

**APPLICATION OF MAGNETO-RHEOLOGICAL  
DEVICES FOR IMPACT LOADS REJECTION**

**MOHD SABIRIN BIN RAHMAT**

**DOCTOR OF PHILOSOPHY  
(MECHANICAL ENGINEERING)**

**UNIVERSITI PERTAHANAN NASIONAL  
MALAYSIA**

**2020**



**APPLICATION OF MAGNETO-RHEOLOGICAL DEVICES FOR IMPACT  
LOADS REJECTION**

**MOHD SABIRIN BIN RAHMAT**

Thesis submitted to the Center for Graduate Studies, **Universiti Pertahanan  
Nasional Malaysia**, in fulfillment of the requirements for the Degree of Doctor of  
Philosophy (Mechanical Engineering)

**January 2020**

## ABSTRACT

This thesis discusses the performance of magneto-rheological (MR) devices in cancelling out the effect of impact energy from the gun system of an armoured vehicle during firing, specifically the performance of magneto-rheological elastomer isolator devices (MREID) and magneto-rheological fluid (MRF) dampers. The main focuses of this work are to implement the MR devices in the recoil rejection system of an armoured vehicle, to develop a model of the MR devices and to develop a control strategy to enhance MR device performance. The aim of this work is to develop and validate MR device behaviour, to develop a basic control strategy and an adaptive mechanism to improve MR device performance under various impact energies and to evaluate the performance of MR devices in real applications. The first step of the methodology was to characterise the proposed MREIDs and MRF dampers in the impact pendulum test rig. The MR device was then modelled using an adaptive neuro-fuzzy inference system (ANFIS), which demonstrated the capability of the ANFIS model to predict the force-velocity and force-displacement characteristics of MR devices. With this, a hybrid skyhook active force control (H-SAFC) was proposed to achieve the optimum target force by rejecting unwanted impact force from the gun system. Gravitational Search Algorithm (GSA) was used to optimize the proposed controller's parameters for both MR devices under various impact energies from low (195.94 J) to high (391.88 J). A single-degree-of-freedom (SDOF) gun recoil test rig was installed on an experimental armoured vehicle in order to evaluate the effectiveness of the proposed controller. The mechanism for H-SAFC to adapt to various impact energies was also formulated. Unlike a passive damper, the proposed controller was found to effectively absorb impact energies and to reduce the force response consistently up to 45.95% for MREID and 44.64% for MRF damper, when compared against a basic controller. Furthermore, agreement was found between the simulation and the experimental results with a minor percentage of error at 3.53%. Experimental results of the two MREIDs and a single MRF damper with an adaptive H-SAFC controller resulted in a substantial reduction in the firing force of up to 63.22%, which reaffirmed MR devices' potential to mitigate firing impact.

## ABSTRAK

Tesis ini membincangkan prestasi peranti magneto-rheologi (MR), khususnya *magneto-rheological elastomer isolator device* (MREID) dan peredam *magneto-rheological fluid* (MRF), dalam membatalkan kesan tenaga impak daripada sistem senjata pada kenderaan perisai ketika menembak. Cabaran dalam kerja ini adalah untuk mengaplikasikan peranti MR pada kenderaan perisai, untuk membangunkan model peranti MR, dan untuk membangunkan sistem kawalan bagi meningkatkan prestasi peranti MR. Matlamat kerja ini adalah untuk membangunkan dan mengesahkan perilaku peranti MR, untuk membangunkan strategi kawalan asas dan mekanisme kawalan suai untuk meningkatkan prestasi peranti MR terhadap pelbagai tenaga impak dan untuk menilai prestasi peranti MR dalam aplikasi sebenar. Kaedah pertama bagi kerja ini adalah melakukan eksperimen terhadap MREID dan MRF dengan menggunakan rig ujian pendulum bagi mengetahui sifatnya. Peranti MR kemudian dimodelkan dengan menggunakan kaedah '*adaptive neuro-fuzzy inference system*' (ANFIS), yang mana kaedah ANFIS berkebolehan meramalkan ciri-ciri daya-halaju dan daya-anjakan peranti MR. Dengan ini, sebuah strategi yang dinamakan *hybrid skyhook active force control* (H-SAFC) telah dibangunkan untuk mencapai daya sasaran yang optimum dengan menolak daya impak yang tidak diingini daripada sistem senjata. *Gravitational Search Algorithm* (GSA) telah digunakan dalam proses pengoptimuman parameter kawalan untuk kedua-dua peranti MR dan keberkesanannya telah dinilai dari tenaga impak rendah (195.94 J) kepada tenaga impak yang tinggi (391.88 J). Rig ujian gegelung satu-darjah-kebebasan dipasang di kenderaan perisai eksperimen. Mekanisme penyesuaian bagi H-SAFC juga telah dirumuskan sesuai dengan pelbagai tenaga impak. Tidak seperti peredam pasif, pengawal yang dicadangkan didapati berkesan menghilangkan tenaga kesan dan secara konsisten mengurangkan tindak balas kuasa sehingga 45.95% untuk MREID dan 44.64% untuk peredam MRF berbanding pengawal asas. Tambahan pula, pengawal yang dicadangkan didapati menghasilkan peratusan yang rendah antara simulasi dan eksperimen iaitu 3.53%. Ujian bagi dua MREID dan satu peredam MRF dengan pengawal adaptif H-SAFC dalam kenderaan perisai menunjukkan pengurangan besar dalam daya tembakan sehingga 63.22% ketika menembak.

## ACKNOWLEDGMENTS

Alhamdulillah. I am grateful to Almighty Allah for fulfilling my desire to complete this doctoral study. Firstly, I would like to express my gratitude towards my supervisor, Associate Professor Dr. Khisbullah Hudha, whose expertise, understanding and patience have inspired and enriched my post graduate experience. I would also like to thank my co-supervisor, Brigadier Jeneral Prof Dato. Dr. Shohaimi Abdullah, for providing invaluable advice for my research. Besides that, this research would not have been possible without the financial assistance of MyBrain15 (MyPhD) from the Ministry of Higher Education of Malaysia, as well as the Faculty of Engineering, National Defence University of Malaysia (UPNM) in providing me the opportunity to pursue my passion.

I would also like to express my appreciation to Dr. Zulkiffli Abd Kadir, Dr. Noor Hafizah Amer, Dr. Vimal Rau Aparaw, Dr Fauzi Ahmad, Mr. Nur Rashid Mat Nuri, and Dr. Muhammad Luqman Hakim Abd Rahman for their suggestions, encouragement, editing assistance and provision of simulation and experimental evaluations. In addition, I would like to thank Abdul Muhaimin Idris, Mohamad Hafiz Ikhwan Md Amin, Mohd Izzat Satar, Mazuan Mansor, Muhammad Akhimullah Subari and Abdurrahman Dwijotomo for their expertise in diverse engineering fields, which facilitated the smooth running of this research. I do sincerely apologise for the names that are not included here; this only means that you are closer to my heart.

Needless to say, I would not have reached this point without the endless support from my loving family. To my beloved parents, Rahmat Md Zain and Siti Hawa Daud, who made education an important part of my life and achievements; not forgetting my father who diligently encouraged me in the pursuit of knowledge. Last but not least, my greatest appreciation and thank you to Nur Diyana Hussein, Muhammad Afif, and Sofia Inara. Without their continuous support, encouragement and love, I would not have made it this far. With the completion of this doctoral journey, I promise to be a good family leader - this is the beginning of our next life chapter.

## **APPROVAL**

The Examination Committee has met on 24 October 2019 to conduct the final examination of MOHD SABIRIN BIN RAHMAT on his degree entitled 'APPLICATION OF MAGNETO-RHEOLOGICAL DEVICES FOR IMPACT LOADS REJECTION'. The committee recommends that the student be awarded the degree of Doctor of Philosophy (Mechanical Engineering).

Members of Examination Committee were as follows.

Professor Dr Aidy Bin Ali  
Faculty of Engineering  
Universiti Pertahanan Nasional Malaysia  
(Chairperson)

Associate Professor Ir Dr Saiddi Ali Firdaus Bin Mohamed Ishak  
Faculty of Engineering  
Universiti Pertahanan Nasional Malaysia  
(Internal Examiner)

Professor Ir. Ts. Dr. Pakharuddin Bin Mohd Samin  
Faculty of Mechanical Engineering  
Universiti Teknologi Malaysia  
(External Examiner)

Associate Professor Dr Azman Bin Abdullah  
Faculty of Mechanical Engineering  
Universiti Teknikal Malaysia Melaka  
(External Examiner)

## **APPROVAL**

This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy (Mechanical Engineering). The members of the Supervisory Committee were as follows.

Khisbullah Hudha, PhD  
Associate Professor  
Faculty of Engineering  
Universiti Pertahanan Nasional Malaysia  
(Main Supervisor)

Shohaimi Abdullah , PhD  
Brigadier General (R) Professor Dato'  
Vice Chancellor Office  
Widad University College  
(Co-Supervisor)



# UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

## DECLARATION OF THESIS

Student's full name : Mohd Sabirin Bin Rahmat  
Date of birth : 02/10/1985  
Title : Application of Magneto-Rheological Devices for Impact Loads Rejection  
Academic session : 2018/2019

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged.

I further declare that this thesis is classified as:

**CONFIDENTIAL** (Contains confidential information under the official Secret Act 1972)\*

**RESTRICTED** (Contains restricted information as specified by the organisation where research was done)\*

**OPEN ACCESS** I agree that my thesis to be published as online open access (full text)

I acknowledge that Universiti Pertahanan Nasional Malaysia reserves the right as follows.

1. The thesis is the property of Universiti Pertahanan Nasional Malaysia.
2. The library of Universiti Pertahanan Nasional Malaysia has the right to make copies for the purpose of research only.
3. The library has the right to make copies of the thesis for academic exchange.

\_\_\_\_\_  
Signature

\_\_\_\_\_  
\*\*Signature of Supervisor/Dean of CGS/  
Chief Librarian

\_\_\_\_\_  
IC/Passport No.

\_\_\_\_\_  
\*\*Name of Supervisor/Dean of CGS/  
Chief Librarian

Date:

Date:

Note: \*If the thesis is CONFIDENTIAL OR RESTRICTED, please attach the letter from the organisation stating the period and reasons for confidentiality and restriction.

\*\* Witness

## TABLE OF CONTENTS

	<b>Page</b>
<b>ABSTRACT</b>	ii
<b>ABSTRAK</b>	iii
<b>ACKNOWLEDGEMENTS</b>	iv
<b>APPROVAL</b>	v
<b>DECLARATION</b>	vii
<b>TABLE OF CONTENTS</b>	viii
<b>LIST OF TABLES</b>	xii
<b>LIST OF FIGURES</b>	xiv
<b>LIST OF ABBREVIATIONS</b>	xviii
<b>LIST OF SYMBOLS</b>	xix
<b>CHAPTER</b>	
<b>1</b>	<b>1</b>
<b>INTRODUCTION</b>	<b>1</b>
1.1 Overview	1
1.2 Background of Study	3
1.3 Problem Statement	5
1.4 Research Objective	6
1.5 Scope of Study	6
1.6 Methodology	7
1.7 Contributions of Study	10
1.8 Thesis Organisation	11
<b>2</b>	<b>14</b>
<b>LITERATURE REVIEW</b>	<b>14</b>
2.1 Introduction	14
2.2 Classification of Impact Rejection Devices	14
2.2.1 Passive Damper System	15
2.2.2 Active Damper System	16
2.2.3 Semi-Active Damper System	16
2.2.3.1 Magneto-Rheological Elastomer	17
2.2.3.2 Magneto-Rheological Fluid	22
2.3 Modelling Approach for Semi-Active Devices	26
2.3.1 Parametric Model	27
2.3.2 Non-Parametric Model	31
2.4 Common Approach of Control Strategy for MR Devices	37
2.4.1 Practical Control	37
2.4.1.1 PID Controller	38
2.4.1.2 Skyhook Controller	40
2.4.1.3 Active Force Controller	43
2.4.2 Modern Controller	45
2.4.2.1 Hybrid Controller	45
2.4.2.2 Adaptive Controller	49
2.5 Recent Development of MR Devices in Impact Loadings Applications	51

2.6	Research Gaps, Challenges and Directions of Developing of MR Devices in Impact Loadings Applications	54
2.7	Chapter Summary	57
<b>3</b>	<b>DESIGN, CHARACTERISATION AND MODELLING OF MAGNETO-RHEOLOGICAL DEVICES UNDER IMPACT LOADINGS</b>	<b>59</b>
3.1	Introduction	59
3.2	Design of Magneto-Rheological Elastomer Isolator Device	60
3.3	Magneto-Rheological Damper	63
3.4	Experimental Setup for Characterisation of MR Devices	64
3.5	Characterisation of Various Impact Energy	67
3.5.1	Characterisation Results of MREID	68
3.5.2	Characterisation Results of MRF Damper	71
3.6	Modelling of MR Devices	75
3.6.1	Modified Bouc-Wen Model	75
3.6.2	Adaptive Neuro-Fuzzy Inference System Model	78
3.7	Validation Results for MREID	82
3.8	Validation Results for MRF Damper	91
3.9	Chapter Summary	97
<b>4</b>	<b>EFFECTS OF CONTROL STRATEGY ON THE PERFORMANCE OF MAGNETO-RHEOLOGICAL DEVICES FOR IMPACT REDUCTION</b>	<b>99</b>
4.1	Introduction	99
4.2	Dynamic Model of Impact Test Rig	100
4.3	Design of Control Strategies for MR Devices	102
4.2.1	Skyhook Controller	103
4.2.2	Active Force Controller	104
4.2.3	Hybrid Skyhook Active Force Control	105
4.4	Optimisation of Control Parameter using Gravitational Search Algorithm	107
4.4.1	Algorithm Structure of GSA	108
4.4.2	Selection of GSA Parameter	112
4.5	A Current Generator Design using Inverse ANFIS Approach	114
4.6	Simulation Result of MR Devices	115
4.6.1	A Single MREID due to Impact Loadings	117
4.6.2	A Single MRF Damper due to Impact Loadings	115
4.7	Chapter Summary	120

<b>5</b>	<b>ADAPTIVE HYBRID SKYHOOK ACTIVE FORCE CONTROL OPTIMISED BY GRAVITATIONAL SEARCH ALGORITHM OF MAGNETO-RHEOLOGICAL DEVICES FOR RECOIL FORCE REJECTION</b>	<b>121</b>
	5.1 Introduction	121
	5.2 Validation of Impact Isolation System	122
	5.3 Control-Oriented Model	123
	5.4 Adaptive H-SAFC for MR Devices	126
	5.5 Simulation Results of MREID with Adaptive H-SAFC under High Impact Energy	128
	5.6 Simulation Results of MRF Damper with Adaptive H-SAFC under High Impact Energy	131
	5.7 Chapter Summary	134
<b>6</b>	<b>EXPERIMENTAL TESTING ON THE POTENTIAL BENEFIT OF MAGNETO-RHEOLOGICAL DEVICES FOR RECOIL FORCE REJECTION CONTROL</b>	<b>135</b>
	6.1 Introduction	135
	6.2 MR Devices for Recoil Force Rejection	137
	6.3 Development of SDOF Recoil Force Rejection System	138
	6.4 Experimental Setup for H-SAFC	141
	6.5 Experimental Results of Individual MR Devices for Recoil Force Rejection Control	143
	6.5.1 MREID	143
	6.5.2 MRF Damper	146
	6.6 Experimental Results of Combined MR Devices for Recoil Force Rejection Control	150
	6.7 Evaluation on the Combine Arrangement Performance of MR Devices with Actual Firing Force in Armoured Vehicle	155
	6.8 Chapter Summary	156
<b>7</b>	<b>CONCLUSION</b>	<b>158</b>
	7.1 Overview	158
	7.2 Conclusions	159
	7.3 Recommendations for Future Research	161
	<b>REFERENCES/BIBLIOGRAPHY</b>	<b>163</b>
	<b>APPENDICES</b>	<b>175</b>
	A. Model Validation Results	175
	B. Simulation Results of Basic Control Strategies	179
	C. Simulation Results of Adaptive Hybrid Skyhook Active Force Control (H-SAFC) for Individual MR Devices	183

D. Experimental Results of Adaptive Hybrid Skyhook Active Force Control (H-SAFC) for Individual MR Devices	188
E. Experimental Results for individual and combined of MR Device in armoured vehicle	193
<b>BIODATA OF STUDENT</b>	<b>198</b>
<b>LIST OF PUBLICATIONS</b>	<b>201</b>

## LIST OF TABLES

TABLE NO.	TITLE	PAGE
3.1	Parameters of linear spring	67
3.2	Impact energy for each impact loading	68
3.3	Parameters of the modified Bouc-Wen model (Xiang et al., 2008)	77
3.4	Parameters of subtractive clustering	82
3.5	Percentage of error based on RMS value	85
3.6	Intermediate data	86
3.7	Percentage of error based on peak damping force	89
3.8	Peak values and deviation percentages of damping force for MREID	90
3.9	Percentage of error for ANFIS model and modified Bouc-Wen model	93
3.10	Percentage of error based on peak damping force	96
3.11	Peak values and deviation percentages of damping force for MRF damper	96
4.1	Parameters of passive stiffness and damping coefficients for passive damper	102
4.2	GSA parameters for H-S AFC control	114
4.3	RMS values for MREID under high impact energy	117
4.4	RMS values for MRF damper under high impact energy	119
5.1	Optimum values of H-S AFC parameters according to impact energy for MREID	126
5.2	Optimum values of H-S AFC parameters according to impact energy for MRF damper	126
5.3	Percentage of deviation of H-S AFC and adaptive H-S AFC under high impact energy for MREID	131
5.4	Percentage of deviation of skyhook controller and adaptive H-S AFC under high impact energy for MRF damper	133
6.1	Weight conversion of the cylinder blocks	139
6.2	Percentage of deviation between H-S AFC and adaptive H-S AFC from experiment data under high impact energy	145
6.3	Comparison between simulation and experimental results under different impact energies for MREID with Adaptive	146

	H-SAFC under different impact energies for MREID with Adaptive H-SAFC	
6.4	Percentage of deviation between H-SAFC and adaptive H-SAFC from experiment data under low impact energy	149
6.5	Comparison between simulation and experimental results under different impact energies for MRF damper with adaptive H-SAFC	149
6.6	PTP values of experimental results on high impact energy	154

## LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
1.1	Flowchart of work	9
2.1	Passive damper system	15
2.2	Active damper system	16
2.3	Semi-active damper system	17
2.4	Schematic of MR materials	18
2.5	Schematic of a magnetic circuit	21
2.6	Material properties for MRE elastomer developed by Yu et al., 2015, (a) shear storage modulus vs magnetic flux density, (b) relative MR effect vs magnetic flux density	22
2.7	Dipole alignment of ferrous particles under (a) no magnetic field, (b) magnetic field and formation of chains	23
2.8	String and beads of activated magneto-rheological fluid	24
2.9	Magneto-rheological fluid used in (a) squeeze mode (b) shear mode and (c) valve mode	25
2.10	Force-velocity characteristics of Bingham model (Guo et al., 2006)	28
2.11	Configuration of Bouc-Wen model (Spencer et al., 1997)	28
2.12	Typical response of force-displacement for Bouc-Wen model (Spencer et al., 1997)	29
2.13	Modified Bouc-Wen model proposed by Spencer et al. (1997)	30
2.14	Typical response of force-displacement for modified Bouc-Wen model (Spencer et al. 1997)	31
2.15	Schematic of the ANFIS structure (Javad et al., 2013)	34
2.16	Typical force-displacement results according to various input currents for long stroke MR damper (Javad et al., 2013)	36
2.17	Typical force-velocity results according to various input currents for long stroke MR damper (Javad et al., 2013)	36
2.18	PID controller diagram for MR systems (Choi et al., 2016)	38
2.19	A concept of a skyhook controller (Choi et al., 2016)	40
2.20	Schematic diagram of AFC structure (Priyandoko et al., 2009)	44



2.21	Block diagram of a hybrid fuzzy neural network controller	46
2.22	A block diagram of a model reference adaptive control system	50
3.1	Concept flow chart for design, characterisation and modelling of MR devices	60
3.2	Schematic diagram of MREID	61
3.3	Physical maps for MREID	62
3.4	Simulation results of MREID electromagnetic circuit	63
3.5	Schematic diagram of MR damper (Ubaidillah et al., 2011)	64
3.6	Configuration of four linear springs for impact pendulum test rig	65
3.7	Experimental setup for the impact test	65
3.8	Quasi-static test	66
3.9	Results of force-displacement characteristics for MREID	69
3.10	Results of force-velocity characteristics for MREID	70
3.11	Behaviours of MREID in the impact test	71
3.12	Results of force-displacement characteristics for MRF damper	72
3.13	Results of force-velocity characteristics for MRF damper	73
3.14	Behaviours of MRF damper in the impact test	74
3.15	Schematic diagram of the impact system	76
3.16	Stiffness versus input current	77
3.17	Damping versus input current	78
3.18	Velocity versus input current	78
3.19	Architecture of ANFIS model for Sugeno system	79
3.20	Validation results of force-displacement characteristics under various impact energies of striker for input current of 3 A	79
3.21	Validation results of force-velocity characteristics under various impact energies of striker for input current of 3 A	84
3.22	Validation results of force-displacement characteristics for intermediate impact energy	87
3.23	Validation results of force-velocity characteristics for intermediate impact energy	88
3.24	Validation results of force-displacement characteristics under various pendulum masses for maximum input current of 2 A	91

3.25	Validation results of force-velocity characteristics under various pendulum masses for maximum input current of 2 A	92
3.26	Validation results of force-displacement characteristics with maximum input current of 2 A	94
3.27	Validation results of force-velocity characteristics with maximum input current of 2 A	95
4.1	Flow chart of simulation work for evaluating control strategy performance	100
4.2	Schematic diagram of SDOF impact isolation system	101
4.3	Schematic diagram of skyhook controller with imaginary damping	104
4.4	Schematic diagram for active force control (AFC)	104
4.5	Schematic diagram for H-SAFC	106
4.6	Flow process of GSA	112
4.7	Simulation results of MREID with control strategy under high impact energy	116
4.8	Simulation results of MRF damper with control strategy under high impact energy	118
5.1	Flow chart of simulation work	122
5.2	Excitation force versus time	123
5.3	Model validation results for low impact energy	124
5.4	Model validation results for medium impact energy	124
5.5	Model validation results for high impact energy	125
5.6	The block diagram for the control structure	127
5.7	Simulation results of SDOF under high impact energy for MREID	129
5.8	Simulation results of SDOF under high kinetic energy for MRF damper	132
6.1	Flow chart of experimentation work for MR devices	136
6.2	The arrangement of the MR devices from (a) top view and (b) side view	138
6.3	Experiment setup for the testing of MR devices	140
6.4	Schematic diagram of the configuration of instruments	140
6.5	Schematic diagram of hardware-in-the-loop-simulation (HILS)	141
6.6	Configuration of accelerometer sensors at the (a) CoG of vehicle body (b) CoG of gun system and in the (c) mechanical gun recoil mechanism	142

6.7	Configuration of a single force transducer	142
6.8	Experimental results of SDOF test rig under high impact energy	144
6.9	Experimental results of SDOF test rig under the high impact energy	147
6.10	Firing impact acceleration at the mechanical gun recoil mechanism in the gun system of armoured vehicle	151
6.11	Firing impact acceleration at the CoG of the gun system	153
6.12	Firing impact acceleration at the CoG of the body of armoured vehicle	153
6.13	Transmitted force response of the firing impact force	154

## LIST OF ABBREVIATIONS

AFC	Active force control
ANFIS	Adaptive neuro fuzzy inference system
CoG	Centre of gravity
CAD	Computer aided design
FEMM	Finite element magnetic method
GA	Genetic algorithm
HILS	Hardware-in-loop simulation
H-SAFC	Hybrid skyhook active force control
LVDT	Linear variable displacement transformer
MF	Membership functions
MR	Magneto-rheological
MRE	Magneto-rheological elastomer
MREID	Magneto-rheological elastomer isolator device
MRF	Magneto-rheological fluid
NN	Neural network
PID	Proportional Integral Derivative
PWM	Pulse width modulation
RTV	Room temperature vulcanisation
SDOF	Single-degree-of-freedom
SWAT	Soil and Water Assessments Tool

## LIST OF SYMBOL

$x$	Displacement
$\dot{x}$	Velocity
$\ddot{x}$	Acceleration
$F_a$	Force actuator
$A$	Ampere
AND	Multiply
$C$	Damping coefficient
$CoG$	Centre of gravity
$J$	Joule
$K$	Stiffness
$N$	Newton
$kN$	Kilo Newton

# CHAPTER 1

## INTRODUCTION

### 1.1 Overview

Gun turret systems generally comprise two main components, the gun platform and the gun barrel. The gun platform has several components, including the barrel, breech, breechblock and muzzle brake (Ahmadian and Norris, 2004). There are also component of gun system which are recoil mechanisms, elevating mechanisms, traversing mechanisms and support gun barrels. The primary components of gun turret systems, particularly the muzzle brake and recoil mechanism, serve to minimise the recoil force when the gun is fired (Li and Wang, 2012).

The development of cushion impact absorption for the gun system of armoured vehicle was not a primary focus before the 19th century. Bulky guns were introduced to minimise recoil force after firing, but they still exhibited several disadvantages, especially as the gun barrel has to return to its initial position prior to re-firing. The impact of recoil force significantly damages the gun's structure and reduces the stability of the armoured vehicle during firing. Since the gun weapon platform is mounted on top of the armoured vehicle, the structure of the vehicle receives the direct impact of the recoil force and additional disturbance from the gun

turret. The impact of recoil force also affects the soldiers operating the gun turret during firing and causes them to lose their target while engaging in combat. In order to accurately set their target lock before firing again, the soldiers have to reset the gun turret, which requires more time and subsequently puts the soldiers in direct exposure to counterattack. The high impact of recoil force can also ignite the ammunition, which could not only destroy the armoured vehicle but also severely injure the soldiers. Most studies overlook the impact of recoil force on the structure of the armoured vehicle, the soldiers and the ammunition itself (Ahmadian and Appleton, 2001; Ahmadian and Norris, 2008).

Hence, there is a need and possibility of improving gun stabilisation, especially for reducing recoil force by using the semi-active damper system. Semi-active damper system is a system that controls the damping force in response to the applied force. Among the semi-active damper system, magneto-rheological damper system behaviour are particularly interesting due to high damping force produced with lower power requirement and simple mechanical design. Therefore, the magneto-rheological (MR) devices, specifically the magneto-rheological elastomer isolator device (MREID) and magneto-rheological fluid (MRF) damper, were explored in this work. Overall, this work incorporated the modelling of semi-active MR devices, force-tracking, and disturbance rejection control. Firstly, the characterisation of MREID and MRF damper were conducted using the impact pendulum test rig. Next, the behaviours of MREID and MRF damper were analytically modelled in a simulation using the adaptive neuro-fuzzy inference system (ANFIS). By using the impact loading application, this work ensued with the development of control strategy for MR devices for enhanced performance.

Subsequently, the performance of control strategy was evaluated in simulation using the MATLAB-Simulink software and experimented via hardware-in-the-loop simulation (HILS) method. The control strategy was studied in response to the performance criteria of jerk, acceleration and transmitted force responses. Next, the gun recoil test rig in the form of a single-degree-of-freedom (SDOF) was developed and installed in the experimental armoured vehicle. Finally, the performance of MR devices for individual and combined arrangements was evaluated to examine the potential benefit of using the MR devices for the recoil force rejection system.

## **1.2 Background of Study**

MR devices are smart materials that produce a controllable damping force in real time according to the applied control strategy. In general, these materials are composed of soft carbonyl iron particles. In the absence of a magnetic field, the particles are randomly distributed; under the influence of an applied magnetic field, a dipole is induced in the external field, forming chains between the particles (Choi et al., 2016). The formation of these chains induces reversible yield stress in the MR elastomer (MRE) and MRF. The yield stress is continuously and rapidly adjusted according to the intensity of the magnetic field.

Interest in the use of MR devices to develop numerous dynamic systems has grown due to remarkable advancements in MREs and MRFs. The use of MR devices to control a damper or isolator for improved dynamic performance yields highly promising results. However, the effective use of MR devices depends on the



accuracy of the damper model and the ability of the designer to develop a suitable controller for the damper model (Imaduddin et al., 2017).

There are several promising control strategies, but further exploration is required to enhance the existing control algorithms. This study aims to identify an accurate behavioural model and an appropriate controller for MR devices to enhance the dynamic performance of armoured vehicles, including their overall gun recoil system. This study proposed a non-parametric modelling of MR devices to formulate an upgraded control algorithm, also known as hybrid control with an adaptive mechanism. The proposed hybrid controller was expected to effectively reject recoil force through the MR devices. Finally, the combined MR devices were installed into the gun recoil test rig to create the recoil force rejection system. The overall performance of the MR devices was evaluated under different levels of firing impact on the armoured vehicle (low, medium and high impact energies) in terms of the acceleration at the gun recoil test rig.

### **1.3 Problem Statement**

One of the common problems of using MR devices in a shock or impact application system is the accuracy of the developed model in predicting the behaviours of the MR devices during impact loading. An accurate model of the MR devices is important to act as the plant in the control structure in order to evaluate the control strategy performance. Creating a suitable control strategy has been an ongoing challenge in work to enhance the performance of MR devices in real