# APPLICATION OF MAGNETO-RHEOLOGICAL DEVICES FOR IMPACT LOADS REJECTION

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**DOCTOR OF PHILOSOPHY**
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# APPLICATION OF MAGNETO-RHEOLOGICAL DEVICES FOR IMPACT LOADS REJECTION

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# 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.

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# 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).
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# 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.

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# 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