pm 0.01\%$  error of current maximum or  $\pm 1$  count of the display. This power supply needed 1 millisecond for the output voltage to recover within 0.5% of its previous level after a step change in load current of up to 50% of the rated output. The initial gap size and magnetic field strength were adjusted by manually monitoring both load and displacement displayed in the UTS machine, and controlling the value of the current supplied to the electromagnetic coil, respectively. All experiments were carried out in a displacement control mode at a room temperature of 20 °C.



Figure 4.8: Schematic diagram of experimental set-up.

MR fluids were transferred from the original case into the gap using a syringe as shown in figure 4.9 in order to precisely measure the appropriate volume of the fluid to be tested.



Figure 4.9: A syringe used to quantify the amount of MR fluids.

The volume *V* is given by

$$V = \pi \times h \times \left(\frac{\phi}{2}\right)^2 \tag{4-11}$$

where *h* is the height of the gap measured from top of the lower cylinder to the bottom of the upper cylinder and  $\phi$  is the inner diameter of the hollow cylinder. Conversions of the initial gap size or height of the gap to volume is shown in table 4.6.

**Table 4.6:** Conversions of gap height to gap volume.

Initial Gap Size	Volume		
( <b>mm</b> )	(mm <sup>3</sup> )	( <b>ml</b> )	
1.0	2042.8	~ 2	
2.0	4085.6	~ 4	

## 4.3.1 Test procedures

In this study, for each type of MR fluid tested, three types of parameters were prepared to perform the compression and the tension tests. Various parameters including different initial gap sizes (step 1), compressive/tensile speeds (step 2) and applied currents (step 3) were set before performing any tests, shown in figure 4.10. Two types of experiments were performed; namely compression and tension tests. There were four sets of tests; two sets in compression and two sets in tension for each MR fluid. For a complete set of each test, the same sample of the MR fluid was used at a specified initial

gap size with different values of compressive/tensile speeds and applied currents. The compression test was carried out by lowering the upper cylinder towards the lower cylinder, while the tension test was carried out by pulling up the upper cylinder away from the lower cylinder using a computer-controlled movement. The temperature in the gap between the upper and the lower cylinders was measured using a Type K thermocouple [178], which was capable of operating over a very wide temperature range. The maximum temperature obtained on the top of test rig when the current was supplied continuously for 20 minutes was 65 °C with the maximum voltage reached 54 Volts. Therefore, in every set of test, the maximum voltage was set to 54 Volts; where the power supply was withdrawn after running every single test.



Figure 4.10: Procedures of the tests.

Initially, one of the parameters in steps 1 and 2 were set firmly to the required values. For the compression and tension tests, the initial gap sizes between the upper cylinder and the lower cylinder were set to either 1.0 or 2.0 mm. Then, different current values supplied to the coil (0.4, 0.8, 1.2 and 1.6 Amps) and were maintained constant throughout the tests. The compression/tension processes began when the upper cylinder was either lowered or raised at a constant speed, set of various values in step 2 (0.5, 1.0, 1.5 and 2.0 mm/min), and simultaneously loads and displacements were recorded continuously.

#### 4.4 Simulation results

An analysis of the magnetic field between the upper cylinder and the lower cylinder (in the gap or across the MR fluids) was performed using FEMM. The magnetic properties of the non-magnetic materials were assumed to be linear such as stainless steel, copper wire and air. The magnetic properties of the magnetic materials such as low carbon steel and MR fluids were assumed to follow the *B-H* curves given in the software package and provided by the manufacturer, respectively. Simulation results were based on the middle half of the test rig (axial symmetric model), where was indicated by black centred line, while the average values of the magnetic flux density were pointed out by the red centred line as shown in figure 4.11.



**Figure 4.11:** Sketch of the test rig showing the black centred lines in the middle half of the test rig and red centred line between the upper and lower cylinders.

The input parameters for the FEMM software package including circuit properties and boundary property when the applied current to the coil was set to 1.6 Amps and the initial gap size was set to 2.0 mm are shown in figure 4.12.



Figure 4.12: Input parameters in the FEMM software package.

#### 4.4.1 Magnetic field distribution

The magnetic flux density distribution in the test rig and the details regarding the magnetic flux density distribution within the air gap are shown in figures 4.13 (a) and (b). The magnetic flux density distribution within the MR fluids are shown in figures 4.14 (a), (b) and (c), whereas magnetic flux lines across the air gap and MR fluids are shown in figures 4.15 (a), (b), (c) and (d). These figures (4.13, 4.14 and 4.15) show the results when the applied current to the coil was set to 1.6 Amps and the initial gap size was set to 2.0 mm.






(b)

**Figure 4.13:** Simulated magnetic flux density distribution (a) in the test rig and (b) in the area of the gap between the upper and lower cylinders.

Upper Cylinder	7.900e-001 : >8.000e-001 7.800e-001 : 7.900e-001 7.800e-001 : 7.900e-001 7.600e-001 : 7.700e-001 7.500e-001 : 7.700e-001 7.400e-001 : 7.500e-001 7.300e-001 : 7.400e-001 7.300e-001 : 7.300e-001 7.100e-001 : 7.200e-001 7.000e-001 : 7.000e-001
MRF-241ES	6.900e-001 : 7.000e-001 6.800e-001 : 6.900e-001 6.700e-001 : 6.800e-001 6.600e-001 : 6.800e-001 6.600e-001 : 6.700e-001 6.400e-001 : 6.500e-001 6.300e-001 : 6.300e-001 6.200e-001 : 6.300e-001
Lower Cylinder	C.100e-001 : 0.200e-001 <6.000e-001 : 6.100e-001 Density Plot:  B , Tesla

(a)



(b)



(c)

Figure 4.14: Simulated magnetic flux density distribution, (a) in MRF-241ES, (b) in MRF-132DG and (c) in MRF-122-2ED.



**Figure 4.15:** Simulated magnetic flux lines across the (a) air gap, (b) MRF-241ES, (c) MRF-132DG and (d) MRF-122-2ED.

The magnetic flux density distribution in the air gap and MR fluids could be considered to be dispersed evenly. Figure 4.16 (a) shows that the average values of the magnetic flux density at the middle line between the upper and lower cylinders starting from the centre of the test rig to the inner diameter of the support cylinder were 0.47, 0.70, 0.67 and 0.61 Tesla for the air gap, MRF-241ES, MRF-132DG and MRF-122-2ED, respectively. As shown in figure 4.15, the magnetic flux lines seemed to penetrate the air gap and MR fluids and were aligned in straight lines with the direction of the magnetic field. However, after about 24 mm distance from the centre of the test rig, the values of normal magnetic flux density tended to reduce, while the values of tangential magnetic flux density become higher as shown in figures 4.16 (a) and (b). The values of the tangential magnetic flux density contributed to the shear mode during the testing, which was not the interest of this study. However, the tangential values were very small (less than 0.04 Tesla in the negative direction) and could be neglected.



**Figure 4.16:** Simulated magnetic flux density distribution inside the air gap and MR fluids from centre line to the edge between the upper and the lower cylinders. (a) Normal magnetic flux density (B.n) and (b) tangential magnetic flux density (B.t).

The negative values of the tangential magnetic flux density in figure 4.16 (b) represented their magnitudes in the opposite direction, depending on the north–south poles of the system. Detailed description regarding the negative value of the tangential

magnetic flux density could be depicted from figure 4.17. The tangential magnetic flux lines showed various directions (values) from the centre line of the test rig towards the edge, which could be divided into three zones; Zone I – zero value ( $0 \le x \le 23.5$  mm), Zone II – negative value ( $23.5 < x \le 25.0$  mm) and Zone III – positive value ( $25.0 < x \le 25.5$  mm). However, as mentioned earlier, the values of the magnetic flux density could be changed in the opposite direction by changing the direction of the applied current which also changed the dipoles location (north-south dipoles) as shown in figure 4.18.



Figure 4.17: Simulated magnetic flux lines towards the edge of the test rig.



Figure 4.18: Simulated tangential magnetic flux density in the opposite direction.

#### 4.4.2 Effects of applied current and initial gap size

Figures 4.19 (a), (b), (c), (d) and (e) show the values of the average magnetic flux density as the applied current increases at different initial gap sizes starting from 2.0 mm down to 0.4 mm. The magnetic flux density increased with increasing applied current. The average values of the magnetic flux density were taken from centre of the test rig through middle line between the upper and the lower cylinders for figures 4.19, 4.20, 4.21 and 4.22.

MRF-241ES always showed the highest values of magnetic flux density at any initial gap size, followed by MRF-132DG, MRF-122-2ED and air. As the initial gap size decreased, the curves variation became smaller in the air and the MR fluids. The curves tended to slowly close match to each other as the initial gap size was decreased. This indicated a small effect on the magnetic flux density.



**Figure 4.19:** Simulated magnetic flux density versus applied current for initial gap sizes of (a) 2.0, (b) 1.6, (c) 1.2, (d) 0.8 and (e) 0.4 mm.

The effects of applied current on magnetic flux density when increasing the initial gap sizes are depicted in figure 4.20 (a), (b), (c) and (d). As the initial gap size increased, the values of magnetic flux density decreased. When the initial gap size increased, MRF-241ES, in figure 4.20 (b), showed the least variation in magnetic flux density, while the air case, in figure 4.20 (a), showed the largest variation of the magnetic flux density.



**Figure 4.20:** Simulated magnetic flux density versus initial gap size for different values of applied current for (a) Air, (b) MRF-241ES, (c) MRF-231DG and (d) MRF-122-2ED.

Figures 4.21 (a), (b), (c) and (d) show the values of magnetic flux density as the initial gap size increased at different applied currents starting from 1.6 Amps down to 0.4 Amps. The values of magnetic flux density decreased with increasing the initial gap size. Curves of the magnetic flux density versus initial gap size initiated at the same point at zero value of the initial gap size. But the initial magnetic flux density depended on the current supplied to the coil, for example 0.79, 0.61, 0.42 and 0.21 Tesla were initial values due to 1.6, 1.2, 0.8 and 0.4 Amps, respectively before proceeding to decrease as the initial gap size increased.



**Figure 4.21:** Simulated magnetic flux density versus initial gap size for the applied currents of (a) 1.6, (b) 1.2, (c) 0.8 and (d) 0.4 Amps.

The effects of initial gap size on magnetic flux density when increasing the applied currents are shown in figure 4.22 (a), (b), (c) and (d). As the applied current increased, the values of magnetic flux density increased. When increasing the current values in the coil, MRF-241ES in figure 4.22 (b), showed the least variation of the magnetic flux density, while air in the gap in figure 4.22 (a), showed the largest variation of the magnetic flux density.



**Figure 4.22:** Simulated magnetic flux density versus current for different values of the initial gap sizes for (a) Air, (b) MRF-241ES, (c) MRF-231DG and (d) MRF-122-2ED.

The effects of the applied current and initial gap size on the magnetic flux density were interdependent. In general, the values of the magnetic flux density turned

into greater values with increasing the value of applied current or decreasing the initial gap size. However, these values depended on the type of carrier fluid in the MR fluid. MRF-241ES showed the highest values of magnetic flux density as compared to the other MR fluids (MRF-132DG and MRF-122-2ED). The reason behind this was simply, due to the relatively higher values of magnetic properties in MRF-241ES as shown in figure 4.1.

#### 4.5 Validation of simulation result

A hand-held 5000 series gaussmeter (F.W Bell) supplied by Sypris Test and Measurement as shown in figure 4.23, was used to validate the results of the FEMM software package for the air gap in terms of the magnetic field intensity generated by the coil. This meter can measure magnetic field intensity of up to 20 kilogauss with accuracy of  $\pm$  4% of reading or  $\pm$  3 counts (milliTesla), and was equipped with a built-in software package to eliminate the requirement for complex calibration procedures [179].



Figure 4.23: The 5000 series hand-held gaussmeter (F.W Bell).

Figure 4.24 shows the magnitude of the magnetic field strength in Tesla (1 Tesla is equal to 10 kilogauss) versus the applied current of both the measured and the simulated results at an initial gap size of 2.0 mm. The magnetic field strength increased when the applied current increased. The gaussmeter had shown less sensitivity at lower currents as compared to higher currents. However, in general, the values of the magnetic field strength obtained by direct measurement and simulation were in a good agreement.



Figure 4.24: Comparison of magnetic field strength between direct measurement and simulation result.

#### 4.6 Summary of chapter 4

A summary and extensive overview of the research process in chapter 4 is shown in figure 4.25. A test rig was designed and built in order to perform the compression and tension tests. The upper and the lower cylinders were made from magnetic materials while the support cylinder was made from a non-magnetic material. The clearance between the outer diameter of the upper cylinder and inner diameter of the support cylinder was finalized to 0.5 mm, so that the gap could release any excess of MR fluids during the compression tests. A coil made from a copper wire 22 SGW was wound around the lower cylinder in order to produce a magnetic field. The wire which had a diameter 0.771 mm was wound 2750 times to make the coil. Instron Universal Electromechanical Testing Machine was used to squeeze the fluid by self-constructed computer-controlled moving plate along the y-axis, in the same direction with the magnetic field. Three types of MR fluids were used in these experimental trials. MRF-241ES was water-based MR fluid and MRF-132DG and MRF-122-2ED were hydrocarbon-based MR fluids, produced by Lord Corporation. A measured amount of MR fluids was sandwiched between two parallel flat surfaces, so that the fluid could be compressed or uncompressed in a direction normal to these surfaces. The upper cylinder was either pushed towards or pulled away from the lower cylinder. All experimental trials were performed in a displacement control mode at room temperature (20 °C). Results in terms of stress-strain relationships will be presented in the next chapter.



Figure 4.25: Summary of the research process in chapter 4.

### CHAPTER 5

## BEHAVIOUR OF MR FLUIDS

#### 5.0 Introduction

This chapter presents the results in terms of stress-strain relationships that were obtained from the compression and tension experiments. MR fluids are free-flowing media whose flow properties change rapidly and reversibly under the influence of a magnetic field. In this study, MR fluids showed a unique behaviour during the compression and tension tests. Discussion of the behaviour of the MR fluids was based on the relative movement between the particles and carrier fluid. Three MR fluids were investigated in this study. The first was a water-based MR fluid (MRF-241ES), the second and third were hydrocarbon-based MR fluids; MRF-132DG and MRF-122-2ED, respectively. There was a significant effect of the solid to liquid ratio, at a given applied current, on the compressive and tensile stresses. Higher ratios of solid particles to carrier liquid are an indication of higher magnetic properties of the MR fluid.

#### 5.1 Behaviour of MR fluids

The relationships between stress and strain in both compression and tension modes, obtained from a large number of experiments, are included in appendices B and C, respectively. Significant sample results, representing the whole set of results in the appendices, are presented and discussed in the following sections.

In this study, the only type of stress (compressive/tensile) experienced by a liquid was volumetric stress which was pressure based. Similarly the compressive/tensile strain exhibited normally by the liquids was volumetric compressive/tensile strain which was related to the compressibility or expandability of the liquid. Volumetric changes or the tendency of an object's to deform when under pressure in three dimensions, was described by volumetric stress over volumetric strain.

Because of this, it would be better to treat and refer to the compressive/tensile stress as an apparent compressive/tensile stress, to be understood in terms of an analogy with solids which deform easily. If the squeeze mode arrangement was examined in greater detail, this compressive/tensile stress could be shown to be related to the pressure experienced by the MR fluid. However, an average value of the compressive/tensile stress measured by the experimental arrangement indicated that various regions of the MR fluid were experiencing different values of pressure. Near the centre line of the equipment, the pressure was very intense, but near the outside rim, the pressure was close to atmospheric pressure. This difference in pressure caused the fluid to accelerate, and some of the forces opposing this movement were related to the viscosity of the fluid. The apparent compressive/tensile stress was also therefore related in a complex way to the viscosity of the fluid.

Similar complications existed in the relationships between the apparent compressive/tensile strain and the fundamental fluid properties. The compressibility or expandability of the liquid was almost certainly so small that its effect on the apparent compressive/tensile strain was negligible. The major effect of these properties was the displacement of the liquid from the region between the upper and lower cylinders to an outside region. While the compressive/tensile strain was applied at a constant rate, the actual fluid velocity changed depending on the region of the fluid and the instantaneous value of the apparent compressive/tensile strain. Near the centre line of the equipment, velocities would be low, but near the rim, the velocities would be high. When the apparent compressive/tensile strain was low, fluid velocities would be comparatively low, but at high values of the compressive/tensile strain, the fluid velocities would be much greater. With each value of the fluid velocity, there would be values for the shear rate. Therefore, to some extent, the apparent compressive/tensile strain endured a complex relationship with the different shear rates experienced by the fluid. A further complication occurred, because in the presence of a magnetic field, there would be a tendency of the carrier fluid to move leaving the magnetic particles behind. The apparent compressive/tensile strain was also, therefore, an indication of the ratio of the amount of solid particles to the amount of liquid in the MR fluid. It followed that when the relationship between apparent compressive/tensile stress and apparent compressive/tensile strain was being examined, it was difficult to draw any conclusions about the relationships between the fundamental characteristics of the MR fluid. From this point onwards in the thesis, where expressions such as compressive/tensile stresses and strains occur and they refer to the MR fluid, they are to be understood to be, apparent compressive/tensile stresses and strains.

#### 5.2 Compression behaviour of MR fluids

The relationships between compressive stress and compressive strain under a constant applied current of 1.6 Amps, a compressive speed of 1.5 mm/min and an initial gap size of 2.0 mm are shown in figure 5.1. If the tested compressive force is F, the compressive stress P during the compressive process can be represented as

$$P = \frac{F}{A} = \frac{F}{\pi r^2}$$
(5-1)

where *A* is the surface area of compression and *r* is the radius of the surface area of the cylinder (r = 25 mm).



Figure 5.1: Compressive stress versus compressive strain of the MR fluids.

The process of compression of the MR fluids always showed the same three regions. All the curves of compressive stress versus compressive strain showed similar characteristics despite the fact that different MR fluids were used. Figure 5.2 shows the three regions for the compression process of individual MR fluids. In the first region, the compressive stress increased gradually with the increased of the compressive strain until it reached nearly 0.46 MPa for MRF-241ES, and 0.51 MPa for MRF-132DG and MRF-122-2ED. Then, there was a plateau with the compressive stress remaining constant

while the strain increased by values of about 10% for all tested materials. Probably the only safe conclusion that could be drawn from this result was that in the so-called constant region, the viscosity of the fluid remained almost constant even though the various shear rates and the solid to liquid ratios were increasing. This phenomenon had not been reported by any previous researchers. In the third region, the compressive stress began to increase again with further increased in the values of the compressive strain.



Figure 5.2: Compression process regions for (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED.

Some aspects of these regions could be explained, by the author, by assuming that there was relative movement between the magnetic particles and the carrier liquid. During the compression, while the liquid was being expelled, the solid particles, being magnetic, were assumed to be able to resist this expulsion to some extent. Therefore the volume fraction of the particle was assumed to increase, because only the carrier liquid was being expelled. Now if this was true, the magnetic properties of the MR fluid would change as a result of this change in composition. Illustrations regarding these phenomena are demonstrated in figure 5.3.



**Figure 5.3:** Schematic of the arrangement of magnetic particles (a) under normal condition without magnetic field, (b) when magnetic field is applied, and at the (c) first region, (d) second region and (e) third region.

An assumption has been made by other researchers concerning this change in magnetic properties. The assumption was that the magnetic permeability was directly proportional to the volume fraction of the magnetic particles in the fluid [2, 125]. For example, the volume fraction of MRF-241ES can be calculated as follows:

% Volume of particles = 
$$\frac{\left[\frac{w}{\rho}\right]_{particles}}{\left[\frac{w}{\rho}\right]_{water} + \left[\frac{w}{\rho}\right]_{particles}} \times 100$$
(5-2)

where *w* is the weight percent (unitless) and  $\rho$  is the density of the two constituents, the particles and the carrier fluid (g/cm<sup>3</sup>). The carrier fluid was assumed to have the same

density as water (1 g/cm<sup>3</sup>) and the density of the particles was given as  $(3.86 \text{ g/cm}^3)$  [47].

Initially the weight percent of the particles and the carrier fluid were 85% and 15% respectively, and therefore the volume percent of the particles was calculated to have been 60%. Now if the initial gap size was 2.0 mm, after the gap has decreased by 0.2 mm, there would be an increase in the volume of the MR fluid by 10%. If it was assumed that this change in volume was due to the expulsion of carrier fluid alone, and that there was no change in the volume of the particles, the new value of the volume fraction of the particles could be calculated to be 66%.

Using the same assumption that other researchers have made, namely, that the magnetic permeability is proportional to the volume fraction of particles, values for the flux density for different values of the magnetic field strength could now be calculated. This latter correlation is illustrated in figure 5.4 where the curves given correspond to a change in volume fraction of particles from 60% to 66%.



Figure 5.4: Magnetic induction curves of MRF-241ES for two different iron volume percents.

It may also be assumed that the greater the flux density, the greater the tendency would be for the magnetic particles to arrange themselves along the lines of magnetic flux, and to form greater resistance to the movement of the carrier fluid. As a result, a greater compressive stress would be required to maintain the constant compressive strain rate. This mechanism therefore helped to explain why the compressive stress increased so sharply in the third region of the stress-strain relationship.

It was equally true, of course, that as the volume fraction of particles increased; there would be an increase in the fluid's viscosity. For concentrated suspension of solids, empirical data suggested that the relationship could be described by equation 3-6. This formula predicted that the viscosity will increase by 1.6 times when the volume fraction increased from 60% to 66%. Because of this higher viscosity, there would be an increase in the fluid's resistance to flow. This would suggest that much higher forces were needed to cause the liquid to flow as the volume fraction increases, and, in turn, it supported the explanation of sharp increase in the compressive stress in the third region of the stress-strain relationship.

Other workers have also postulated that for very high volume fractions, at values approaching the maximum packing density of the solid particles, there may be a tendency for the particles to agglomerate. This causes trapping some of the carrier fluid and reducing the effective volume for the movement of the "free" carrier fluid. If this occurred, the result would be further resistance to the flow, and even higher compressive stresses would be required to overcome this resistance, which has to occur in the system if a constant strain rate is to be maintained.

All of these mechanisms helped to explain why in the third region, there was a very steep slope in the compressive stress versus the compressive strain. The mechanisms also helped to explain why the slope was even steeper when the magnetic field strength was high, because the volume fraction of particles was likely to increase more rapidly under these conditions.

#### 5.2.1 Comparison of compression behaviour of MR fluids

At the beginning of compression as shown in figure 5.1, all curves increased slowly as the compressive strain increased. Then the curves turned almost constant before proceeding to increase tremendously. However, different types of the MR fluids have showed different positions of the stress-strain curves.

The basic phenomenon of the MR effect was understood to consist of the following. Under the influence of a magnetic field, the particles, which were initially in random positions, formed chains along the field direction, and later these chains, tended to form into thicker structures. These formations in the MR fluids were reversible, but as the magnetic field increased, there was growth in the structures from single chains to columns and then thicker columns.

In general, the responses of the MR fluids to compressive strains can be divided into two stages. The first and second regions of the compression can be interpreted as the formation of the fluid movement with the particles arranged in single chains, and in the third region the particles are arranged in thicker structures. However, different values of compressive stress can be achieved by different sets of conditions. For instance, figure 5.1 shows that MRF-241ES, MRF-132DG and MRF-122-2ED started to experience large compressive stresses at very different values of compressive strain. In one case it was at a strain value of approximately 0.14, and in other cases it was at strain values of about 0.52 and 0.66.

It seemed clear that the increased in the compressive stress at these particular points were due mainly to the values of the ratio of solids-to-liquid in the fluids. The three liquids started off with very different ratios of solids-to-liquid, and this factor, amongst others, gave the liquids different magnetic properties. By the process described in the preceding sentences, the ratio of solids-to-liquid in each fluid was steadily increasing. It was probable that at a certain critical value of the solids-to-liquid ratio, the point was reached when the compressive stress suddenly increased, while the compressive strains continued to increase at a steady rate. (These points occurred at the beginning of the third region.) Since one of the MR fluids started off with a comparatively high solids-to-liquid ratio, it reached this critical value at quite a low value of the compressive strain. Consequently the MRF-241ES fluid shows this characteristic response at a much lower value of the compressive strain when compared with the MRF-132DG and MRF-122-2ED.

It follows that one could make an MR fluid with magnetic particles composed of a material with a saturation of magnetisation which is lower than iron. If one then made a second MR fluid with iron particles, its magnetic properties would be superior. However if the second MR fluid had a lower ratio of solids-to-liquid, this would compensate for the difference in magnetic properties, and the two fluids could be tuned to have identical magnetic properties. However, in compression mode, the fluid with the particles of poorer saturation properties and initial higher solids-to-liquid ratio would reach the critical value of this ratio after only a small compressive strain value had been reached. The other fluid would reach this critical ratio after a much larger amount of compressive strain. For the cases of fluids with lower ratios of solids-to-liquid (MRF-132DG and MRF-122-2ED), the compressive stresses were mainly determined by the strength of magnetic field but the influence of this factor was less significant for the fluid with the higher ratio of solids-to-liquid (MRF-241ES). The factor of greater significance for this fluid was the steadily increasing solids-to-liquid ratio.

#### 5.2.2 Compression behaviour of hydrocarbon-based MR fluids

Values of the compressive stress of the MRF-132DG and MRF-122-2ED suddenly dropped at end of the second region, at about 0.53 and 0.53 MPa, respectively, and then continued to increase again as shown in figure 5.5. Since the particles were all approximately the same size, it was expected that the force required to break a chain composed of a single column of the particles would be of approximately the same magnitude throughout the volume occupied by the MR fluid. Also, as mentioned earlier, various regions of the fluid will move with very different velocities. Because of this, and since the resistance to flow was mainly due to viscosity, the force tending to break the chains of particles apart would be much greater in a region of high velocity and much smaller in a region of low velocity. However, the effect of a pressure drop phenomenon

as large as shown in figure 5.6, if it were caused by particle chains being broken, would have to be caused by a substantial number of chains being broken within a very short period of time (1.1 seconds).



**Figure 5.5:** In the data, already given in figure 4.1, was scaled to show details in the range of values of compressive stress between 0.40 and 0.59 MPa.



**Figure 5.6:** The compressive stress versus time data for the (a) MRF-132DG and (b) MRF-122-2ED.

In view of these facts, it would seem that the pressure drop effect could be due to a large number of single column chains of particles being broken almost instantaneously by forces resisting the movement of the MR fluid. It was more likely that this was the explanation for the occurrence of the complete second region in the stress-strain relationship. The chains of particles were broken successively beginning in those regions where the velocity is greatest and moving to regions where the velocity was originally smaller but increased as the size of the gap decreases. An effect similar to the pressure drop could be caused by air bubbles, originally in the MR fluid, being expelled from the region between the upper and lower cylinders. These air bubbles would introduce a small amount of compressibility as noted by Tang et al. [160], and this might explain the observed phenomenon. It also has been reported by Tang et al. [160] that MR fluids based on hydrocarbon carriers were very difficult to bleed satisfactorily, so that all air bubbles were removed. However, when the experimental trials were repeated, the same pressure drop was observed, and this would suggest that the same amount of air bubbles were present again and were expelled in the same way. In this work, no special attempts were made to expel air bubbles from the equipment before the experiments. In fact the equipment was not designed to allow for such a procedure to be carried out.

#### 5.3 Tension behaviour of MR fluids

The relationships between tensile stress and tensile strain under a constant applied current of 1.2 Amps, a tensile speed of 1.5 mm/min and initial gap size of 2.0 mm for the MR fluids are shown in figure 5.7.



Figure 5.7: Tensile stress versus tensile strain relationships for the MR fluids.

Similar to the compression process, the tension process of the MR fluids consisted of three regions. Stress-strain curves of the MR fluids under tension showed similar characteristics despite the fact that different types of the carrier fluids were used. Figure 5.8 shows that the process of tension for each MR fluid could be divided into the three regions. In the first region, the tensile stress curve initially increased to an inflection point closely at 0.14 MPa for MRF-241ES, and 0.12 MPa for MRF-132DG and MRF-122-2ED, with the increased of the tensile strain. After the inflection points had been reached, the tensile stress decreased with increasing tensile strain in the second region. The stress-strain curves displayed a concave shape. In the third region, the tensile stress further decreased, slowly, with further elongation. The same behaviour was reported by Tian et al. [13] under tension process of the ER fluid when voltage ranging from 0.4 to 0.6 kV was applied.



**Figure 5.8:** The three regions of tension process in (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED.

The same assumption, had been made by the author about the relative movement between the particles and the carrier fluid under compression process, could also be made to describe the transformation of the elongation patterns as shown in figure 5.9. When a magnetic field was applied to MR fluids between two parallel surfaces, the particles formed chains aligned in the direction of the magnetic field. For tension process under constant applied current and initial gap size, as the gap size between the surfaces increased, the instantaneous magnetic field decreased.



**Figure 5.9:** Schematic of the aggregation of MR fluids under tensile elongation (a) with the magnetic field applied, and at the (b) first region, (c) second region and (d) third region.

The tension process was interrelated between the structure strengthening effect and the decreasing magnetic field in which was a direct consequence of the widening gap between the surfaces. Initially, the particle chains could be considered as a combination structure of the magnetic particles and the carrier fluid. In the first region, when the upper cylinder was moved up, the particle chains stretched a little bit while maintaining their structure. In order to elongate, a higher resistance was given to the MR fluids by the particle chains. In the second region, the particle chains rearranged to form a new structure, which consisted of the magnetic particles only. The magnetic particles could easily move and build-up new particle chains because the interaction among the magnetic particles was stronger than the interaction between the particles and the carrier fluid. Therefore, as the particle chains further elongated, they started to expel the carrier fluid until they reached a steady state. During this region, the structure aggregation effect compensated most of the field effect. Then in the third region, the new single chains tended to aggregate forming columns. The effect of the decreasing magnetic field was therefore more obvious and consequently decreased the tensile strength of the MR fluid.

#### 5.3.1 Comparison of tension behaviour of MR fluids

At the beginning of the tensile process (first region), the stress-strain curves increased rapidly as the tensile strain increased. Then, after reaching the peak point, the tensile stress decreased quickly (second region) before proceeding to decrease slowly (third region) with further increased of the tensile strain. The second and the third regions could be differentiated by the decreasing rate of the tensile stress. However, the values of tensile stress versus tensile strain were depending on the type of the MR fluid as shown in figure 5.7. Different values of the maximum tensile stress and the range of tensile strain of the MR fluids for each region under tension are shown in table 5.1.

		MRF-241ES	MRF-132DG	MRF-122-2ED
Maximum value of tensile stress		0.139 MPa	0.123 MPa	0.118 MPa
Range of the tensile strain	Region 1	0 – 0.066 (0.066)	0 – 0.046 (0.046)	0 – 0.043 (0.043)
	Region 2	0.066 - 0.094 (0.028)	0.046 - 0.099 (0.053)	0.043 - 0.105 (0.062)
	Region 3	> 0.094	> 0.099	> 0.105

Table 5.1: Comparison values of the tensile stress and strain of MR fluids.

It seemed clear that the maximum value of the tensile stress was due mainly to the value of the ratio of solids-to-liquid in the fluids. Basically, all the MR fluids had different magnetic properties because their ratios of solids-to-liquids were not the same. Since one of the MR fluids started off with a comparatively high solids-to-liquid ratio, (MRF-241ES), the tensile stress reached the maximum value at a relatively a higher value of tensile strain. This can be clearly seen in figure 5.7. However, the range of tensile strain of the second region was smaller for this material with high ratio of solidsto-liquid. A fluid with high magnetic properties tended to rearrange its particles more efficiently than the one with lower magnetic properties. Therefore, the process of expelling the liquid occurred in a shorter range of tensile strain. It followed that in the third region, the tensile stress corresponding to higher magnetic properties of MR fluid began at a higher point of the tensile stress. Moreover, the values of tensile stress at any points of strain were higher for the high ratio of solids-to-liquid. As an overall comparison under tension process, tensile stress of MR fluids was mainly determined by the amount of solids-to-liquid ratio. As shown in figure 5.7, at any point, MRF-241ES showed the highest values of the tensile stress, followed by MRF-132DG and finally by MRF-122-2ED with slightly lower values of tensile stress than those of MRF132DG.

#### 5.4 Summary of chapter 5

Experimental trials were performed on individual compression and tension of the MR fluids. The influence of the applied current, initial gap size and compressive/tensile speed on the three types of MR fluids under compression and tension processes have been experimentally investigated. In all cases, during the compression, the water-based MR fluid showed a stable behaviour while the hydrocarbon-based MR fluids experienced a very fast drop in the compressive stress at a constant region for a small amount of compressive strain before proceeding to increase again. The compressive stress of the water-based MR fluid showed a response to the compressive strain in a greater magnitude than the hydrocarbon-based MR fluids. This result was probably due to the high ratio of solids-to-liquid in the water-based MR fluid as compared to the hydrocarbon-based MR fluids at the same value of the magnetic field intensity. Experimental results also emphasized that the compressive stress of the MR fluids was strongly affected by the type of the carrier fluid. A summary and a comprehensive outline of the main research process of chapter 5 are shown in figure 5.10.



Figure 5.10: Summary of the research process in chapter 5.

# CHAPTER 6 EFFECTS OF VARIOUS FACTORS

#### 6.0 Introduction

This chapter presents the effects of various factors such as initial gap size, applied current and compressive/tensile speeds on MR fluids in terms of stress-strain relationships that were obtained from the compression and tension experiments. The resulting MR effect corresponded to the changes or increases in compressive and tensile stresses due to changes in magnetic field. This chapter also includes discussions of each factor that contributes to effects on the performance of MR fluids. The discussion is intended to support the knowledge gained in the previous sub-chapters. A brief conclusion with respect to the results and discussions is presented at the end of the chapter.

#### 6.1 Effect of applied current

Applying Ampere's circuital law for magnetic circuits, the number of turns N (in a coil) and the applied current I determined the magnitude of the magnetic field strength H as depicted by equation 2-3,  $NI = \oint H \cdot dl$ . In this equation, l refers to the total length of the whole magnetic circuit. This must include not only the length of the lower cylinder around which the coil is wound, but also the rest of the magnetic circuit, and most of the flux lines that pass through the MR fluid. Therefore, l was also larger if the gap size was large. For the same number of turns, a higher electrical current or a small gap size would result in a greater magnetic field strength.

#### 6.1.1 Effect of applied current under compression

All the investigated MR fluids; MRF-241ES, MRF-132DG and MRF-122-2ED exhibited the same behaviour under a constant compressive speed of 1.5 mm/min, an initial gap size of 2.0 mm and different applied currents as shown in figure 6.1. However, under the same values of compressive strain, the value of compressive stress

seemed to be higher for higher applied currents. Consequently, lower values of compressive stress could be achieved by reducing the applied currents to lower values. The relationships showed greater values of compressive stresses as the gap between the two cylinders became smaller as shown in figure 6.2. Even though all the curves started at the same point of initial gap size, the values of compressive stress showed significant variations according to the applied current.



**Figure 6.1:** Compressive stress versus compressive strain under different applied currents for (a) MRF-241ES, (c) MRF-132DG and (e) MRF-122-2ED, and a zoom in when the curves became plateau for (b) MRF-241ES, (d) MRF-132DG and (f) MRF-

122-2ED.






**Figure 6.2:** Initial gap size as a function of compressive stress at different applied currents ranging from 0.4 to 1.6 Amps of (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED.

For a given compressive strain or initial gap size, a higher value of stress could be achieved by increasing the applied current. This influence of the applied current or magnetic field strength on stress complied with the results observed by other researchers [8, 10, 14, 17, 24]. The stress-strain curves developed quickly with the increase of compressive strain as can be clearly depicted from figures 6.1 (b), (d) and (f). At higher currents, the curves stabilized at higher values of compressive stress for the same range values of compressive strain. At the initial compression deformation (first region), the stress increased as the strain increased. When the stress reached a particular point, the curve became constant (second region) as the strain increased swiftly for a certain value of strain. As the strain further increased, the curves proceeded to increase drastically in the third region. The higher the applied current, the faster the stress-strain curve developed. All curves seemed to have the same behaviour and to be shifted either to the left, right, bottom or top of the graph depending on the value of the applied current.

When applying different values of currents with a constant speed and an initial gap size, the stress-strain relationships, figure 6.1, are affected. Early formation of particles (due to compressive strain) could be achieved by applying a higher current. The particles formed chains rapidly and, correspondingly, reacted to the applied pressure/stress. Under various magnetic field strengths (different applied currents), the structures formed inside the MR fluids had a constructive effect on the compressive stress to the compressive strain relationship. Hence, the stress-strain curves developed rapidly as shown in figure 6.1, and then stabilized at a slightly higher value of compressive stress before starting to increase drastically again. This process seemed to be more significant when applying higher values of current.

On the other hand, the influence of the applied current could be described by an MR fluid's solids-to-liquid ratio. For a higher magnetic field strength (higher applied current), the compressive stress would be greater. When working with the same MR material with a higher applied current in compression mode, a maximum value of compressive stress at the first region is reached after only a small compressive strain value as shown in figures 6.1 (b), (d) and (f). For the same fluid with a lower applied current, this maximum value would be reached after a larger value of compressive strain. Furthermore, at the first region, a higher maximum value of compressive stress could be obtained when a higher current was applied. The carrier fluid was being expelled for the same range of compressive strain, but starting at different values of compressive stress and compressive strains. The process of expelling the carrier liquid with a higher applied current occurred at a smaller value of compressive strain and a higher value of compressive stress.

According to Lukkarinen and Kaski [157], thicker structures may have occurred in a system for a small gap size between the two plates. Therefore, as shown in figure 6.2, at the beginning of compression, the gap is considered to have a large size and this occurs during the first and second regions. The stress-strain relationships for these regions were similar, but during the third region, as the gap size decreases further, the stress-strain relationship changed. Based on this consideration, the thick columns occurring in the third region were assumed to be the main structure, and were responsible for the changes in the stress-strain relationship. Hagenbuchle and Liu [3] have reported that chain formation also depended on the applied field strength. As the applied current increased, there was also an increased in the magnetic field strength, and so the tendency of the particles to form thick columns also increased. This explains why the change from the second to the third region also dependent on the size of the current.

#### 6.1.2 Effect of applied current under tension

Figure 6.3 shows the effect of the applied current on MR fluids under a constant tensile speed of 1.5 mm/min and an initial gap size of 2.0 mm. As can be seen, under the same value of the tensile strain, the value of tensile stress was higher at higher values of applied currents. Lower values of tensile stress could be achieved as the applied current was reduced.



**Figure 6.3:** Tensile stress versus tensile strain under different applied currents at initial gap size of 2.0 mm for (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED.

Similar effect of the applied current could also be found in the discussion of the compression process in the preceding section. Higher values of the tensile stress could be achieved with increased in the applied current [12, 13]. When an external magnetic field was applied to MR fluids, the polarized particles formed particle chains along the field direction. The interactions between the particles for a higher applied current were much stronger than those for a lower applied current. Initially, when the upper cylinder was moved up, the required force was high in order to break up the particle chains, which corresponded to the highest value of tensile stress, shown in figure 6.3. As the gap size was further increased, the broken particle chains aggregated to form columns. Even though the interactions between the particles in columns were expected to be stronger

than particle chains, the increased in gap size reduced the magnetic field strength. The effect of decreasing the magnetic field was more significant than the interaction between the particles in the columns. Therefore, as the gap size increased, the tensile strength of the MR fluid decreased. Tensile stresses of the MR fluids were higher at a higher applied current rather than at a lower applied current. This was because magnetic field strength was one of the factors that influenced the tensile stress as demonstrated by different values of applied current.

# 6.2 Effect of initial gap size

Equation 2-3 shows that for a fixed number of turns and applied current, a small gap size would result in a greater magnetic field strength. Moreover, Tian et al. [14] showed that the instantaneous electric field E during the compression process can be calculated by

$$E = \frac{V}{h} \tag{6-1}$$

where V is the voltage (Volt) and h is the instantaneous gap size (mm). Similar to equation 6-1, the instantaneous magnetic field H is calculated by

$$H = k \frac{I}{h} \tag{6-2}$$

where k is the constant value on account of the length of the lower cylinder around which the coil is wound, I is the applied current (Amps) and h is the instantaneous gap size in between the two parallel cylinders of the test rig (mm). Therefore, reducing the initial gap size between the two cylinders could increase the instantaneous magnetic field. As mentioned in section 6.1.1, the particles of the MR fluids were polarized and strongly interacted with each other to form regular chains and columns along the field direction. Therefore, the stresses achieved depend on the strength of the magnetic field. Consequently, the initial gap size was inversely proportional to the achieved stresses.

# 6.2.1 Effect of initial gap size under compression

Figure 6.4 illustrated the compressive stress-strain curves of the MR fluids at a constant applied current of 1.6 Amps, a compressive speed of 1.5 mm/min and different initial gap sizes. The stress-strain curve of MRF-241ES looked steeper at a large initial gap size indicating that the compressive stress increased as the initial gap size increased for the same value of compressive strain. The usual three regions of the compression process were also obtained under different initial gap sizes. The stress-strain relationships, at the first region, were having almost identical curve. At the second region for a particular material, the stress-strain curves for the initial gap size of 2.0 mm started to become plateau at slightly lower values of compressive stress and compressive strain as compared to the case of initial gap size of 1.0 mm. These results emphasized that the stress-strain relationship of MR fluids was strongly affected by the initial gap size was difficult to illustrate for fluids with poorer solids-to-liquid ratio at the third region of the initial gap size of 1.0 mm. This can be seen in figures 6.4 (c), (d), (e) and (f), indicated by the red curves.



**Figure 6.4:** Effect of the initial gap size under compression tests and a zoom in when the curves became plateau of (a) and (b) MRF-241ES, (c) and (d) MRF-132DG, and (e) and (f) MRF-122-2ED.

In view of this, one might have expected that a higher compressive stress would have occurred where the applied magnetic field strength was greatest by reducing the initial gap size between the two cylinders. However, in fact, higher values of compressive stresses were obtained when the initial gap size was set to 2.0 mm in comparison to the situation when the initial gap size of 1.0 mm has been set. During the compression, the volume fraction of the solid particles would increase because the liquid was being expelled from the MR fluid. In terms of the compressive strain, the process of expelling the carrier fluid was more obvious for a small initial gap size. By increasing the initial gap size, more particles were consumed inside the MR fluids. Even though the solids-to-liquid ratios of the MR fluids were the same, the achievable compressive stresses were not the same. However, in terms of the compressive stress versus displacement, the expelling process of the liquid for a large initial gap size was almost the same as that for a small initial gap size (represented by the second region) as shown in figure 6.5.





**Figure 6.5:** Compressive stress versus displacement of MRF-241ES under a constant compressive speed of 1.5 mm/min and applied current of (a) and (b) 1.6, (c) and (d) 1.2, (e) and (f) 0.8, and (g) and (h) 0.4 Amps.

When converting the stress-displacement curves (figure 6.4) to stress-strain curves (figure 6.5), the effect of the initial gap size on the MR fluids seemed to be more significant. The same magnetic field strength could be delivered to the MR fluid using different combinations of applied currents and initial gap sizes. The relationship between the magnetic field strength and the current to gap size ratio was disclosed in equation 6-2. Figures 6.6 (a) and (b) illustrated the stress-displacement curves corresponding to equal current to gap size ratios. It can be seen that both curves were identical. This was because the magnetic field strength in the two cases was the same. Similar behaviour was shown in figures 6.6 (c) and (d). Consequently, the effect of the magnetic field

strength on the performance of the MR fluid during the compression process could also be demonstrated by changing the initial gap size.



**Figure 6.6:** Stress-strain curves of MRF-241ES corresponding to, (a) current-to-gap size ratio is equal to 0.8 Amps/mm, (b) zoom in on (a), (c) current-to-gap size ratio is equal to 0.4 Amps/mm, and (d) zoom in on (c).

As can be seen in figure 6.6, the same stress-strain curves could be obtained when compensating between the applied current and the initial gap size to maintain the same current to initial gap size  $\left(\frac{I}{h}\right)$  ratio. In the same figure, even though the increase of the initial gap size increased the volume of the MR fluid, the solids-to-liquid ratio remained constant. Therefore, the behaviour of the MR fluid for both initial gap sizes remained identical. The applied stress could be considered as the resistance of the solid particles along the magnetic flux direction under compression. Decreasing the initial gap size is a means of increasing the magnetic field strength. The degree of deformation resistance was a function of the applied magnetic field strength or applied current [3]. Once the magnetic field was applied, the particles of MR fluids were polarized and strongly interacted with each other to form regular chains and columns along the field direction.

# 6.2.2 Effect of initial gap size under tension

Tensile stress-strain curves of MR fluids at a constant tensile speed of 1.5 mm/min, applied current of 1.2 and 0.8 Amps, and different initial gap sizes are shown in figure 6.7.



**Figure 6.7:** Effect of the initial gap size under constant tensile speed of 1.5 mm/min for (a) MRF-241ES at applied current of 1.2 Amps, (b) MRF-241ES at applied current of 0.8 Amps, (c) MRF-132DG at applied current of 1.2 Amps, (d) MRF-132DG at applied current of 0.8 Amps, (e) MRF-122-2ED at applied current of 1.2 Amps and (f) MRF-122-2ED at applied current of 0.8 Amps

122-2ED at applied current of 0.8 Amps.

As can be seen, higher values of the tensile stress were observed at lower initial gap sizes when a constant current was applied to the MR fluids. The effect of the initial gap size under tension tests was contradicted with the same effect under compression tests in terms of the stress-strain relationships. In sight of this, one might have expected that a higher tensile stress would occur where the applied magnetic field strength was greatest. Therefore, higher values of tensile stresses were required when the initial gap size was set to 1.0 mm in comparison to the situation when the initial gap size of 2.0 mm has been set. At the beginning of the tension process, the volume fraction of the solid particles remained the same. Then, this amount will increase because of the liquid being expelled from the MR fluid. However at any values of tensile strain, as the initial gap size increased, the tensile stresses always showed lower values. This was because the influence of the magnetic field strength was greater than the structure strengthening as discussed in section 6.1.2.

The effect of the initial gap size under tension could also be presented in terms of stress-displacement relationships as depicted from figure 6.8. The values of tensile stresses corresponding to two different initial gap sizes when the same value of current was applied to the MR fluids were clearly demonstrated by the case of MRF-241ES in figure 6.8 (a). The stress-displacement curves increased as the initial gap size reduced. The same results have also been observed in the MRF-132DG and MRF-122-2ED cases at high applied currents (1.2 and 1.6 Amps) as shown in figures 6.8 (b) and (c). However, the increases in tensile stresses were less significant at 0.4 and 0.8 Amps of the applied current.







**Figure 6.8:** Tensile stress versus displacement under a constant tensile speed of 1.5 mm/min for (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED.

In view of this, one might have expected that the tensile stress was dependent on the structure strengthening effect due to particle chains restructuring and the decreasing magnetic field as the gap size increased. The structure strengthening effect for a high solids-to-liquid ratio (MRF-241ES) was greater at any strength of the applied magnetic field. Therefore, the increased in tensile stresses could be considered proportional with the increased in magnetic field strength. However, the structure strengthening effect at low ratios of solids-to-liquid was very weak in comparison with decreasing magnetic field strength. When lower magnetic fields (0.4 and 0.8 Amps of applied current) were applied to the MR fluids (MRF-132DG and MRF-122-2ED), the difference in values of tensile stresses were very little for both initial gap sizes. However, the effect of structure strengthening could be increased by increasing the magnetic field strengths (1.2 and 1.6 Amps of applied current).

# 6.3 Effect of compressive/tensile speed

Investigating the properties of MR fluids under different speeds of compression and tension was helpful for further understanding of the MR effect. The formation of particle chains was strongly dependent on the applied field strength. This structure formation occurred on a time scale of milliseconds and caused the fluid to respond to compressive/tensile stresses at the direction of magnetic field [3]. Consequently, the effect of compressive/tensile speed on the stress-strain relationships needed to be studied.

#### 6.3.1 Effect of compressive speed

Figure 6.9 reveals the effect of the compressive speed on the stress-strain relationships of the MR fluids. In this investigation, the applied current was set to 1.2 Amps and the compressive speeds were in the range of 0.5 to 2.0 mm/min. The compressive stress changed correspondingly as the compressive strain changed. When applying a constant current, the results showed that the compressive speed had a small effect on the stress-strain relationship which is considered as being neglected. The same characteristics were observed at all values of the compressive speed with reference to the types of the MR fluids and the initial gap sizes. As the compressive speed increased, the stress-strain curves remained the same.





**Figure 6.9:** Stress-strain relationships under different compressive speeds at 1.2 Amps of applied current of (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED.

These results were in contradiction with the employment of the experiments carried out on ER fluids as reported by Choi et al. [17]. The authors found that the compressive stress decreased as the compressive speed increased. The particle clusters of an ER fluid were assumed to elongate and suddenly break as the compressive speed increased. However, See et al. [156] discovered that there was no difference between fast and slow compressions (step compression). In the slow compression, the gap was reduced by 0.01 mm until the final gap has reached 0.9 mm from an initial gap size of 1.0 mm, and the interval time between compression steps was set to 60 seconds. While

for the fast compression or one step compression, the total time taken to reach final gap was about 2 to 3 seconds. Their result was as anticipated since the formation of particle chains and columns occurred in a very short period of time. According to Tao [161], the strongest structure of MR fluids was built up after the magnetic field was applied only by a few milliseconds. Therefore, the particles had more than sufficient time for the structural rearrangements to take place. Similar results on the effect of the compressive speed could also be found in another study of ER fluids by Tian et al. [154].

# 6.3.2 Effect of tensile speed

Stress-strain relationships under different tensile speeds are shown in figure 6.10. The tests were conducted at 1.0 and 2.0 mm of initial gap sizes. The current passing through the coil was 1.2 Amps for all cases. It could be observed that the stress-strain curves were well overlapped for all values of the tensile speed.



**Figure 6.10:** Effects of the tensile speed under a constant current of 1.2 Amps of (a) MRF-241ES, (c) MRF-132DG and (e) MRF-122-2ED at initial gap size of 2.0 mm, and (b) MRF-241ES, (d) MRF-132DG and (f) MRF-122-2ED at initial gap size of 1.0 mm.

The tensile speeds used in this study were in the range of 0.0083 to 0.0333 mm/s, which were comparable to speeds used by other researchers. For instance, Tian et al. [13] used a constant speed of 0.0524 mm/s to investigate the tensile behaviour of ER fluids. It might be anticipated that the effect of the tensile speed was not significant on the tensile stress since the structure formation occurred on a time scale of milliseconds [39, 62]. Even though, in this study, various values of the compressive/tensile speeds were applied to move the upper cylinder, the speeds were still considered slow compared to the structure formation. Based on the speed and initial gap size ranges experimented in this study, the compression/tension time ranges were, approximately, between 30 and 240 seconds. A much higher speed range was necessary to detect the variance, on a millisecond scale, in MR effect due to the structure formation. However, the use of high speeds was prohibited by the gap size restriction in the design and the motor movement mechanisms in the UTS machine.

#### 6.4 General discussion

In figures 6.11, the plots on the left hand side were the original stress-strain curves. The plots on the right hand side of these figures were edited versions of the left hand side ones. These curves were adjusted or shifted, generally to the right and slightly to the bottom, to fall onto the curve with the lowest value of applied current, which was 0.4 Amps in all cases. The curves in figure 6.12 were treated similarly. For each type of MR fluid in compression mode under different applied currents, the stress-strain curves were observed to be well overlapped as shown in the right hand side plots of figure 6.11 and figure 6.12. However, in figures 6.12 (b) and (c), the curves were not perfectly overlapped. This was due to the poorer solids-to-liquid ratios in hydrocarbon-based MR fluids. This repeating MR behaviour under different applied currents and initial gap sizes supported the categorization of the MR effect regions. Consequently, the MR effect could be modelled or explained, independently, in each region.



**Figure 6.11:** The adjusted or shifted curves of compressive stress versus compressive strain at the initial gap size of 2.0 mm for (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED.











**Figure 6.12:** The adjusted or shifted curves of compressive stress versus compressive strain at the initial gap size of 1.0 mm for (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED.

According to equation 3-16, the compressive stresses  $\sigma$  of the MR fluids in the first region were assumed to increase linearly, which were represented by

$$\sigma_1 = G_1 \gamma_1, \qquad \qquad \sigma < \sigma_{\gamma}$$

where  $\sigma_1$  is the compressive stress at the first region (MPa),  $G_1$  is the compressive modulus at the first region (MPa),  $\gamma_1$  is the compressive strain at the first region (unitless) and  $\sigma_y$  is the maximum value of compressive stress at the first region (MPa).

In the second region, equation 6-3 was applicable when the compressive stresses were equal to the maximum values of the compressive stresses  $\sigma = \sigma_y$  at the first region. The values of the compressive strains  $\gamma_2$  were between the maximum values of the compressive strains at the first region  $\gamma_{1,max}$  and the minimum values of the compressive strains at the third region  $\gamma_{3,min}$ .

$$\gamma_{1,\max} \le \gamma_2 \le \gamma_{3,\min}, \qquad \sigma = \sigma_y$$
 (6-3)

When the compressive stresses were greater than the maximum values of the compressive stresses at the first region as indicated by the third region, the compressive stresses were representing by

$$\sigma_3 = G_3 \gamma_3 + C, \qquad \sigma > \sigma_y \tag{6-4}$$

where  $\sigma_3$  is the compressive stress at the third region (MPa),  $G_3$  is the compressive modulus at the third region (MPa),  $\gamma_3$  is the compressive strain at the third region (unitless) and *C* is the constant value (MPa). All parameters obtained from the stress-strain curves of experimental values are listed in table 6.1.

	Initial gap	Maximum stress at the first region σ <sub>y</sub> (MPa)	$\begin{array}{c} \text{Region 1} \\ (\sigma < \sigma_y) \end{array}$	$\begin{array}{c} \text{Region 2} \\ (\sigma = \sigma_y) \end{array}$		$\begin{array}{c} \text{Region 3} \\ (\sigma > \sigma_y) \end{array}$	
	size (mm)		<i>G</i> <sub>1</sub> (MPa)	γ1,max	∕∕3,min	G <sub>3</sub> (MPa)	C (MPa)
MRF-241ES	2.0	0.41	5.13	0.08	0.17	51.45	-9.77
	1.0	0.43	2.77	0.16	0.28	25.70	-8.34
MRF-132DG	2.0	0.42	0.79	0.53	0.64	40.74	-27.34
MRF-122-2ED	2.0	0.41	0.59	0.69	0.80	37.26	-30.35

**Table 6.1:** Experimental values of the mechanical properties of MR fluids.

Based on equations 3-16 and 6-4 as represented by the first and third regions, the values of compressive moduli were always constant in the linear regions with the increase of compressive strain. The values of compressive moduli were smaller in the first region than they are in the third region. These results showed that the third region was more dominant in terms of MR effect. Small changes in strain in the third region induced larger stress changes than they did in the first region.

#### 6.4.1 Comparisons between compressive and tensile stresses

Figure 6.13 shows the compressive and tensile stresses versus magnetic field density at 1.0 and 2.0 mm of initial gap sizes. The compressive stress values in figure 6.13 were the maximum stresses during the compressing process, taken from the end points of the curves at the first region. The tensile stresses in figure 6.13 were taken from the peak values of the tension curves, which also were symbolized by the maximum values of the tensile stress at the first region. As can be seen in figure 6.13, linear relationships could be established for both the compression and tension processes under various magnetic flux densities.



**Figure 6.13:** Compressive and tensile stresses versus magnetic flux density at different initial gap sizes of (a) MRF-241ES, (b) MRF-132DG and (c) MRF-122-2ED.

The relationship between the compressive and the tensile stresses under the influence of the magnetic flux density could be described by a general linear equation as follow

$$\sigma_{y} = kB + \sigma_{\min} \tag{6-5}$$

where  $\sigma_y$  is the maximum value of compressive or tensile stress at the first region (MPa), k is the constant value (MPa/Tesla), B is the magnetic flux density (Tesla) and  $\sigma_{min}$  is the value of the compressive or tensile stress at zero magnetic flux density. In these cases, the values of  $\sigma_{min}$  were not equal to zero. This was because the values of the stresses taken, and used in figure 6.13, were not at the same value of the compressive strain for each process.

The parameter values corresponding to the compressive and tensile stresses explained by equation 6-5 are listed in table 6.2.

	Comp	ression	Tension		
Type of MR fluid	k (MPa/Tesla)	σ <sub>min</sub> (MPa)	k (MPa/Tesla)	σ <sub>min</sub> (MPa)	
MRF-241ES	$109.4 \times 10^{-3}$	379.2 ×10 <sup>-3</sup>	274.7 ×10 <sup>-3</sup>	$0.6 \times 10^{-3}$	
MRF-132DG	$183.2 \times 10^{-3}$	387.9 ×10 <sup>-3</sup>	272.8 ×10 <sup>-3</sup>	-16.1 ×10 <sup>-3</sup>	
MRF-122-2ED	200.4 ×10 <sup>-3</sup>	379.8 ×10 <sup>-3</sup>	297.1 ×10 <sup>-3</sup>	-19.2 ×10 <sup>-3</sup>	

**Table 6.2:** Parameter values obtained from equation 6-5.

During the compression process, the distance between the solid particles in the MR fluid decreased. As discussed earlier in section 5.2, the relative movement between the solid particles and the carrier liquid had an effect on particle condensation. Therefore, the particle volume fraction of the MR fluid increased and the structure of the particles was more compact. However, the tension process was different from compression process in having no effect on the particle condensation. Figure 6.13 also shows that the compressive stresses were much higher than the tensile stresses under the same magnetic flux density. Similar results have been found by other researchers. Tian et al. [8] have done comparisons between (compressive stress was much higher than the tensile and shear) stresses of ER fluids. The authors encountered that the compressive stress was much higher than the tensile and shear stresses under the same DC electrical field. These results were also supported by Lukkarinen and Kaski [9, 157] using computer simulations.

#### 6.4.2 Combinations of compressive and tensile stresses

Figures 6.14, 6.15 and 6.16 show the combination of the compressive and tensile stresses versus displacement under different applied currents. The maximum displacement was taken at 0.5 mm for both compression and tension modes. The positive values of the stresses in these figures, above the zero dotted lines, represented the tension process, while the negative values represented the compression process.



Figure 6.14: Combination of compressive and tensile stresses of MRF-241ES at (a) 2.0 mm and (b) 1.0 mm of initial gap size.



Figure 6.15: Combination of compressive and tensile stresses of MRF-132DG at (a) 2.0 mm and (b) 1.0 mm of initial gap size.



**Figure 6.16:** Combination of compressive and tensile stresses of MRF-122-2ED at (a) 2.0 mm and (b) 1.0 mm of initial gap size.

The combination of stress modes in figures 6.14, 6.15 and 6.16 were assumed to represent the behaviour of the MR fluids under dynamic loading (combination of compression and tension). As the applied current was increased, the area of the loop curves along with the maximum compressive and tensile stresses increased. The increased in the area of the loop curves was an indication on the increased in the damping performance of the MR fluids. A low initial gap size also contributed to larger area of the loop curves. Obviously, the damping performance of MRF-241ES was better than MRF-132DG, while the performance of MRF-132DG was better than MRF-122-2ED. Furthermore, the maximum stresses obtained in the compression mode were much greater than those obtained in the tension mode.

The combination results, obtained in this study, were in agreement with the results of other researchers. Kulkarni et al. [16] have obtained similar results from the dynamic loadings of a hydrocarbon-based MR fluid under squeeze mode. The authors found less effect of the tensile stresses under various applied currents as compared to the compressive stresses. They also observed that the compressive side of the stress loop was highly non-linear and had a peak on the left side of the curve, similar to figure 6.14.

However, they did not report the magnetic properties of the MR fluid and the magnetic field strength generated by the coil. However, it was assumed to contain highly solid magnetic particles. In another study done by the same group, Vieira et al. [24] further compared the behaviour of three different types of MR fluids under squeeze mode. The authors obtained similar results, which are also in agreement with the results in figures 6.14, 6.15 and 6.16. The types of the carrier fluids and the applied magnetic field strengths were discovered to influence the behaviour of the MR fluids.

# 6.5 Summary of chapter 6

Experimental results emphasized that the compressive stress of the MR fluids was strongly affected by the applied current and the initial gap size. The compressive stress changed correspondingly as the compressive strain changed. The compressive stress of the MR fluids increased with increasing the applied current or decreasing the initial gap size. However, when applying constant currents and initial gap sizes, the results showed that the compressive/tensile speed had a small effect on the stress-strain relationship, which was considered as being neglected. A summary and a comprehensive outline of the main research process of chapter 6 are shown in figure 6.17.



Figure 6.17: Summary of the research process in chapter 6.

# CHAPTER 7

# CONCLUSIONS

# 7.0 Conclusions

Magnetorheological (MR) fluids are liquid materials whose consistency is strongly influenced by magnetic fields. This behaviour can be utilized for a large number of applications in various technological fields like vibration damping, clutches, actuators and haptic devices. The basic properties of MR fluids which change their rheological behaviour in the presence of a magnetic field are described. In this study, special equipment was designed and set-up to carry out experiments in compression and tension modes. The design was assisted via Finite Element Method Magnetics (FEMM) software package. The equipment was capable of varying the strength of the magnetic field by changing the electric current values supplied to the coil. Combinations of process parameters of initial gap size, applied current and speed were used in both compression and tension processes. For each experiment, the speed and the current in the coil were kept constant, while the instantaneous forces and displacements were recorded. In addition, three types of MR fluids were used in these experiments; namely MRF-241ES, a water-based MR fluid, and MRF-132DG and MRF-122-2ED, hydrocarbon-based MR fluids. Results, mainly in terms of stress-strain relationships were presented and discussed. The conclusions of the study are listed in the following:

# I. Test rig

The test rig was a type of uniaxial testing in either compression or tension modes. The primary components of the test rig consisted of an upper cylinder, a lower cylinder and a support cylinder. The main design parameters of the test rig were the selection of materials, dimensions of the cylinders, number of windings around the coil and initial gap size between the flat parallel surfaces of the upper and the lower cylinders. Low carbon steel, type of a magnetic material, was used to make the upper and the lower cylinders, while stainless steel, type of a non-magnetic material, was used to make the support cylinder. A coil made from copper wire, type of 22SWG with 2750 turns was wound around the lower cylinder in order to produce a magnetic field. The diameter of the effective surfaces of the upper and the lower cylinders to contain the tested materials were set to 50.0 mm. The investigated initial gap sizes were 1.0 and 2.0 mm. The clearance between the outer diameter of the upper cylinder and the inner of the

support cylinder was 0.5 mm. A measured amount of the MR fluids was placed between the two parallel flat surfaces. Instron Universal Electromechanical Testing Machine was used to compress or decompress the tested MR fluids in the same direction of the magnetic field. The upper cylinder was either pushed towards or pulled away from the lower cylinder containing the MR fluid between them, and surrounded by a support cylinder. The test rig was observed to be suitable to perform the investigations of the behaviour of MR fluids.

# **II.** Simulation of magnetic fields

A magnetic field finite element analysis for the test rig was conducted using the FEMM software package. The purpose of the analysis was to identify the magnetic field strength of the magnetic circuit and to evaluate the effects of the design parameters on the magnetic flux density in the gap. A number of design changes were simulated in FEMM in order to produce the best value for the magnetic field intensity H, which was mutually related to the magnetic flux density B. Input data in terms of materials selection for each component of the test rig, type of coil, number of turns of the coil wrapping around the core and values of the electric current that runs in the coil were used in FEMM. Subsequent to the most adequate design of the test rig predicted by the simulation, a few changes and modifications on the test rig have been constructed due to certain limitations. Throughout this analysis, an optimized test rig was used to perform the compression and tension tests with maintaining magnetic flux density at given values of the applied current in the gap. Consequently, magnetic flux density was found to distribute evenly in the MR fluids and the air gap. The average maximum values of the magnetic flux density at the centre of the gap were achieved at 0.70, 0.67, 0.61 and 0.47 Tesla for MRF-241ES, MRF-132DG, MRF-122-2ED and air, respectively, taken from the middle half of the test rig. The effects of the applied current (magnetic field) and initial gap size on the magnetic flux density were interdependent. The magnetic flux density increased with increasing the applied current or decreasing the gap size. When increasing the applied current or initial gap size, MRF-241ES showed the least variation in the magnetic flux density, while air in the gap showed the largest variation in the magnetic flux density. Results from the simulations agreed well with the results from the direct measurement.

#### **III.** Behaviour of MR fluids

#### a) General behaviour of the MR fluids under compression

Stress-strain relationships were obtained for a water-based MR fluid (MRF-241ES) and hydrocarbon-based MR fluids (MRF-132DG and MRF-122-2ED) in squeeze mode using compression test equipment. The curves could be divided into three different regions, because of distinct characteristics in the relationship between stress and strain changes as the process was carried out. In the first and third regions the compressive stress increased as the compressive strain increased, whereas in the second region the compressive stress remained almost constant as the compressive strain increased. Some aspects of the phenomenon could be explained by assuming that when the squeeze mode operated to cause the fluid to move, the liquid carrier moved to a greater extent than the solid particles, which were restricted by the magnetic field. In addition, experimental results also emphasized that the magnitude of the compressive stress of MR fluids was strongly affected by the nature of the carrier fluid. The compressive stress in the water-based MR fluid, in response to a given value of the compressive strain, was of greater magnitude than the compressive stress in the hydrocarbon-based MR fluids corresponding to the same compressive strain. This result, occurring at the same value of the magnetic field strength, was probably due to the higher ratio of solids-to-liquid in the water-based fluid compared to the hydrocarbon-based fluids.

#### b) Compression behaviour of hydrocarbon-based MR fluids

During compression, the MRF-241ES fluid showed a more stable behaviour. MRF-132DG and MRF-122-2ED experienced a very sudden drop in the compressive stress, in a region where the compressive stress would be expected to rise steadily, before proceeding to increase again abruptly. The pressure drop phenomenon could be caused by air bubbles, where a substantial number of chains were found being broken in a very short period of time. The same pressure drop was observed when the experiments were repeated. This phenomenon would suggest that the same amount of air bubbles were present again and were expelled in the same way.

#### c) General behaviour of the MR fluids under tension

Stress-strain curves of the MR fluids under tension process could be divided into three regions. In the first region, the tensile stress curves increased drastically to a peak point, with increases of the compressive strain. Then, in the second region, the tensile stress decreased with increasing tensile strain. Finally, in the third region, the tensile stress further decreased slowly, with further elongation. Similar assumptions about the relative movement between the particles and the carrier fluid under the compression process can be made to describe the behaviour of the MR fluids under the tension mode. The tension process was a relationship between structure strengthening effect and decreasing magnetic field. Structure strengthening effect was due to particle chains restructuring, while decreasing magnetic field was due to the gap widening between the two flat parallel surfaces. The maximum value of the tensile stress in the water-based MR fluid was of greater magnitude than those of the hydrocarbon-based MR fluids. Furthermore, the tensile stress reached the maximum value at a higher tensile strain in the water-based MR fluid as compared to the hydrocarbon-based MR fluids. These results were comparable to the MR fluids under compression. These observations were apparently due to the higher ratio of solids-to-liquid in the water-based MR fluid when compared to the hydrocarbon-based MR fluids.

#### IV. Effects of various factors on the MR fluids

The results were presented starting with different electrical currents to generate magnetic fields, using different initial gap sizes and compressive or tensile speeds. The results revealed that high values of stress occurred where the strain was high, and that even higher values were obtained when the electrical current was high. Furthermore, the magnitude of the stress, for a given strain, depended on the initial gap size. Curves showing the relationships between the stress and the strain were constructed for two different initial gap sizes. In compression, it was seen that, for larger initial gap sizes, there were larger stress values. In the first two regions, the stress seemed to be almost independent of the value of the

electrical current generating the magnetic field. Furthermore, in the third region, higher values of the stress occurred when the electrical current was higher. However, the effect of the initial gap size under tension tests was contradicted with the same effect under compression tests. For smaller initial gap sizes, there were larger stress values. The sizes of the three regions depended on the initial gap sizes. In addition, the compressive or tensile speed had a small effect on the stress-strain relationship which was considered as being neglected.

# V. Comparison between compressive and tensile stresses of the MR fluids

The relationship between the stresses and the magnetic flux density at maximum values of the first region could be represented by a general linear equation. The compressive stresses were found to be much higher than the tensile stresses for the same experimental parameters throughout this study. On the other hand, combinations of the stress-displacement curves in compression and tension modes were assumed to be similar with the stress-strain curves under dynamic loading. The damping performance of the water-based MR fluid was found to be higher than that of the hydrocarbon-based MR fluids. The damping performance was greater at a low initial gap size. Furthermore, the maximum stresses obtained in the compression mode were much greater than those obtained in the tension mode at a given displacement of 0.5 mm.

#### 7.1 Contributions of the thesis

In this thesis, the problem of lack of investigation of individual compression and tension behaviour in terms of stress-strain relationship has been addressed. In order to enhance the knowledge regarding this matter, the behaviour of MR fluids under squeeze mode has been studied thoroughly. The results obtained from the compression and tension processes showed that MR fluids have potentials in many applications that require controlling small, millimetre-order movements but involving large stresses. Consequently, the contributions of this thesis are listed in the following:

a) This thesis contributed to the experimental results of the MR fluids using a constructed test rig under compression mode. This was the first time that a

unique behaviour of the MR fluids had been demonstrated. The behaviour of the MR fluids in terms of stress-strain relationships could be divided into three different regions. This was because of the distinct characteristics in the relationship between stress and strain changes.

- b) The second contribution was related to the behaviour of the hydrocarbon-based MR fluids. During the compression process, the hydrocarbon-based MR fluids appeared to show a distinct behaviour where an abrupt pressure drop was discovered in a region where the compressive stress would be expected to increase steadily.
- c) The third contribution was the description of the MR fluids' behaviour during the experiments. The behaviour was reasonably explained by the relative movement between the solid magnetic particles and the carrier liquid in the MR fluids. The explanation can be utilized in both modes; compression and tension.

# 7.2 **Recommendations for future work**

The results in this thesis lay the groundwork for a good understanding of the behaviour of the MR fluids under squeeze mode. Following these investigations, there are some extensions to this work that would help expand and strengthen the results, involving the modification of the test rig:

- a) Further study of the conformational behaviour of the MR fluid under squeeze mode. Different ratios of the amount of solid particles to the amount of liquid in the same MR fluid could be performed in order to gain understanding regarding the behaviour of the fluid.
- b) Further investigation of the phenomenon regarding the relative movement between the solid particles and the carrier liquid in the MR fluid during the compression and tension processes. This can be done by using scanning electron
microscopy (SEM) to estimate the average particle size, particle size distribution, shape and surface morphology of the particles.

- c) It would be interesting to model the field-responsive behaviour of MR fluids to describe the mechanism of stress formation during the compression and tension processes. The model would assist characterizing the physics behind the interaction between the solid magnetic particles and the magnetic field and may help developing new materials with improved performance.
- d) Further improvement of the test rig design where the volume of tested materials would be constrained in the gap between the two flat parallel surfaces. The new design could be achieved by avoiding the clearance, in this case, the gap between the outer diameter of the upper cylinder and the inner diameter of the support cylinder. Therefore, this arrangement could be adopted to deal effectively with the compression and tension processes.
- e) To investigate the achievable stresses when two working modes, such as compression and shear modes combined. The process is called compression-assisted-aggregation and it employs forcing MR fluid to form a new microstructure that is much stronger than the existing structure. It can be done by compressing the MR fluid until the compressive strain reaches the third region of stress-strain relationship before shear stress is applied. This stress process is recommended for the clutch applications.

## References

- N. D. Sims, R. Stanway and A. R. Johnson, Vibration Control Using Smart Fluids: A State-of-the-Art Review, The Shock and Vibration Digest, Vol. 31, No. 3, 1999, 195-203.
- [2] M. R. Jolly, J. W. Bender and J. D. Carlson, Properties and Applications of Commercial Magnetorheological Fluids, Journal of Intelligent Material Systems and Structures, Vol. 10, No. 1, 1999, 5-13.
- [3] M. Hagenbuchle and J. Liu, Chain Formation and Chain Dynamics in a Dilute Magnetorheological Fluid, Applied Optics, Vol. 36, No. 30, 1997, 7664-7671.
- [4] A. G. Olabi and A. Grunwald, Design and Application of Magneto-Rheological Fluid, Materials and Design, Vol. 28, No. 10, 2007, 2658-2664.
- [5] R. Bolter and H. Janocha, Design Rules for MR Fluid Actuators in Different Working Modes, in proceedings of the SPIE, Symposium on Smart Structures and Materials, Vol. 3045, 1997, 148-159.
- [6] J. Huang, J. Q. Zhang, Y. Yang and Y. Q. Wei, Analysis and Design of a Cylindrical Magneto-Rheological Fluid Brake, Journal of Materials Processing Technology, Vol. 129, Nos. 1-3, 2002, 559-562.
- [7] J. -H. Yoo and N. M. Wereley, Design of a High-Efficiency Magnetorheological Valve, Journal of Intelligent Material Systems and Structures, Vol. 13, 2002, 679-685.
- [8] Y. Tian, Y. Meng, H. Mao and S. Wen, Electrorheological Fluid Under Elongation, Compression, and Shearing, Physical Review E, Vol. 65, No. 3, 2002, 031507.
- [9] A. Lukkarinen and K. Kaski, Computational Studies of Compressed and Sheared Electrorheological Fluid, Journal of Physics D: Applied Physics, Vol. 29, 1996, 2729-2732.
- [10] G. J. Monkman, The Electrorheological Effect under Compressive Stress, Journal Physics D: Applied Physics, Vol. 28, 1995, 588-593.
- [11] Y. Tian, Y. Meng, H. Mao and S. Wen, Mechanical Property of Electrorheological Fluid Under Step Compression, Journal of Applied Physics, Vol. 92, No. 11, 2002, 6875-6879.
- [12] Y. Tian and Q. Zou, Normalized Method for Comparing Tensile Behaviors of Electrorheological Fluids, Applied Physics Letters, Vol. 82, No. 26, 2003, 4836-4838.
- Y. Tian, Q. Zou, Y. Meng and S. Wen, Tensile Behavior of Electrorheological Fluids Under Direct Current Electric Fields, Journal of Applied Physics, Vol. 94, No. 10, 2003, 6939-6944.

- [14] Y. Tian, S. Wen, and Y. Meng, Compressions of Electrorheological Fluids Under Different Initial Gap Distances, Physical Review E, Vol. 67, No. 5, Part 1, 2003, 051501.
- [15] M. Nilsson and N. G. Ohlson, An Electrorheological Fluid in Squeeze Mode, Journal of Intelligent Material Systems and Structures, Vol. 11, 2000, 545-554.
- [16] P. Kulkarni, C. Ciocanel, S. L. Vieira and N. Naganathan, Study of the Behavior of MR Fluids in Squeeze, Torsional and Valve Modes, Journal of Intelligent Material Systems and Structures, Vol. 14, 2003, 99-104.
- [17] S. B. Choi, H. J. Choi, Y. T. Choi and N. M. Wereley, Preparation and Mechanical Characteristics of Poly(methylaniline) Based Electrorheological Fluid, Journal of Applied Polymer Science, Vol. 96, 2005, 1924-1929.
- [18] S. Genc and P. Phule, Rheological Properties of Magnetorheological Fluids, Smart Materials and Structures, Vol. 11, 2002, 140-146.
- [19] P. Forte, M. Paternò and E. Rustighi, A Magnetorheological Fluid Damper for Rotor Applications, International Journal of Rotating Machinery, Vol. 10, No. 3, 2004, 175-182.
- [20] Y. K. Ahn, J. -Y. Ha and B. -S. Yuk, A New Type Controllable Squeeze Film Damper Using an Electromagnet, Journal of Vibration and Acoustics, Vol. 126, 2004, 380-383.
- [21] C. Carmignani, P. Forte and E. Rustighi, Design of a Novel Magneto-Rheological Squeeze-Film Damper, Smart Materials and Structures, Vol. 15, No. 1, 2006, 164-170.
- [22] J. Wang, G. Meng, N. Feng, and E. J. Hahn, Dynamic Performance and Control of Squeeze Mode MR Fluid Damper-Rotor System, Smart Materials and Structures, Vol. 14, No. 4, 2005, 529-539.
- [23] J. Wang, N. Feng, G. Meng and E. J. Hahn, Vibration Control of Rotor by Squeeze Film Damper with Magnetorheological Fluid, Journal of Intelligent Material Systems and Structures, Vol. 17, 2006, 353-357.
- [24] S. L. Vieira, C. Ciocanel, P. Kulkarni, A. Agrawal and N. Naganathan, Behaviour of MR Fluids in Squeeze Mode, International Journal of Vehicle Design, Vol. 33, Nos. 1-3, 2003, 36-49.
- [25] R. Lane and B. Craig, Materials That Sense and Respond: An Introduction to Smart Materials, The AMPTIAC Quarterly, Vol. 7, No. 2, 2003, 9-14.
- [26] S. Saadat, J. Salichs, M. Noori, Z. Hou, H. Davoodi, I. Bar-on, Y. Suzuki and A. Masuda, An Overview of Vibration and Seismic Applications of NiTi Shape Memory Alloy, Smart Materials and Structures, Vol. 11, 2002, 218-229.

- [27] S. B. Lang, Pyroelectric Applications of Ferroelectric Polymers, in proceedings of the 6<sup>th</sup> International Symposium on (IEEE Cat. No. 88CH2593-2), Electrets, Oxford, UK, 1988, 251-255.
- [28] G. Park, H. Sohn, C. R. Farrar and D. J. Inman, Overview of Piezoelectric Impedance-Based Health Monitoring and Path Forward, The Shock and Vibration Digest, Vol. 35, No. 6, 2003, 451-463.
- [29] C. Niezrecki, D. Brei, S. Balakrishnan and A. Moskalik, Piezoelectric Actuation: State of the Art, The Shock and Vibration Digest, Vol. 33, No. 4, 2001, 269-280.
- [30] S. -S. Kwon, U. -Y. Lee, S. -G. Park, K. -J. Lim, H. -H. Kim, D. -H. Park and B. -H. Ryu, Electrical and Luminant Properties in Powder Type Electroluminescent Device, in proceedings of the 5<sup>th</sup> International Conference on Properties and Applications of Dielectric Materials, Seoul, Korea, 1997, 620-623.
- [31] T. Kubo, T. Shinada, Y. Kobayashi, H. Imafuku, T. Toya, S. Akita, Y. Nishikitani and H. Watanabe, Current State of the Art for NOC-AGC electrochromic Windows for Architectural and Automotive Applications, Solid State Ionics, Vol. 165, 2003, 209-216.
- [32] R. Stanway, J. L. Sproston and A. K. El-Wahed, Applications of Electro-Rheological Fluids in Vibration Control: A Survey, Smart Materials and Structures, Vol. 5, 1996, 464-482.
- [33] M. Hu, H. Du, S. -F. Ling, Z. Zhou and Y. Li, Motion Control of an Electrostrictive Actuator, Mechatronics, Vol. 14, 2004, 153-161.
- [34] Y. Bar-Cohen, Electroactive Polymers (EAP) as Actuators for Potential Future Planetary Mechanisms, in proceedings of the 2004 NASA/DoD Conference on Evolution Hardware (EH'04), IEEE Computer Society, Seattle, USA, 2004, 1-9.
- [35] F. D. Goncalves, J. -H. Koo and M. Ahmadian, 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, Vol. 38, No. 3, 2006, 203-219.
- [36] M. Kroell, M. Pridoehl, G. Zimmermann, L. Pop, S. Odenbach and A. Hartwig, Magnetic and Rheological Characterization of Novel Ferrofluids, Journal of Magnetism and Magnetic Materials, Vol. 289, 2005, 21-24.
- [37] F. T. Calkins, A. B. Flatau and M. J. Dapino, Overview of Magnetostrictive Sensor Technology, Journal of Intelligent Materials Systems and Structures, Vol. 18, No. 10, 2007, 1057-1066.

- [38] N. B. Ekreem, A. G. Olabi, T. Prescott, A. Rafferty and M. S. J. Hashmi, An Overview of Magnetostriction, Its Use and Methods to Measure these Properties, Journal of Materials Processing Technology, Vol. 191, 2007, 96-101.
- [39] J. D. Carlson and M. R. Jolly, MR Fluid, Foam and Elastomer Devices, Mechatronics, Vol. 10, Nos. 4-5, 2000, 555-569.
- [40] P. P. Phule, Magnetorheological (MR) Fluids: Principles and Applications, Smart Materials Bulletin, Vol. 2001, No. 2, 2001, 7-10.
- [41] O. Ashour, C. A. Rogers and W. Kordonsky, Magnetorheological Fluids: Materials, Characterization, and Devices, Journal of Intelligent Material Systems and Structures, Vol. 7, No. 2, 1996, 123-130.
- [42] J. D. Carlson, D. M. Catanzarite and K. A. St. Clair, Commercial Magnetorheological Fluid Devices, in proceedings of the 5<sup>th</sup> International Conference on ER Fluids, MR Suspensions and Associated Technology, World Scientific, Singapore, 1996, 20-28.
- [43] S. P. Kelso, Experimental Characterization of Commercially Practical Magnetorheological Fluid Damper Technology, in proceedings of the SPEE Conference on Smart Structures and Materials, Newport Beach, CA, 2001, 4332-4339.
- [44] J. Wang and G. Meng, Magnetorheological Fluid Devices: Principles, Characteristics and Applications in Mechanical Engineering, in proceedings of the Institution of Mechanical Engineers, Part L, Journal of Materials: Design and Applications, Vol. 215, 2001, 165-174.
- [45] D. J. Klingenberg, Magnetorheology: Applications and Challenges, AIChE Journal, Vol. 47, No. 2, 2001, 246-249.
- [46] J. H. Park and O. O. Park, Electrorheology and Magnetorheology, Korea-Australia Journal, Vol. 13, No. 1, 2001, 13-17.
- [47] Lord Corporation, www.Mrfluid.com, 23/01/2005.
- [48] S. Genc, Synthesis and Properties of Magnetorheological (MR) Fluids, Ph.D. Thesis, School of Engineering, University of Pittsburgh, 2002.
- [49] M. A. Golden, J. C. Ulicny, K. S. Snavely and A. L. Smith, Magnetorheological Fluids, US Patent 6932917, 2005.
- [50] J. A. Starkovich and E. M. Shtarkman, High Yield Stress Magnetorheological Material for Specacraft Applications, US Patent 6610404, 2003.
- [51] J. Rabinow, The Magnetic Fluid Clutch, Transactions of the AIEE, Vol. 67, 1948, 1308-1315.

- [52] J. H. Park, M. H. Kwon and O. O. Park, Rheological Properties and Stability of Magnetorheological Fluids using Viscoelastic Medium and Nanoadditives, Korean Journal of Chemical Engineering, Vol. 18, No. 5, 2001, 580-585.
- [53] J. Claracq, J. Sarrazin and J. -P. Montfort, Viscoelastic Properties of Magnetorheological Fluids, Rheologica Acta, Vol. 43, 2004, 38-43.
- [54] G. Song and M. Zeng, A Thin-Film Magnetorheological Fluid Damper/Lock, Smart Materials and Structures, Vol. 14, 2005, 369-375.
- [55] P. J. Rankin, A. T. Horvath and D. J. Klingenberg, Magnetorheology in Viscoplastic Media, Rheological Acta, Vol. 38, 1999, 471-477.
- [56] S. T. Lim, M. S. Cho, I. B. Jang, H. J. Choi and M.S. Jhon, Magnetorheology of Carbonyl-Iron Suspensions with Submicron-Sized Filler, IEEE Transactions on Magnetics, Vol. 40, No. 40, 2004, 3033-3035.
- [57] J. S. Choi, B. J. Park, M. S. Cho and H. J. Choi, Preparation and Magnetorheological Characteristics of Polymer Coated Carbonyl Iron Suspensions, Journal of Magnetism and Magnetic Materials, Vol. 304, 2006, e674-e376.
- [58] N. M. Wereley, A. Chaudhuri, J. -H. Yoo, S. John, S. Kotha, A. Suggs, R. Radhakrisnan, B. J. Love and T. S. Sudarshan, Bidisperse Magnetorheological Fluids using Fe Particles at Nanometer and Micron Scale, Journal of Intelligent Material and Structures, Vol. 17, 2006, 393-401.
- [59] H. Bose and A. Trendler, Smart Fluids Properties and Benefit for New Electromechanical Devices, AMAS Workshop on Smart Materials and Structures, SMART'03, Jadwisin, 2003, 329-336.
- [60] T. Shiraishi, S. Morishita and H. P. Gavin, Estimation of Equivalent Permeability in Magnetorheological Fluid Considering Cluster Formation of Particles, Journal of Applied Mechanics, Transactions of the ASME, Vol. 71, No. 2, 2004, 201-207.
- [61] G. Bossis, S. Lacis, A. Meunier and O. Volkova, Magnetorheological Fluids, Journal of Magnetism and Magnetic Materials, Vol. 252, 2002, 224-228.
- [62] K. Kim and D. Jeon, Vibration Suppression in an MR Fluid Damper Suspension System, Journal of Intelligent Material Systems and Structures, Vol. 10, 1999, 779-786.
- [63] Liquids Research Limited, www.liquidsresearch.com, 23/01/2005.
- [64] A. W. Duff, Viscosity of Polarized Dielectrics, Physical Review (Series I), Vol. 4, 1896, 23-38.

- [65] W. M. Winslow, Method and Means for Translating Electrical Impulses into Mechanical Force, US Patent 2417850, 1947.
- [66] W. M. Winslow, Induced Fibration of Suspensions, Journal of Applied Physics, Vol. 20, 1949, 1137-1140.
- [67] D. L. Klass and T. W. Martinek, Electroviscous Fluids. I. Rheological Properties, Journal of Applied Physics, Vol. 38, No. 1, 1967, 67-74.
- [68] K. K. Mekela, Characterization and Performance of Electrorheological Fluids Based on Pipe Oils, Journal of Intelligent Material Systems and Structures, Vol. 10, 1999, 609-614.
- [69] N. Umamori, M. Arai, M. Kanbara and M. Hayafune, Electrorheological Fluid Containing Silica Particles Esterified by an Alcohol-Modified Silicone Oil, US Patent 5925288, 1999.
- [70] F. E. Filisko, S. Henley and G. Quist, Recent Development in the Properties and Composition of Electrorheological Fluids, Journal of Intelligent Material Systems and Structures, Vol. 10, 1999, 476-480.
- [71] X. Duan, H. Chen, Y. He and W. Luo, Enhancing Yield Stress of Electrorheological Fluids with Liquid Crystal Additive, Journal of Physics D: Applied Physics, Vol. 33, 2000, 696-699.
- [72] C. Shen, W. Wen, S. Yang and P Sheng, Wetting-Induced Electrorheological Effect, Journal of Applied Physics, Vol. 99, 2006, 106104.
- [73] H. Block and J. P. Kelly, Electro-Rheology, Journal of Physics D: Applied Physics, Vol. 21, 1988, 1661-1677.
- [74] L. Zhang, K. Su and X. Li, Electrorheological Effects of Polyaniline-Type Electrorheological Fluids, Journal of Applied Polymer Science, Vol. 87, 2003, 733-740.
- [75] X. Duan, W. Luo, H. Chen and Y. He, The Effect of Particle Shape on Water-Free Mica ER fluids, Journal of Intelligent Material Systems and Structures, Vol. 11, 2000, 43-46.
- [76] S. -B. Choi, S. -R. Hong, C. -C. Cheong and Y. -K. Park, Comparison of Field-Controlled Characteristics between ER and MR Clutches, Journal of Intelligent Material Systems and Structures, Vol. 10, 1999, 615-619.
- [77] A. K. El Wahed, J. L. Sproston and G. K. Schleyer, A Comparison between Electrorheological and Magnetorheological Fluids Subjected to Impulsive Loads, Journal of Intelligent Material Systems and Structures, Vol. 10, 1999, 695-700.

- [78] C. Scherer and A. M. F. Neto, Ferrofluids: Properties and Applications, Brazilian Journal of Physics, Vol. 35, No. 3A, 2005, 718-727.
- [79] J. Popplewell, Technological Applications of Ferrofluids, Physics in Technology, Vol. 15, No. 3, 1984, 150-156.
- [80] K. Butter, P. H. Bomans, P. M. Frederik, G. J. Vroege, and A. P. Philipse, Direct Observation of Dipolar Chains in Ferrofluids in Zero Field Using Cryogenic Electron Microscopy, Journal of Physics Condensed Matter, Vol. 15, No. 15, 2003, S1451-S1470.
- [81] J. Liu, E. M. Lawrence, A. Wu, M. L. Ivey, G. A. Flores, K. Javier, J. Bibette and J. Richard, Field-Induced Structures in Ferrofluid Emulsions, Physical Review Letters, Vol. 74, No. 14, 1995, 2828-2832.
- [82] E. Lemaire, Y. Grasselli and G. Bossis, Field Induced Structure in Magneto and Electro-Rheological Fluids, Journal De Physique II, Vol. 2, 1992, 359-369.
- [83] D. R. Askeland, The Science and Engineering of Materials, 3<sup>rd</sup> Ed., Chapman and Hall, London, 1996.
- [84] F. T. Ulaby, Fundamentals of Applied Electromagnetics, Prentice Hall, Upper Saddle: New Jersey, 1997.
- [85] G. L. Gulley and R. Tao, Structures of an Electrorheological Fluid, Physical Review E, Vol. 56, No. 4, 1997, 4328-4336.
- [86] W. D. Callister Jr., Materials Science and Engineering: An Introduction, 3<sup>rd</sup> Ed., John Wiley and Sons, Inc., New York, 1994.
- [87] A. Ramesh, M. R. Govindaraju, D. C. Jiles, and S. B. Biner, Magnetic Property Variations in Nickel Caused by Non-Magnetic Inclusions, IEEE Transactions on Magnetics, Vol. 32, No. 5, Part 2, 1996, 4836-4838.
- [88] S. Takahashi, L. Zhang and T. Ueda, Magnetic Hysteresis Minor Loops in Fe Single Crystal, Journal of Physics Condensed Matter, Vol. 15, No. 46, 2003, 7997-8002.
- [89] J. D. Kraus, Electromagnetics, International Edition, 4<sup>th</sup> Edition, Mc-Graw-Hill Inc., Singapore, 1991.
- [90] A. Nicolaides, Electrical and Electronic Principles II, 2<sup>nd</sup> Ed., PASS Publications, London, 1996.
- [91] A. K. Giri, K. M. Chowdary and S. A. Majetich, AC Magnetic Properties of Compacted FeCo Nanocomposites, Materials Physics and Mechanics, Vol. 1, 2000, 1-10.

- [92] B. C. Munoz, G. W. Adams, V. T. Ngo and J. R. Kitchin, Stable Magnetorheological Fluids, US Patent 6203717, 2001.
- [93] C. Fang, B. Y. Zhao, L. S. Chen, Q. Wu, N. Liu and K. A. Hu, The Effect of the Green Additive Guar Gum on the Properties of Magnetorheological Fluid, Smart Materials and Structures, Vol. 14, No. 1, 2005, N1-N5.
- [94] E. H. Carman, Technical Properties of Iron Powder Magnets, British Journal of Applied Physics, Vol. 6, 1955, 426-429.
- [95] M. R. Jolly, J. D. Carlson and B. C. Muñoz, A Model of the Behaviour of Magnetorheological Materials, Smart Materials and Structures, Vol. 5, 1996, 607-614.
- [96] J. Rabinow, Magnetic Fluid Torque and Force Transmitting Device, US Patent 2575360, 1951.
- [97] W. A. Gross, Valve for Magnetic Fluids, US Patent 3010471, 1961.
- [98] J. Rabinow, Magnetic Fluid Shock Absorber, US Patent 2667237, 1954.
- [99] E. Germer, Magnetic Valve, US Patent 2670749, 1954.
- [100] H. -J. Pan, H. -J. Huang, L. -Z. Zhang, J. -Y Qi and S. -K. Cao, Rheological Properties of Magnetorheological Fluid Prepared by Gelatin-Carbonyl Iron Composite Particles, Journal of Central South University of Technology, Vol. 12, No. 4, 2005, 411-415.
- [101] J. D. Carlson, What Makes a Good MR Fluid? Journal of Intelligent Material Systems and Structures, Vol. 13, Nos. 7-8, 2002, 431-435.
- [102] P. P. Phulé, Magnetorheological Fluid, US Patent 5985168, 1999.
- [103] J. H. Park, B. D. Chin and O. O. Park, Rheological Properties and Stabilization of Magnetorheological Fluids in a Water-in-Oil Emulsion, Journal of Colloid and Interface Science, Vol. 240, No. 1, 2001, 349-354.
- [104] Y. Qi, L. Zhang and W. Wen, Anisotropy Properties of Magnetic Colloidal Materials, Journal of Physics D: Applied Physics, Vol. 36, 2003, L10-L14.
- [105] B. -J. de Gans, H. Hoekstra and J. Mellema, Non-Linear Magnetorheological Behaviour of an Inverse Ferrofluid, Faraday Discussions, Vol. 112, 1999, 209-224.
- [106] T. E. Faber, Fluid Dynamics for Physicists, Cambridge University Press, Cambridge: UK, 1995.
- [107] N. de Nevers, Fluid Mechanics for Chemical Engineers, 2<sup>nd</sup> Ed., McGraw-Hill Inc., New York, 1991.

- [108] I. H. Shames, Mechanics of Fluids, 3<sup>rd</sup> Ed., McGraw-Hill Inc., New York, 1992.
- [109] S. J. Dyke, B. F. Spencer Jr., M. K. Sain and J. D. Carlson, An Experimental Study of MR Dampers for Seismic Protection, Smart Materials and Structures, Vol. 7, 1998, 693-703.
- [110] L. E. Nielson, Polymer Rheology, Marcel Dekker Inc., New York, 1977.
- [111] C. A. Shook, Slurry Pipeline Flow, in Processing of Solid-Liquid Suspensions, edited by P. A. Shamlou, Butterworth-Heinemann, 1993, 287-309.
- [112] K. Toda and H. Furuse, Extension of Einstein's Viscosity Equation to That for Concentrated Dispersions of Solutes and Particles, Journal of Bioscience and Bioengineering, Vol. 102, No. 6, 2006, 524-528.
- [113] J. F. Douglas, J. M. Gasiorek and J. A. Swaffield, Fluid Mechanics, 3<sup>rd</sup> Ed., Longman Scientific & Technical, Harlow Essex, UK, 1995.
- [114] B. S. Massey, Mechanics of Fluids, 6<sup>th</sup> Ed., Chapman & Hall, London, 1989.
- [115] Y. Grasselli, G. Bossis and E. Lemaire, Structure Induced in Suspensions by a Magnetic Field, Journal De Physique II, France 4, 1994, 253-263.
- [116] H. Nishiyama, S. Fushimi and M. Nakano, Numerical Simulation of MR Fluid Damping Characteristics Using a Modified Bingham Model, Journal of Intelligent Material Systems and Structures, Vol. 13, 2002, 647-653.
- [117] T. Butz and O. von Stryk, Modelling and Simulation of Electro- and Magnetorheological Fluid Dampers, Zeitschrift Fur Angewandte Mathematik Und Mechanik, Vol. 82, 2002, 3-20.
- [118] J. M. Gere and S. P. Timonshenko, Mechanics of Materials, 3<sup>rd</sup> Ed., PWS-KENT Publishing Company, Boston, 1990.
- [119] K. Goldsmith, Note on the Rheological Properties of Elasto-Plastic Materials, British Journal of Applied Physics, Vol. 1, No. 4, 1950, 107-109.
- [120] J. D. Carlson and K. D. Weiss, Magnetorheological Materials Based on Alloy Particles, US Patent 5382373, 1995.
- [121] R. T. Foister, Magnetorheological Fluids, US Patent 5667715, 1997.
- [122] A. A. Zaman and C. S. Dutcher, Viscosity of Electrostatically Stabilized Dispersions of Monodispersed, Bimodal, and Trimodal Silica Particles, Journal of the American Ceramic Society, Vol. 89, No. 2, 2006, 422-430.
- [123] P. Carletto, and G. Bossis, Field-Induced Structures and Rheology of a Magnetorheological Suspension Confined Between Two Walls, Journal of Physics Condensed Matter, Vol. 15, No. 15, 2003, S1437-S1449.

- [124] T. Ukai and T. Maekawa, Patterns Formed by Paramagnetic Particles in a Horizontal Layer of a Magnetorheological Fluid Subjected to a DC Magnetic Field, Physical Review E, Statistical, Nonlinear, and Soft Matter Physics, Vol. 69, No. 3, Part 1, 2004, 032501.
- [125] T. M. Simon, F. Reitich, M. R. Jolly, K. Ito and H. T. Banks, The Effective Magnetic Properties of Magnetorheological Fluids, Mathematical and Computer Modelling, Vol. 33, Nos. 1-3, 2001, 273-284.
- [126] R. H. Davis, Y. Zhao, K. P. Galvin and H. J. Wilson, Solid-Solid Contacts Due to Surface Roughness and Their Effects on Suspension Behaviour, Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences, Vol. 361, No. 1806, 2003, 871-894.
- [127] N. C. Rosenfeld and N. M. Werely, Volume-Contrained Optimization of Magnetorheological Valves and Dampers, Smart Materials and Structures, Vol. 13, 2004, 1303-1313.
- [128] A. Milecki, Investigation and Control of Magneto-Rheological Fluid Dampers, International Journal of Machine Tools & Manufacture, Vol. 41, No. 3, 2001, 379-391.
- [129] J. -H. Yoo, J. Sirohi and N. M. Wereley, A Magnetorheological Piezohydraulic Actuator, Journal of Intelligent Material Systems and Structures, Vol. 16, 2005, 645-953.
- [130] A. Grunwald, Design and Optimization of Magnetostrictive Actuator, Ph.D. Thesis, School of Mechanical and Manufacturing Engineering, Dublin City University, 2007.
- [131] S. Sassi, K. Cherif, L. Mezghani, M. Thomas and A. Kotrane, An Innovative Magnetorheological Damper for Automotive Suspension: From Design to Experimental Characterization, Smart Materials and Structures, Vol. 14, No. 4, 2005, 811-822.
- [132] S. F. Masri, R. Kumar and R. C. Ehrgott, Modeling and Control of an Electrorheological Device for Structural Control Applications, Smart Materials and Structures, Vol. 4, 1995, A121-A131.
- [133] B. F. Spencer Jr., S. J. Dyke, M. K. Sain and J. D. Carlson, Phenomenological Model of a Magnetorheological Damper, Journal of Engineering Mechanics, ASCE, Vol. 123, 1997, 230-138.
- [134] A. Dominguez, R. Sedagahati and I. Stiharu, Modelling the Hysteresis Phenomena of Magnetorheological Dampers, Smart Materials and Structures, Vol. 13, 2004, 1351-1361.

- [135] F. Ikhouane and S. J. Dyke, Modeling and Identification of a Shear Mode Magnetorheological Damper, Smart Materials and Structures, Vol. 16, 2007, 605-616.
- [136] D. -Y. Lee, Y. -T. Choi and N. M. Wereley, Performance Analysis of ER/MR Impact Damper Systems Using Herschel-Bulkley Model, Journal of Intelligent Material Systems and Structures, Vol. 13, 2002, 525-531.
- [137] J. An and D. -S. Kwon, Modeling of a Magnetorheological Actuator Including Magnetic Hysteresis, Journal of Intelligent Material Systems and Structures, Vol. 14, 2003, 541-550.
- [138] V. A. Neelakantan and G. N. Washington, Modeling and Reduction of Centrifuging in Magnetorheological (MR) Transmission Clutches for Automotive Applications, Journal of Intelligent Material Systems and Structures, Vol. 16, 2005, 703-711.
- [139] I. -R. Park, Automobile Brake Device, US Patent 2002/0074196 A1, 2002.
- [140] P. L. Wong, W. A. Bullough, C. Feng and S. Lingard, Tribological Performance of a Magneto-Rheological Suspension, Wear, Vol. 247, No. 1, 2001, 33-40.
- [141] R. Stanway, J. L. Sproston, M. J. Prendergast, J.R. Case and C. E. Wilne, ER Fluids in the Squeeze-Flow Mode: An Application to Vibration Isolation, Journal of Electrostatics, Vol. 28, No. 1, 1992, 89-94.
- [142] J. L. Sproston, S. G. Rigby, E. W. Williams and R. Stanway, A Numerical Simulation of Electrorheological Fluids in Oscillatory Compressive Squeeze-Flow, Journal of Physics D: Applied Physics, Vol. 27, 1994, 338-343.
- [143] J. L. Sproston, A. K. El Wahed and R. Stanway, Electrorheological Fluids in Dynamic Squeeze Flow, in proceedings of the IEEE International Conference on Conduction & Breakdown in Dielectric Liquids, ICDL, Roma, Italy, 1996, 515-519.
- [144] A. K. El Wahed, J. L. Sproston and R. Stanway, Performance of an Electrorheological Fluid in Dynamic Squeeze Flow Under Constant Voltage and Constant Field, Journal of Physics D: Applied Physics, Vol. 31, No. 20, 1998, 2964-2974.
- [145] A. K. El Wahed, J. L. Sproston and R. Stanway, The Rheological Characteristics of Electrorheological Fluids in Dynamic Squeeze, Journal of Intelligent Material Systems and Structures, Vol. 13, 2002, 655-660.
- [146] A. K. El Wahed, J. L. Sproston, R. Stanway and E. W. Williams, An Improved Model of ER Fluids in Squeeze-Flow Through Model Updating of the Estimated Yield Stress, Journal of Sound and Vibration, Vol. 268, No. 3, 2003, 581-599.

- [147] S. -P. Yang and K. -Q. Zhu, Analytical Solutions for Squeeze Flow of Bingham Fluid with Navier Slip Condition, Journal of Non-Newtonian Fluid Mechanics, Vol. 138, 2006, 173-180.
- [148] S. R. Hong, S. B. Choi, W. J. Jung and W. B. Jeong, Vibration Isolation of Structural Systems Using Squeeze Mode ER Mounts, Journal of Intelligent Material Systems and Structures, Vol. 13, Nos. 7-8, 2002, 421-424.
- [149] V. Hartel, Spring Element with Hydraulic Damping, US Patent 4773632, 1988.
- [150] C. R. Burrows, N. C. Kucuk, M. N. Sahinkaya and R. Stanway, Linearized Squeeze-Film Dynamics: A Model Structure and the Interpretation of Experimentally Derived Parameters, in proceedings of the Institution of Mechanical Engineers, Part C, Journal of Mechanical Engineering Science, Vol. 204, No. 4, 1990, 263-272.
- [151] K. -J. Kim and C. -W. Lee, Design and Modeling of Semi-Active Squeeze Film Damper Using Magnetorheological Fluid, in proceedings of the 7<sup>th</sup> International Conference on Motion and Vibration Control (MOVIC 2004), Saint Louis, USA, 2004, 1-11.
- [152] N. Sgambelluri, R. Rizzo, E. P. Scilingo, M. Raugi and A. Bicchi, Free Hand Haptic Interfaces Based on Magbetorheological Fluids, in proceedings of the 14<sup>th</sup> International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS 2006), VA, USA, 2006, 367-371.
- [153] M. Farshad and M. Le Roux, Compression Properties of Magnetostrictive Polymer Composite Gels, Polymer Testing, Vol. 24, No. 2, 2005, 163-168.
- [154] Y. Tian, M. Zhang, Y. Meng and S. Wen, Transient Response of Compressed Electrorheological Fluid, Journal of Colloid and Interface Science, Vol. 290, No. 1, 2005, 289-297.
- [155] Y. Meng and F. E. Filisko, Unidirectional Compression of Electrorheological Fluids in Electric Fields, Journal of Applied Physics, Vol. 98, 2005, 074901.
- [156] H. See, S. Mackenzie and B. T. Chua, Effect of Compression on the Response of a Magneto-Rheological Suspension, Korea-Australia Rheology Journal, Vol. 18, No. 3, 2006, 121-126.
- [157] A. Lukkarinen and K. Kaski, Simulation Studies of Electrorheological Fluids under Shear, Compression, and Elongation Loading, Journal of Applied Physics, Vol. 83, 1998, 1717-1725.
- [158] N. M. Wereley and L. Pang, Nondimensional Analysis of Semi-Active Electrorheological and Magnetorheological Dampers Using Approximate Parallel Plate Models, Smart Materials and Structures, Vol. 7, No. 5, 1998, 732-743.

- [159] G. M. Kamath, M. K. Hurt and N. M. Wereley, Analysis and Testing of Bingham Plastic Behavior in Semi-Active Electrorheological Fluid Dampers, Smart Materials and Structures, Vol. 5, No. 5, 1996, 576-590.
- [160] X. Tang, X. Zhang, R. Tao and Y. Rong, Structure-Enhanced Yield Stress of Magnetorheological Fluids, Journal of Applied Physics, Vol. 87, 2000, 2634-2638.
- [161] R. Tao, Super-Strong Magnetorheological Fluids, Journal of Physics: Condensed Matter, Vol. 13, 2001, R979-R999.
- [162] X. Z. Zhang, X. L. Gong, P. Q. Zhang and Q. M. Wang, Study on the Mechanism of the Squeeze-Strengthen Effect in Magnetorheological Fluids, Journal of Applied Physics, Vol. 96, 2004, 2359-2364.
- [163] J. D. Carlson and J. C. JonesGuion, Aqueous Magnetorheological Materials, US Patent 5670077, 1997.
- [164] H. Pu and F. Jiang, Towards High Sedimentation Stability: Magnetorheological Fluids based on CNT/Fe3O4 Nanocomposites, Nanotechnology, Vol. 16, No. 9, 2005, 1486-1489.
- [165] I. B. Jang, H. B. Kim, J. Y. Lee, J. L. You, H. J. Choi and M. S. Jhon, Role of Organic Coating on Carbonyl Iron Suspended Particles in Magnetorheological Fluids, Journal of Applied Physics, Vol. 97, 2005, 10Q912.
- [166] C. Kormann, E. Schwab and M. Laun, Magnetorheological Fluid, US Patent 5505880, 1996.
- [167] IKA RW 20 digital, www.ika.net/ika/home\_ika.html, 09/02/2006.
- [168] D. C. Meeker, Finite Element Method Magnetics, Version 4.0.1 (03Dec2006 Build), http://femm.foster-miller.net, 21/08/2006.
- [169] N. Ida, Engineering Electromagnetics, 2<sup>nd</sup> Ed., Springer Verlag, New York, 2004.
- [170] R. Grossingger, M. Kupferling, P. Kasperkovitz et al., Eddy Currents in Pulsed Field Measurements, Journal of Magnetism and Magnetic Materials, Vols. 242-245, 2002, 911-914.
- [171] J. Bohlmark, M. Ostbye, M. Lattemann, H. Ljungcrantz, T. Rosell and U. Helmersson, Guiding the Deposition Flux in an Ionized Magnetron Discharge, Thin Solid Films, Vol. 515, No. 4, 2006, 1928-1931.
- [172] D. Vasic, V. Bilas and D. Ambrus, Pulsed Eddy-Current Nondestructive Testing of Ferromagnetic Tubes, IEEE Transactions on Instrumentation and Measurement, Vol. 53, No. 4, 2004, 1289-1294.

- [173] Resistance and Resistivity, hyperphysics.phy-astr.gsu.edu/hbase/electric/resis. html, 01/08/2006.
- [174] Tobin, www.tobins.com.au, 06/03/2006.
- [175] S. Bakir, Design and Development of Equipment to Measure the Coefficient of Magnetostriction, M.Sc. Thesis, School of Mechanical and Manufacturing Engineering, Dublin City University, 2004.
- [176] Instron Machine, http://www.dcu.ie/mechanical\_engineering/technical/ postgrad/MaterialsRandD/Instron/Instron.shtml, 10/09/2006.
- [177] Xantrex, Operating Manual, http://www.elgar.com/products/XHR/downloads/ XHR\_RS-232\_User\_Guide\_RSRF-01XN.pdf, 01/08/2006.
- [178] Radionics, Thermocouple Technical Data, http://docs-europe. electrocomponents.com/webdocs/001b/0900766b8001ba88.pdf., 01/08/2006.
- [179] Sypris Test and Measurement, Hand Held Gaussmeter Technical Manual, www.sypris.com/library/documents/5000-Datasheet.pdf., 23/01/2007.

### APPENDICES

#### APPENDIX A

## CAD DRAWINGS



Figure A1: Upper cylinder.



Figure A2: Lower cylinder.



Figure A3: Upper ring.



Figure A4: Lower ring.



Figure A5: Support cylinder.

#### APPENDIX B

# DETAILED COMPRESSION MODE RESULTS



**Figure B1:** Stress-strain relationship of MRF-241ES under compression mode at 2.0 mm initial gap size, 0.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B2:** Stress-strain relationship of MRF-241ES under compression mode at 2.0 mm initial gap size, 1.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B3:** Stress-strain relationship of MRF-241ES under compression mode at 2.0 mm initial gap size, 1.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B4:** Stress-strain relationship of MRF-241ES under compression mode at 2.0 mm initial gap size, 2.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B5:** Stress-strain relationship of MRF-241ES under compression mode at 1.0 mm initial gap size, 0.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B6:** Stress-strain relationship of MRF-241ES under compression mode at 1.0 mm initial gap size, 1.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B7:** Stress-strain relationship of MRF-241ES under compression mode at 1.0 mm initial gap size, 1.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B8:** Stress-strain relationship of MRF-241ES under compression mode at 1.0 mm initial gap size, 2.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B9:** Stress-strain relationship of MRF-132DG under compression mode at 2.0 mm initial gap size, 0.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B10:** Stress-strain relationship of MRF-132DG under compression mode at 2.0 mm initial gap size, 1.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B11:** Stress-strain relationship of MRF-132DG under compression mode at 2.0 mm initial gap size, 1.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B12:** Stress-strain relationship of MRF-132DG under compression mode at 2.0 mm initial gap size, 2.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.


**Figure B13:** Stress-strain relationship of MRF-132DG under compression mode at 1.0 mm initial gap size, 0.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B14:** Stress-strain relationship of MRF-132DG under compression mode at 1.0 mm initial gap size, 1.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B15:** Stress-strain relationship of MRF-132DG under compression mode at 1.0 mm initial gap size, 1.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B16:** Stress-strain relationship of MRF-132DG under compression mode at 1.0 mm initial gap size, 2.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B17:** Stress-strain relationship of MRF-122-2ED under compression mode at 2.0 mm initial gap size, 0.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B18:** Stress-strain relationship of MRF-122-2ED under compression mode at 2.0 mm initial gap size, 1.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B19:** Stress-strain relationship of MRF-122-2ED under compression mode at 2.0 mm initial gap size, 1.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B20:** Stress-strain relationship of MRF-122-2ED under compression mode at 2.0 mm initial gap size, 2.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B21:** Stress-strain relationship of MRF-122-2ED under compression mode at 1.0 mm initial gap size, 0.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B22:** Stress-strain relationship of MRF-122-2ED under compression mode at 1.0 mm initial gap size, 1.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B23:** Stress-strain relationship of MRF-122-2ED under compression mode at 1.0 mm initial gap size, 1.5 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure B24:** Stress-strain relationship of MRF-122-2ED under compression mode at 1.0 mm initial gap size, 2.0 mm/min compressive speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.

## APPENDIX C

## DETAILED TENSION MODE RESULTS



**Figure C1:** Stress-strain relationship of MRF-241ES under tension mode at 2.0 mm initial gap size, 0.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C2:** Stress-strain relationship of MRF-241ES under tension mode at 2.0 mm initial gap size, 1.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C3:** Stress-strain relationship of MRF-241ES under tension mode at 2.0 mm initial gap size, 1.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C4:** Stress-strain relationship of MRF-241ES under tension mode at 2.0 mm initial gap size, 2.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C5:** Stress-strain relationship of MRF-241ES under tension mode at 1.0 mm initial gap size, 0.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C6:** Stress-strain relationship of MRF-241ES under tension mode at 1.0 mm initial gap size, 1.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C7:** Stress-strain relationship of MRF-241ES under tension mode at 1.0 mm initial gap size, 1.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C8:** Stress-strain relationship of MRF-241ES under tension mode at 1.0 mm initial gap size, 2.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C9:** Stress-strain relationship of MRF-132DG under tension mode at 2.0 mm initial gap size, 0.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C10:** Stress-strain relationship of MRF-132DG under tension mode at 2.0 mm initial gap size, 1.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C11:** Stress-strain relationship of MRF-132DG under tension mode at 2.0 mm initial gap size, 1.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C12:** Stress-strain relationship of MRF-132DG under tension mode at 2.0 mm initial gap size, 2.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C13:** Stress-strain relationship of MRF-132DG under tension mode at 1.0 mm initial gap size, 0.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C14:** Stress-strain relationship of MRF-132DG under tension mode at 1.0 mm initial gap size, 1.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C15:** Stress-strain relationship of MRF-132DG under tension mode at 1.0 mm initial gap size, 1.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C16:** Stress-strain relationship of MRF-132DG under tension mode at 1.0 mm initial gap size, 2.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C17:** Stress-strain relationship of MRF-122-2ED under tension mode at 2.0 mm initial gap size, 0.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C18:** Stress-strain relationship of MRF-122-2ED under tension mode at 2.0 mm initial gap size, 1.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C19:** Stress-strain relationship of MRF-122-2ED under tension mode at 2.0 mm initial gap size, 1.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C20:** Stress-strain relationship of MRF-122-2ED under tension mode at 2.0 mm initial gap size, 2.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C21:** Stress-strain relationship of MRF-122-2ED under tension mode at 1.0 mm initial gap size, 0.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C22:** Stress-strain relationship of MRF-122-2ED under tension mode at 1.0 mm initial gap size, 1.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.



**Figure C23:** Stress-strain relationship of MRF-122-2ED under tension mode at 1.0 mm initial gap size, 1.5 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.


**Figure C24:** Stress-strain relationship of MRF-122-2ED under tension mode at 1.0 mm initial gap size, 2.0 mm/min tensile speed and applied currents of (a) 0.4, (b) 0.8, (c) 1.2 and (d) 1.6 Amps.