MODELING AND FORCE TRACKING CONTROL OF BOUC-WEN MR DAMPER MODEL

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This report is submitted
in fulfillment of the requirement for the degree of
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DECLARATION

I declare that this project report entitled "Modeling and Force Tracking Control of Bouc Wen MR Damper Model" is the result of my own work except as cited in the references

Signature : ....

Name of Supervisor : ....

Date : ....

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :. ....

Name of Supervisor : ....

Date : ....

DEDICATION

To my beloved mother Rosnida Binti Ramli and my father Sanusi Bin Che Abdullah

ABSTRACT

The modeling of magnetorheological (MR) dampers is essential in understanding the operation, working principles and behavior of the suspension. The models of MR dampers divided into two type which are parametric and non-parametric model. Parametric model consists of Bouc-Wen and modified Bouc-Wen model which have been study and compared to understand the performance of both models. The verification method is used for this study to compare the performances for both models using MATLAB Simulink. The structure of the force tracking control for the proposed MR damper model uses as a continuous state control to achieve the desired force. The performance of the proposed controller is evaluated by simulation using sinusoid, square and sawtooth signal to represent several classes of continuous and discontinuous functions. Analysis through experiment and non-parametric model should be developed in future works.

ABSTRAK

Pemodelan magnetorheologi (MR) adalah penting dalam memahami operasi, prinsip kerja dan tingkah laku penggantungan. Model pembawa MR terbahagi kepada dua jenis iaitu model parametrik dan bukan parametrik. Model parametrik terdiri daripada Bouc-Wen dan model Bouc-Wen diubahsuai yang telah dikaji dan dibandingkan untuk memahami prestasi kedua-dua model. Kaedah pengesahan digunakan untuk kajian ini untuk membandingkan prestasi kedua-dua model menggunakan MATLAB Simulink. Struktur kawalan pengesanan daya untuk model peredam MR yang dicadangkan digunakan sebagai kawalan keadaan berterusan untuk mencapai daya yang dikehendaki. Prestasi pengawal yang dicadangkan dinilai oleh simulasi menggunakan isyarat sinusoid, persegi dan gergaji untuk mewakili beberapa kelas yang berterusan dan tidak berterusan fungsi. Analisis melalui model percubaan dan tidak parametrik perlu dibangunkan pada masa akan datang.

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Alhamdulillah, with His Mercy and Blessings, this study was finally completed. First of all, I would like to express my deepest appreciation to my supervisor Mr. Mohd Hanif Bin Harun for giving me this opportunity to do final year project with him. He never hesitated to give me advice and guidance whenever I confronted problems. I am thankful for his patience and advice while leading me in this project.

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Lastly, I would like to thank my family and also my course mates for giving me their support, patience and encouragement supports along my journey to complete this thesis.

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LIST OF ABBEREVATIONS

MR	:	Magnetorheological
BW	:	Bouc-Wen
MBW	:	Modified Bouc-Wen
ER	:	Electrorheological
LQG	:	Linear-Qudratic Control
NN	:	Neural Network
NNC	:	Neural Network Controller
NNI	:	Neural Network Identifier
PSM	:	Projek Sarjana Muda

LIST OF SYMBOLS

F	:	Damping force
c_0	:	Damping coefficient
c_1	:	Damping coefficient
k_0	:	Spring stiffness coefficient
k_1	:	Spring stiffness coefficient
x	:	Displacement
$\dot{x}$	:	First derivatives of x
$\ddot{x}$	:	Second derivatives of x
y	:	Secondary displacement y
$\dot{y}$	:	First derivatives of y
$\ddot{y}$	:	Second derivatives of y
z	:	Hysteretic deformation
$\dot{z}$	:	First derivatives of z
γ	:	Fluid properties
β	:	Fluid properties
α	:	Fluid properties
A	:	Fluid properties
n	:	Number of orders

v	:	Applied current
u	:	Filtered current
η	:	Frequency
Fc	:	desired damping force
Fd	:	actual damping force
G	:	feedback gain
B.	:	proportional gain

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CHAPTER 1

INTRODUCTION

1.1 Background

Semi-active damping system is one of the most important system for automotive suspension system. This damping device can minimize the response of the unwanted motion and external disturbance by adjusting the properties of the device. There semi-active devices that can generate forces from viscous fluid which is magnetorheological (MR) damper (Spencers, Dyke et al. 1997).

Atray and Roschke (2003), said that an MR damper is relatively damping device, during which the magnitude of the resisting force acting upon a mechanical structure will be adjusted in real time. There are two main categories of MR damper which is parametric and non-parametric (Metered, Bonello et al. 2010). Parametric model consists of some mechanical element such as linear viscous, friction and spring, Parameter model associated with this mechanical part are determined by examination the models with experimental results.

Next, non-parametric model establish between measured quantities and the occurring parameters does not have an instantaneous physical. Even though, the non-parametric model can represent MR damper behavior effectively, they are slightly complex and require additional experimental dataset. MR damper has major disadvantage lies within the non-linear and hysteretic force–velocity response. To employ the MR damper the design of a controller usually needs a model of the actuator. The Bouc-Wen model was initially proposed by Bouc early in 1971 and generalized by Wen in 1976 and since then it has been called the Bouc-Wen model. The general Bouc-Wen model predicts the force displacement behavior of the damper well, and it possesses force velocity (İ, Engin et al. 2010).

1.2 Problem statement

In order to fulfill the objective of this project, which is to analyze MR damper model and to design force tracking control of MR damper. In order to analyze the MR damper model, it is necessary to select the best method and model to analyze. Parametric model has been chosen to conduct this study compare to non-parametric model. This is because non-parametric model has more complicated steps to conduct which is non-parametric model has to conduct the experiment first before the simulation to get the accurate result. It will consume more time and cost more money to undergo this study using non-parametric model. Thus, parametric model has been used to conduct this study.

1.3 Objective

The objectives of this project are as follows:

1. To analyze MR damper model based on parametric modeling method.
2. To design force tracking control of MR damper.

1.4 Scope of Project

The scope of this project is:

1. MR damper mathematical model is developed based on Bouc-Wen and Modified Bouc-Wen model which are in the class of parametric model.

1.5 Thesis Outline

Chapter 1: Introduction

In this chapter, there are four section that will be covered which is background of the study, problem statement, objective and scope of project for this study.

Chapter 2: Literature Review

This chapter provide a basic description of the various mechanism of MR damper. Parametric model of MR damper was explored and presented in this chapter. The mathematical model for Bouc-Wen and Modified Bouc-Wen also been covered in this chapter. The theory and the type of controller in MR damper system were study and presented.

Chapter 3: Methodology

Methodology present the method and steps that were used in this study. The content of this chapter is step of project, flowchart of this project, MATLAB Simulink Model and the parameter identification for Bouc-Wen and Modified Bouc-Wen Simulink model.

Chapter 4: Result and Discussion

For this chapter included all the result from the MATLAB Simulink simulation of MR damper have been analysed and compared between Bouc-Wen and Modified Bouc-Wen model.

Chapter 5: Conclusion and Recommendation

This is the last chapter which conclude all the result that have been achieved along this project and give the recommendation for future study.

1.6 Summary

The main objective of this project is to develop MR damper model based on parametric modeling method and to design force tracking control of MR damper. MR damper mathematical model is developed based on Bouc-Wen and Modified Bouc-Wen model which are in the class of parametric model and simulate both models using MATLAB Simulink.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will be present a complete literature review to sum up the previous work related to this thesis was introduced in Chapter 1. This section starts by giving background of MR damper then follow up by a review of parametric model of MR damper which is Bouc-Wen and Modified Bouc-Wen models. Next, this chapter continue by showing the MR damper mathematical model that have been developed based on Bouc-Wen and Modified Bouc-Wen method. Finally, the system controller for MR damper will be covered.

2.2 Magnetorheological damper background

MR fluids ever since it was discovered by Jacob Rabinow in the 1940's have in recent years has been identified to the researchers as a multi-functional fluid for its property of obtaining attractable on the applying of magnetic field. When magnetic field is applied, MR fluid has the unique ability to change its properties (Carlson and Jolly 2000). Application of MR damper is important among numerous applications of MR fluids (Carlson and Jolly 2000, Choi, Nam et al. 2000, van Kasteel, Cheng-guo et al. 2003, Lee, Sung et al. 2011) .

When exposed to a magnetic field MR damper can change their mechanical properties. This device is able to reversibly change from a free-flowing linear viscous liquid to a semi-solid within milliseconds (Carlson and Jolly 2000). Under certain loading condition the modeling of a MR damper device is one of the challenges in analysing the essential nonlinear dynamical behaviour of the entire system.

A lot of model are put forward to characterize the dynamic behaviours of MR dampers, which include the Bingham model (Peel, Stanway et al. 1996) the nonlinear bi-viscous model (Peel, Stanway et al. 1996), the bi-viscous hysteresis model (Nicholas and Norman 2004) the phenomenological Bouc-Wen model (Spencers, Dyke et al. 1997) the polynomial model (Choi, Nam et al. 2000) the modified Bingham hysteresis model (Guo, Yang et al. 2006) and a unified model for ER and MR vibration damper (Sims, Holmes et al. 2003). All these models can capture the post-yield behaviour of MR dampers.

In the modelling, MR dampers can be divided into two categories which is parametric and non-parametric. For the parametric method, the damper is characterized by a system of linear and non-linear parts, that outline the parameters of spring, dashpots and different mechanical parts, dominant the mechanisms and their operative space. For the non-parametric method, the damper is consist of polynomials, hyperbolic tangent, delay, offset or by a polynomial with the power of damper piston velocity and the artificial intelligence methods (Choi, Nam et al. 2000).

2.3 Parametric Models

To simulates the behavior of the model, parametric models need assumptions due to the structure of the mechanical (Wang and Liao 2005). By arranging the spring and viscous dashpot some models are require mechanical idealization involving illustration (Spencers, Dyke et al. 1997). There a lot of mathematical models that have been published in order to simulate the behaviour of MR dampers. The Bouc-Wen model is extensively used to model hysteresis in systems (Ismail, Ikhouane et al. 2009). It is a particularly versatile model that is ready to emulate a range of hysteretic behaviours.

According to Spencers, Dyke et al. (1997) MR damper can yield a hysteresis loop which mean that this loop will not match the experimental results adequately in those regions wherever the acceleration and velocity had opposite signs. In order to solve this problem, a modified Bouc-Wen model or called as Spencer model was proposed firstly in (Spencers, Dyke et al. 1997).This modified Bouc-Wen model representation through the introduction of an additional degree of freedom.

2.3.1 Bouc-Wen Model

Bouc-Wen model has been extensively used in the present literature to explain mathematically parts with hysteretic behavior and also significantly implemented in the civil and engineering field (Wand and Liao el al., 2011). By choosing a set of parameters precisely, it is possible to accommodate the response of the model to the hysteresis loops (Ismail, Ikhouane et al. 2009). This model has the advantage of simplicity, as a result of only one auxiliary nonlinear equation is required to explain the hysteretic behaviour.

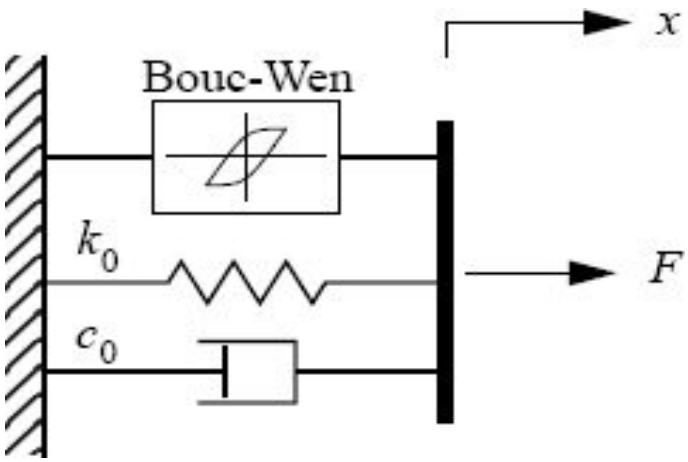

Figure 2.1 Bouc-Wen model (Şahin, Engin et al. 2010).

This model contains viscous damper, spring and hysteretic component. This model can be described by the force equation and the associated hysteretic variable, given by:

$$F = \alpha z + c_0 \dot{x} + k_0 (x - x_0) \qquad (2.1)$$

Where α is the Bouc-Wen model parameter related to the MR material yield stress, k0 and c0 are spring stiffness and damping coefficient respectively; and z is hysteretic deformation of the model which is defined by following equation in which A, β and γ are the Bouc-Wen model parameters (Hudha, Harun et al. 2011, Talatahari, Kaveh et al. 2012).

$$\dot{z} = -\gamma z |\dot{x}| |z|^{n-1} - \beta\dot{x} |z|^{n} + A\dot{x} \qquad (2.2)$$

In order to achieve the optimal performance of the control systems, current must be applied to the MR damper according to the measured feedback at any moment, so that damping force of the MR damper will be change. Thus, for accounting this accordance, the coefficient α , damping coefficient c0 and stiffness k0 are defined as a linear function of the efficient voltage as given by the following equations (B. Farahmand Azar* , Kwok, Ha et al. 2006):

$$\alpha(u) = \alpha_a + \alpha_b u,\ c_0(u) = c_{0a} + c_{0b} u,\ k_0(u) = k_{0a} + k_{0b} u \qquad (2.3)$$

To assist the dynamic that involved in the MR damper reaching rheological equilibrium, the following first order filter is apply to calculate the efficient voltage, u and η is a constant (Zapateiro, Karimi et al. 2009).

$$\dot{u} = -\eta\left(u - v\right) \qquad (2.4)$$

According to Kori and Jangid (2009) Eq. (2.4) it is necessary to model the dynamics involved in reaching rheological equilibrium and in driving the electromagnet in the MR damper.

2.3.2 Modified Bouc-Wen model

The extension of the Bouc-Wen model proposed by Spencer which called as Modified Bouc-Wen (MBW) model or Spencer model concern the introduction of an additional damping coefficient c_1 and spring stiffness k_1. This rheological structure of Modified Bouc-Wen model is shown in Figure 2.2 (Sapiński, Filuś et al. 2003).

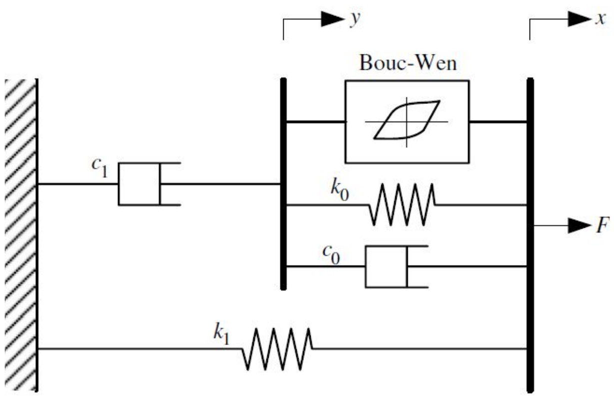

Figure 2.2 Modified Bouc-Wen model (Kim, Langari et al. 2008)

In the Modified Bouc-Wen model, additional parameters are introduced in order to obtain much more accurate result. The non-linear force generated by MR damper is calculated by this equation:

$$F=\alpha z+c_0(\dot{x}-\dot{y})+k_0(x-y)+k_1(x-y) \tag{2.5}$$

In this case, hysteretic displacement z is given by this equation:

$$\dot{z}=-\gamma z|\dot{x}-\dot{y}||z|^{n-1}-\beta(\dot{x}-\dot{y})|z|^n+A(\dot{x}-\dot{y}) \tag{2.6}$$

Where y is an internal dynamical variable which can be given as :

$$\dot{y} = \frac{1}{c_0 + c_1}\left[\alpha z + c_0 \dot{x} + k_0 (x - y)\right] \tag{2.7}$$

To determine a comprehensive model that is valid for fluctuating magnetic fields, the parameters α , c0 and c1 defined as a linear function of the efficient voltage, u in which u is related to applied voltage through Eq (2.4) (Talatahari, Kaveh et al. 2012) .

$$\alpha(u) = \alpha_a + \alpha_b u,\ c_0(u) = c_{0a} + c_{0b} u,\ c_1(u) = c_{1a} + c_{1b} u \tag{2.8}$$

2.4 System Controller

The desired force required from the MR damper are measured in order by system controller to obtain optimized conditions for the systems. A huge number of system controller have been forward, and these can be broadly classified according to the control strategy used to optimize the system conditions.

- Direct optimization of the state variables:
  i. H∞ controller (Zong, Gong et al. 2013, Shin, You et al. 2014)
  ii. Linear-Qudratic (LQG) control (Zamzuri, Zolotas et al. 2007, Ronghui, Zolotas et al. 2010)
  iii. Neural Network (NN) system control (Guo, Hu et al. 2004, Lai and Liao 2016)
  iv. Robust control (Zribi and Karkoub 2004)
- Forcing the system to emulate the behaviour of some idealised system:
  i. Skyhook model and its variants (Hudha, Harun et al. 2011, Kwak, Lee et al. 2014, Oh, Shin et al. 2016)
  ii. Model-reference sliding mode control (Lam and Liao 2003).

2.4.1 H∞ controller

H∞ control is a semi-active controller which is use with MR damper for railway vehicle suspension system to improve the lateral ride quality by reducing the vibration on the car body. This method have been investigated in 2013 in China by Zong, Gong et al. (2013) and at 2014 in Korea by Shin, You et al. (2014) in order to increase the comfort level of the passenger in the railway vehicle by reducing the vibration. According to Shin, You et al. (2014) the H∞ controller design is described as associate degree extended area state model as well as coefficient functions, wherever controller degrees increase because the degree of freedom within the model that be controlled is exaggerated. In practical applications, Zong, Gong et al. (2013) said that it is significant to build a simplified control model, which might reveal the influence from the controller to the controlled system however does not contain all of the detail, as a result of the additional complicated model can cause a more complex controller.

2.4.2 Linear Quadratic Gaussian (LQG)

Next, for LQG (Linear Quadratic Gaussian) are an attractive controller use when mulitple control objective problem need to be addressed simultaneously. The purpose of this controller have been studied by Zamzuri, Zolotas et al. (2007) where to find the control gain that provide the best possible performance with repect to a given performance index. Besides that, according to the study from Liao, Wang et al. (2003) LQG controller is proposed to make the MR dampers track optimal damping forces by command the voltage to current drivers for the MR dampers.

The LQG controller was the combination of a Kalman filter and a Linear Quadratic Regulator (LQR) shown in (Liao, Wang et al. 2003, Zamzuri, Zolotas et al. 2007) study. The selection of weighting matrices for the vector of regulated response and control forces encourage the performances of LQG.

2.4.3 Neural Networks (NN)

Besides that, neural networks (NN) also one of the popular methods for designing robust, adaptive and intelligent control system. An adaptive system controller was designing using this method to control a semi-active suspension system incorporating an MR damper based on a quarter vehicle model (Guo, Hu et al. 2004). This algorithm consisted of two sub-controllers which is neural network controller (NNC) and neural network identifier (NNI). The NNC has a single output since the input voltage of the MR damper is a unique control variable. While, NNI can traces the system reponse and also can computes the back propogation error for NNC units. NNI can be trained in advances and less correction is needed in the control process. During NNI is trained, the errors propogated back to its input layer are indeed the training errors of the NNC.

2.4.4 Robust Control

Robust control technique has become a typical idea up to speed engineering system as a result of real system depends on external disturbance and measure noise. Robust control have been studied and according to Zribi and Karkoub (2004) two type of robust control schemes proposed which is an inverse dynamics control scheme and a sliding mode control scheme.

These controllers guarantee that the vertical and motion displacements of the chassis converge to zero. The simulation results confirmed that a decent performance of vehicle suspension was achieved, particularly with reference to vertical and motion displacements.

2.4.5 Skyhook Control

A skyhook controller is used to evaluate the control performance of the semi-active railway suspension system with MR damper (Hudha, Harun et al. 2011, Kwak, Lee et al. 2014, Oh, Shin et al. 2016). The skyhook controller is a semi-active controller and non-model controller. According to Oh, Shin et al. (2016) this controller is straightforward but very effective skyhook controller that does not need correct dynamic model is incredibly ofttimes utilized in railway vehicle system. Based on Hudha, Harun et al. (2011) bogie-based skyhook is able to remove the unwanted vehicle motion effectively and shows good performance in all three criteria compared to body-based skyhook and the passive system. This is thanks to the actual fact that bogie-based skyhook is in a position to do away with the impact of track irregularity before being transmitted to the vehicle body. Due to the fact, bogie-based skyhook is able to remove the result of track irregularity before being transmitted to the vehicle body.

2.5 Summary

Chapter 2 presented previous study on MR damper using parametric model to understand the behaviour of Bouc-Wen and Modified Bouc-Wen model. This chapter also presented the mathematical model from previous study of Bouc-Wen and Modified Bouc-Wen model to use in modelling the model in Matlab Simulink. Last but not least, system controller has been developed in order to improve the dynamical behaviour of MR damper.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will present about steps that have been taken in modelling the Bouc-Wen and Modified Bouc-Wen model using MATLAB Simulink. The simulation was developed by referring the mathematical model that have been discussed in Chapter 2 for Bouc-Wen and Modified Bouc-Wen model. This chapter will begin with a brief explanation of the step involved along this project and followed by project flow chart of this project. Next, the explanations are then followed by presentation for the modelling and force tracking control of MR damper model. This section will explain the step and mathematical model that involved to develop the force tracking control of MR damper.

3.2 Step involved

This action that will be carried out to achieve the objective in this project are listed below.

1) Exploring the MR damper background from any article that related and analyzing its problems through extensive literature review.
2) Studying and develop the mathematical model for Bouc-Wen and Modified Bouc-Wen model
3) The mathematical model that have been produce from Bouc-Wen and Modified Bouc-Wen will be transferred to the MATLAB Simulink software.
4) Based on the result that have been produced by the MATLAB Simulink software, the simulation result will be analyze and compare with the experimental result of the performance between Bouc-Wen and Modified Bouc-Wen model. If the result not same with the experimental result, then the simulation had to start over and fix the error occurred during simulation.
5) Analyze the PSM I data and result. Then, perform force-tracking control of MR damper using continuous state control in MATLAB Simulink.
6) The actual damping force of the MR damper is fed back with a feedback gain B and compared with the desired force. The resulting error is scaled using a proportional gain G.
7) Tune the value of B and G by a trial and error until the actual force of MR damper is same or close to the desired force waveform.
8) Final report will be written at the end of this project.

3.3 Project Flow Chart (PSM I)

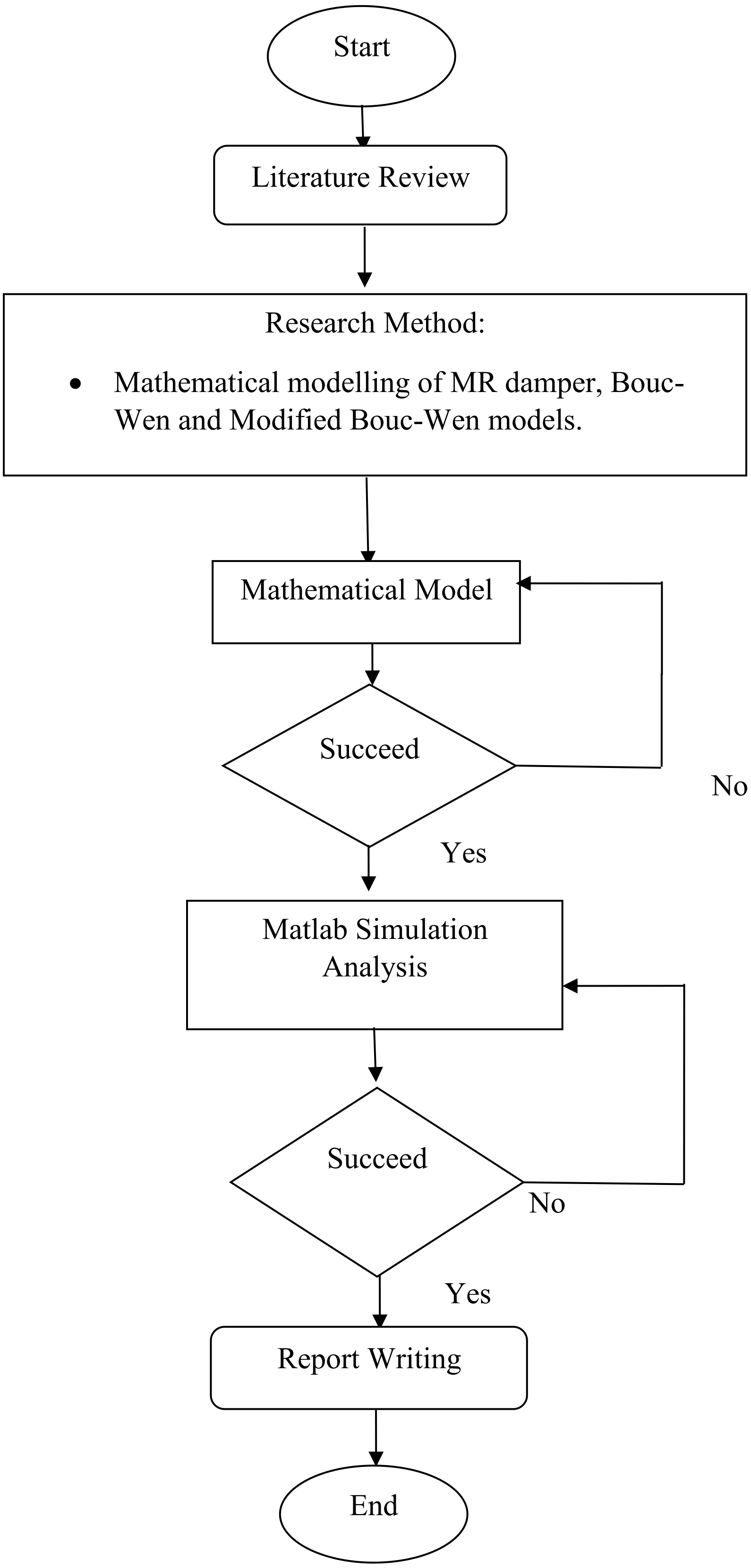

Figure 3.1 Flow chart (PSM I) of methodology

3.3.1 Project Flow Chart (PSM II)

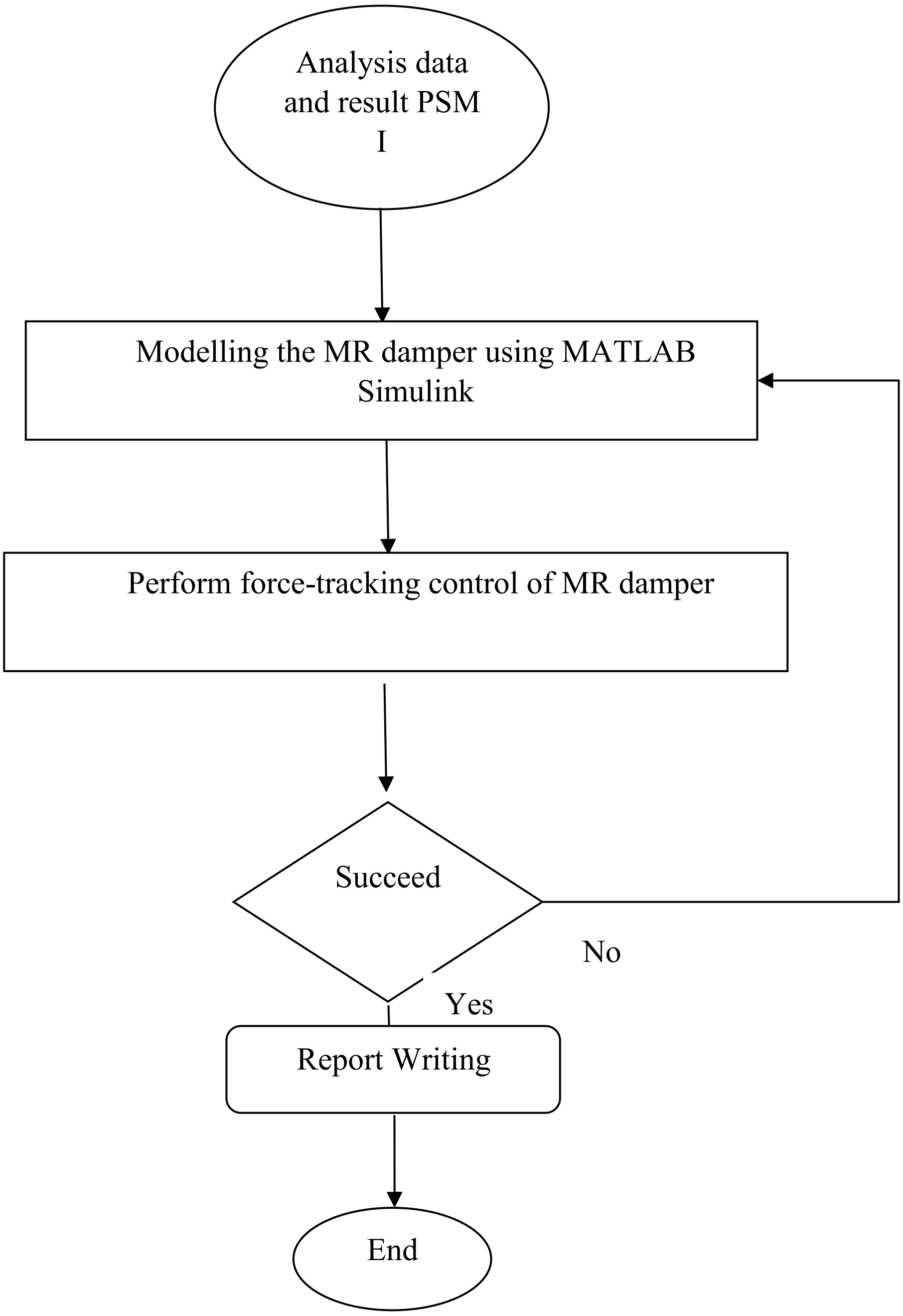

Figure 3.2 Flow chart (PSM II) of methodology

3.4 MATLAB Simulink Model

First of all, the mathematical model for Bouc-Wen and Modified Bouc-Wen model will be design using MATLAB Simulink simulation. The equations of mathematical model will be represented into block diagram using MATLAB Simulink Library block function. In order to avoid any error, the modelling must be precisely following the required equations during running the simulation.

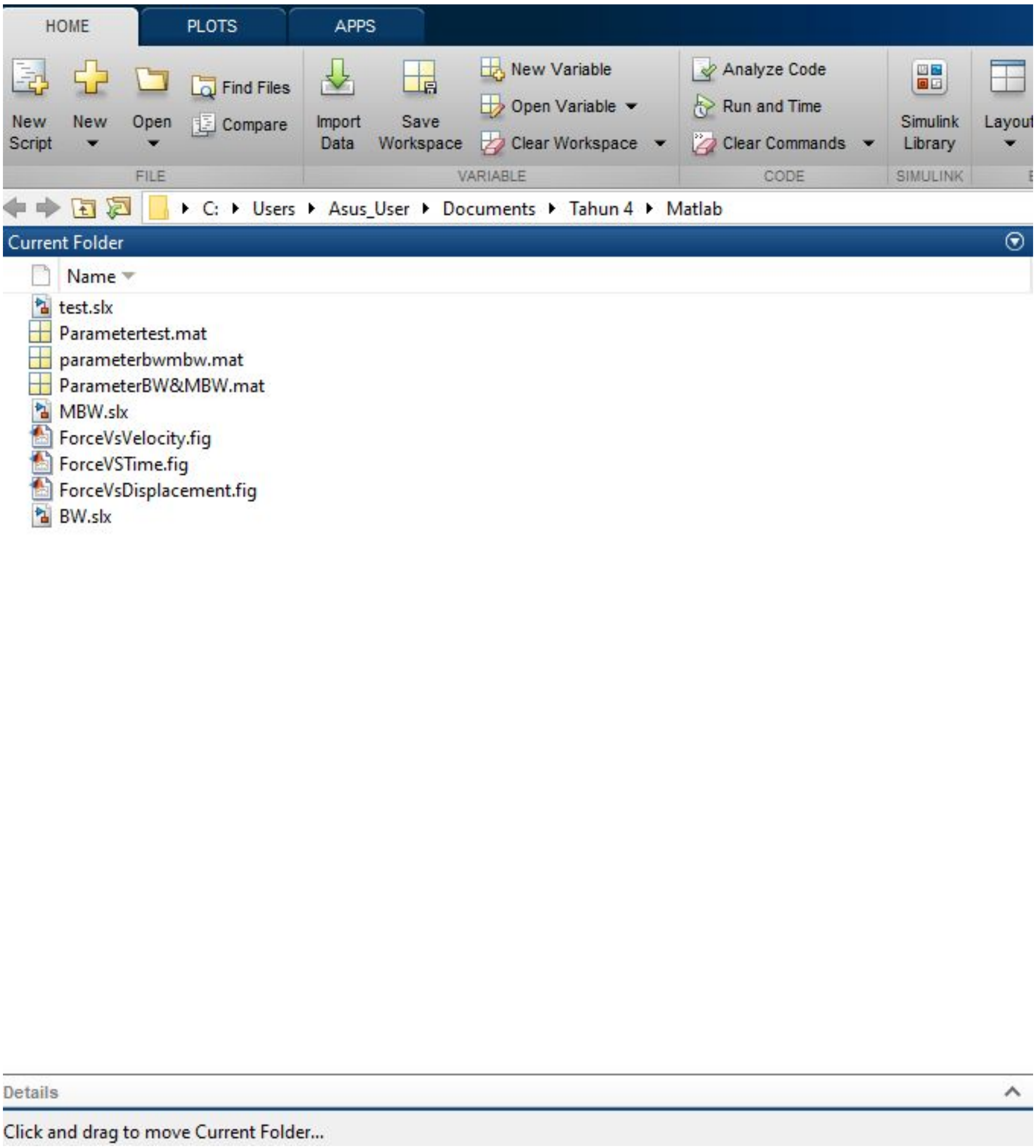

Figure 3.3 MATLAB interface

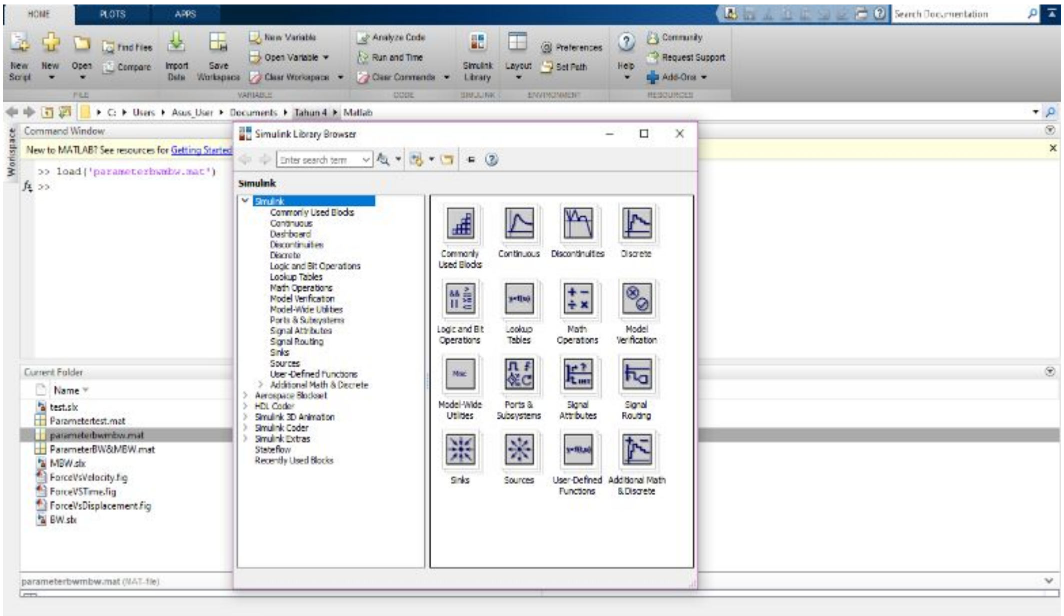

Figure 3.4 MATLAB Simulink Library

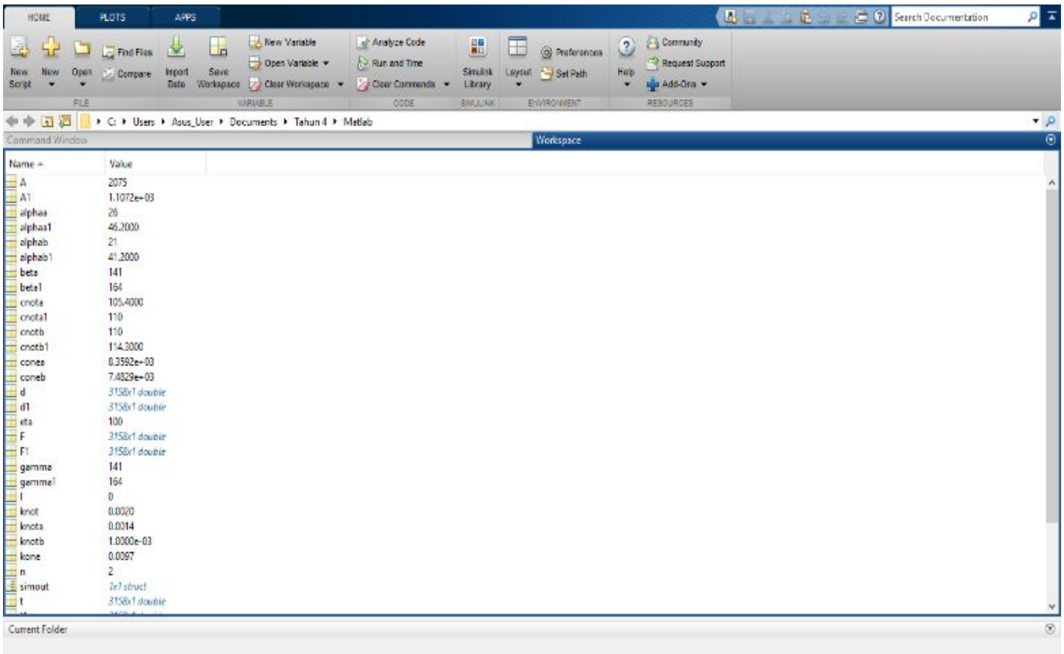

Figure 3.5 MATLAB Workspace for parameter of BW and MBW

3.4.1 Bouc-Wen Matlab Simulink Model

In this section, Bouc-Wen Simulink model will be presented in Figures 3.6 through 3.11. First thing first, the simulation in modelling Bouc-Wen model will be demonstrate step by step and begin with Eq (2.4) in Chapter 2 that has been used to develop model as shown in Figure 3.6.

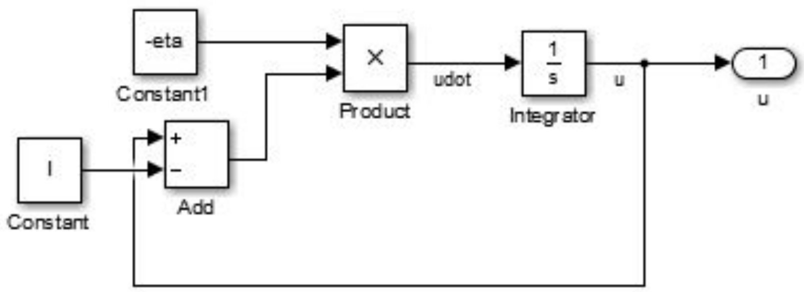

Figure 3.6 Subsystem for applied current, *v* for Bouc-Wen model

Next, the simulation modelling continued with Eq (2.3) in chapter 2 which include parameters of *a*, k_o and c_o as shown in Figure 3.7, 3.8, and 3.9.

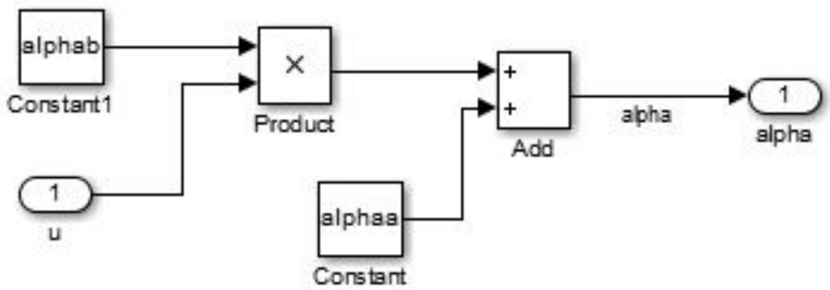

Figure 3.7 Subsystem of parameter *a* for Bouc-Wen model

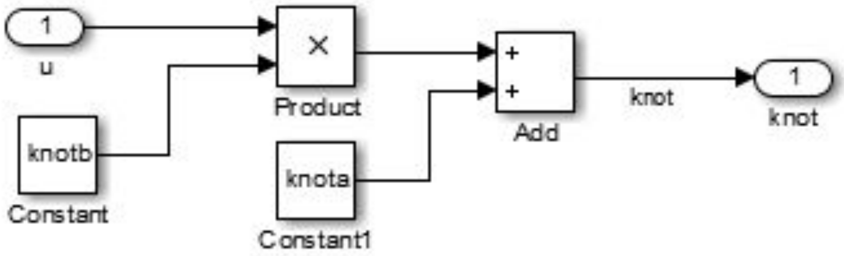

Figure 3.8 Subsystem of parameter k_o for Bouc-Wen model

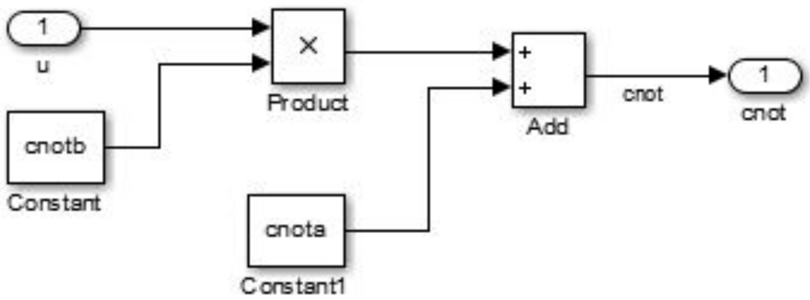

Figure 3.9 Subsystem of parameter c_o for Bouc-Wen model

Next, proceed with step of modelling that developed by Eq (2.2) which related to hysteresis behaviour of Bouc-Wen model as presented in Figure 3.10. Last but not least, the modelling of Bouc-Wen model will be completed by inserting the Eq (2.1) in the simulation as shown in Figure 3.11.

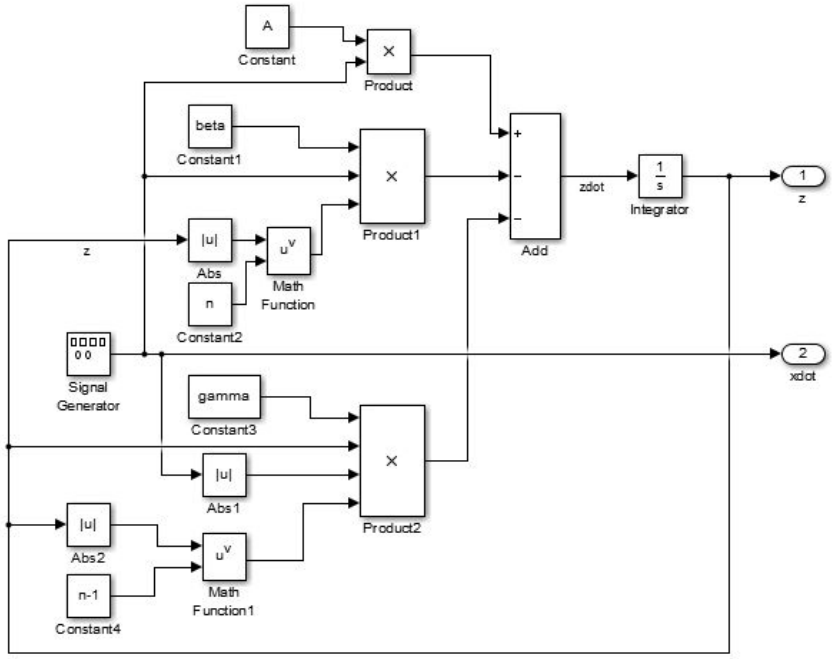

Figure 3.10 Subsystem of hysteresis, z for Bouc-Wen model

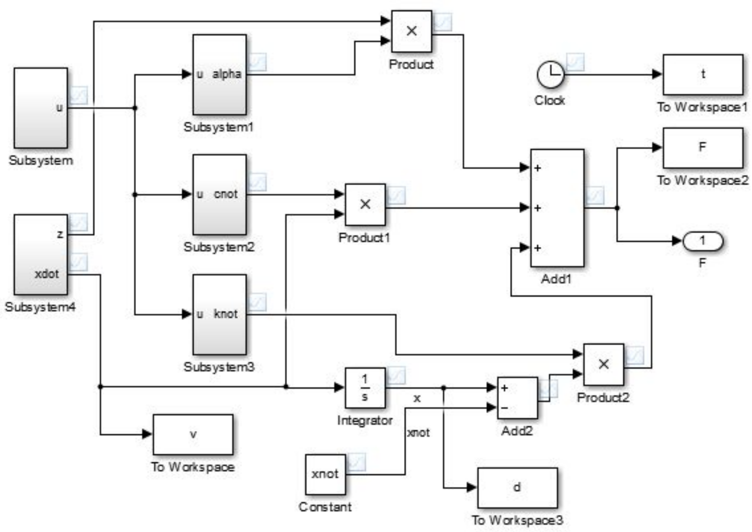

Figure 3.11 Complete set of Bouc-Wen Simulink model

3.4.2 Modified Bouc-Wen Matlab Simulink model

In this section, the Simulink of Modified Bouc-Wen model is shown in Figures 3.12 through 3.19. These figure shows the steps that use in the process of modelling the Modified Bouc-Wen model. First of all, Eq (2.4) in Chapter 2 again use as the first step to develop this model as shown in Figure 3.12.

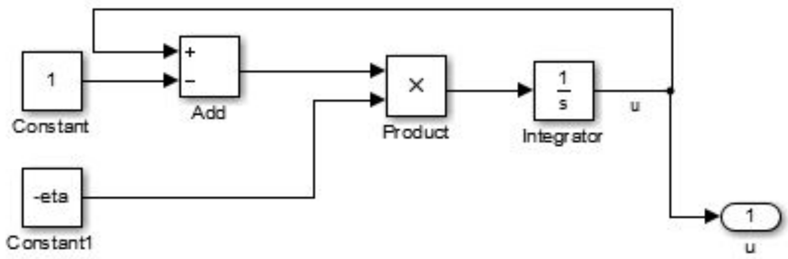

Figure 3.12 Subsystem for applied current, v for Modified Bouc-Wen model

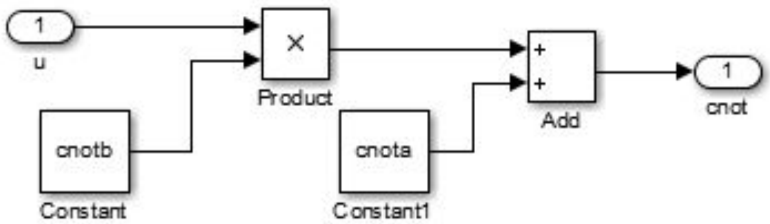

Figure 3.13 Subsystem of parameter c_o for Modified Bouc-Wen model

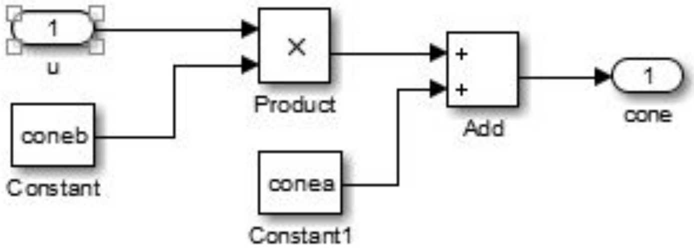

Figure 3.14 Subsystem of parameter c_{1a} and c_{1b} for Modified Bouc-Wen model

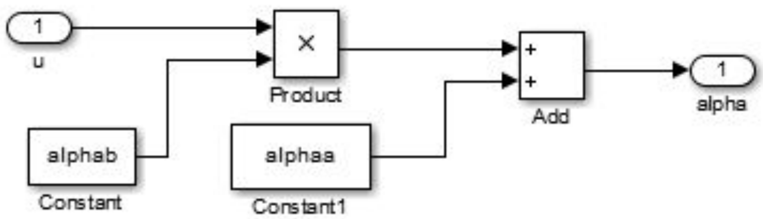

Figure 3.15 Subsystem of parameter a_a and a_b for Modified Bouc-Wen model

Next, Eq (2.7) are apply for the next step of modelling process that relate to the hysteresis behaviour of Modified Bouc-Wen model as shown in Figure 3.15.

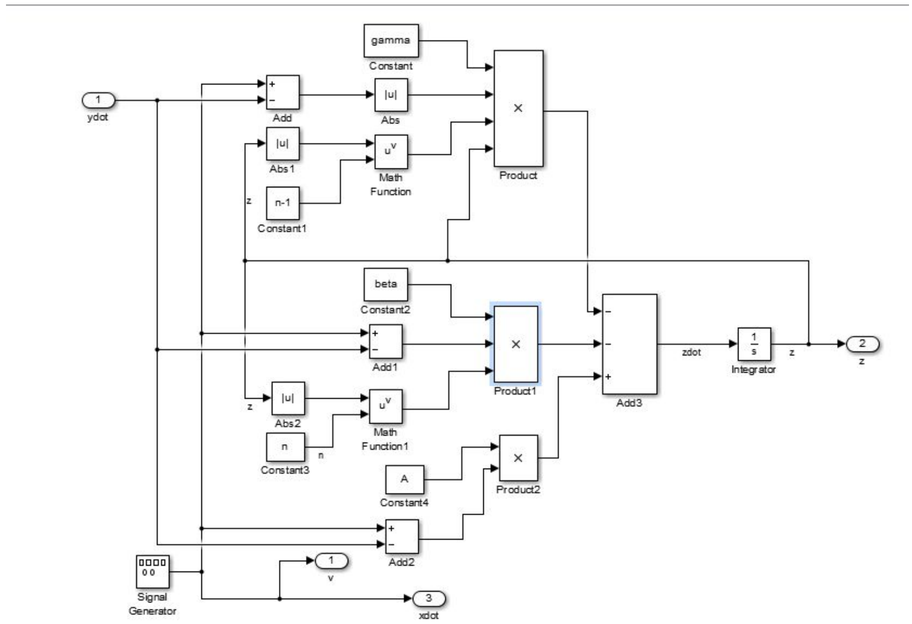

Figure 3.16 Subsystem for Modified Bouc-Wen model hysteresis

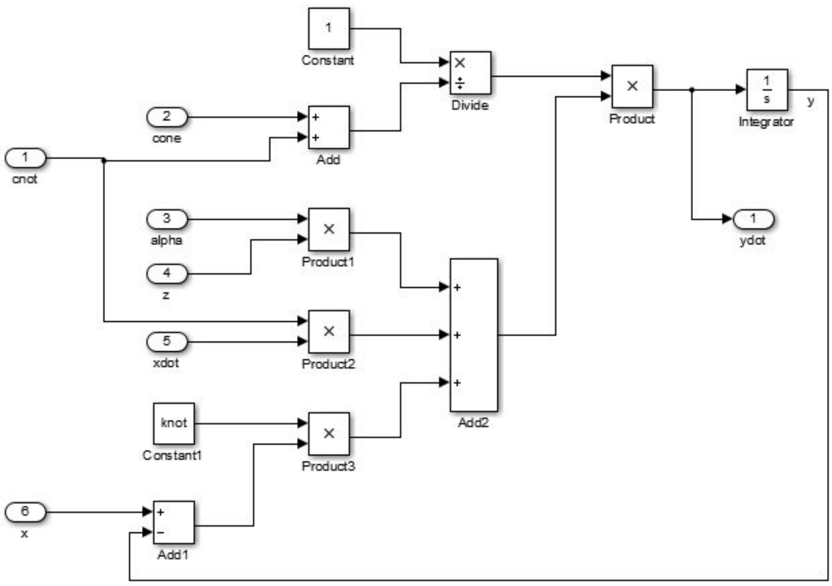

Figure 3.17 Subsystem of displacement, *y* for Modified Bouc-Wen model.

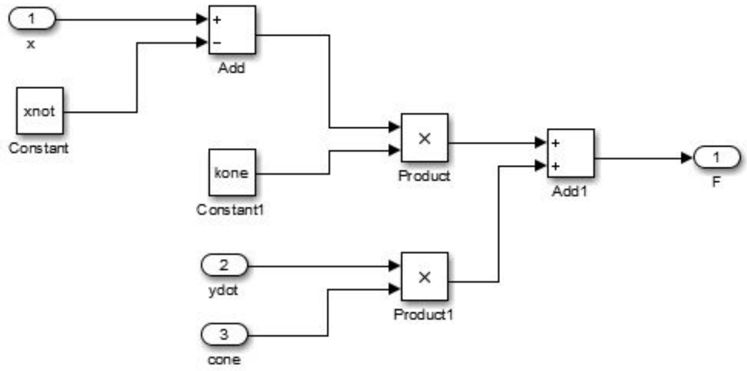

Figure 3.18 Subsytem of damping force, *F* for Modified Bouc-Wen model

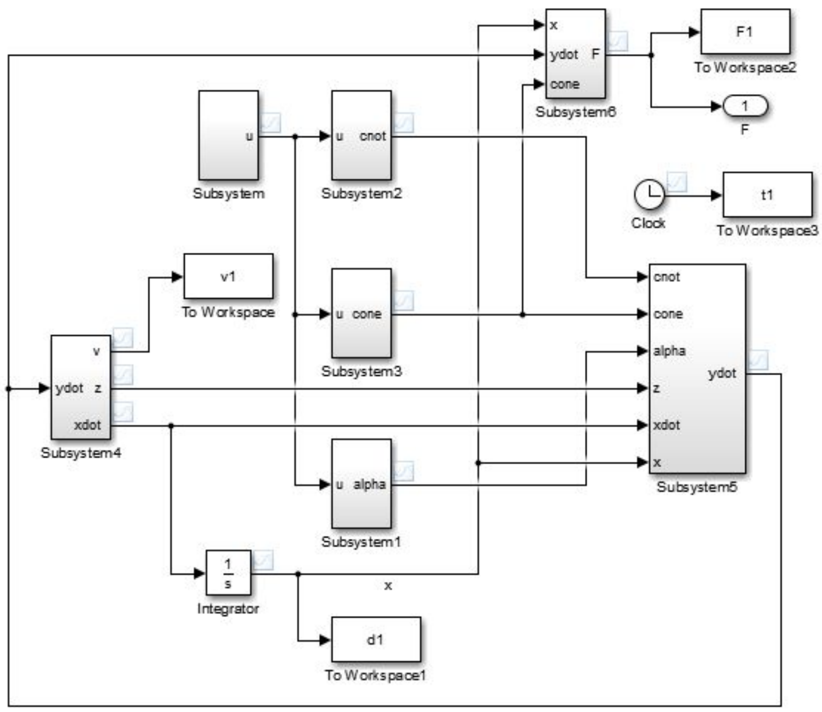

Figure 3.19 Complete set of Modified Bouc-Wen model simulation

3.5 Parameter identification of Bouc-Wen and Modified Bouc-Wen

In order to accurately evaluate the performance of the identification algorithm, an experimental data are obtained which the parameters for Bouc-Wen model which is α_a, α_b, k_{0a}, k_{0b}, c_{0a}, c_{0b}, γ, β , A, n, η and parameters of Modified Bouc-Wen model which is α_a, α_b, α_b, c_{0a}, c_{0b}, c_{1a}, c_{1b}, k_0, k_1, γ, β , A, n, η due to just one representative test of random inputs (displacement and voltage) to the damper. The parameter clarification is:

γ, β , A, - Parameter representing the control of the linearity during unloading and the smoothness of the transition from the pre-yield to post-yield area.

α - Parameter representing the stiffness for the damping force component associated with the evolution variable z

k_0 - Parameter representing the stiffness of the spring associated with the nominal damper due to the accumulator

c_0 - Parameter representing viscous damping

c_1 - Parameter representing the dashpot included in the model to produce the roll-off at low velocities

Table 3.1: Parameters of Bouc-Wen and Modified Bouc-Wen for 1000N MR damper.

Source : (Talatahari, Kaveh et al. 2012)

Parameter	Unit	Bouc-Wen	Modified Bouc-Wen
α_a	kN/m	26.0	46.2
α_b	kN/m/V	29.1	41.2
c_{0a}	kN s/m	105.4	110.0
c_{0b}	kN s/m/V	131.6	114.3
c_{1a}	kN s/m	-	8359.2
c_{1b}	kN s/m/V	-	7482.9
k_0	kN/m	-	0.002
k_{0a}	kN s/m	0.0014	-
k_{0b}	kN s/m/V	0.001	-
k_1	kN/m	-	0.0097
γ	m^{-2}	141.0	164.0
β	m^{-2}	141.0	164.0
A	-	2074.5	1107.2
n	-	2	2
η	s^{-1}	100	100

3.6 Modelling MR damper for Force Tracking Control

3.6.1 Flowchart for force tracking control of MR damper

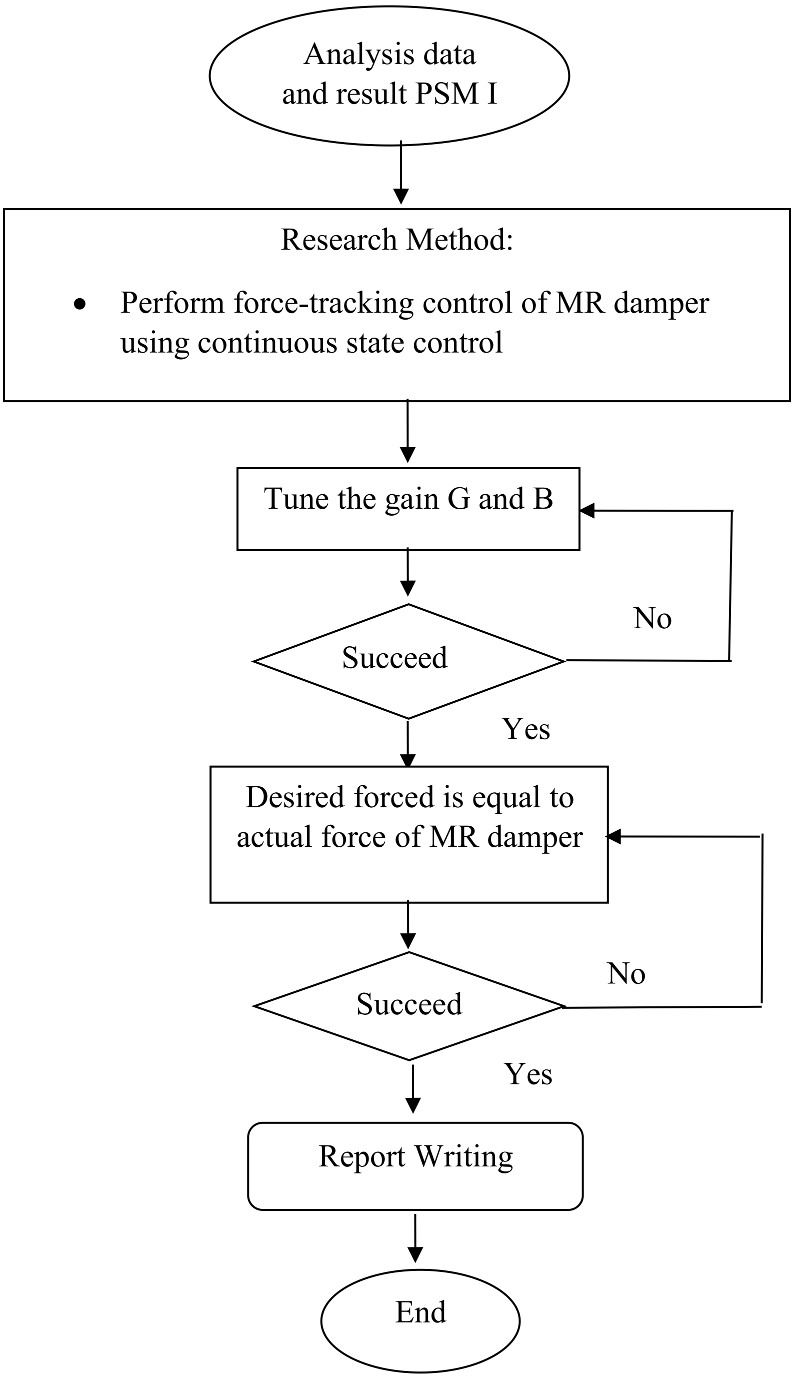

Figure 3.20 Flow chart of force tracking control of MR damper

The purpose for force tracking control of MR damper is to track the desired force by obtaining several input functions which are wave of sinusoidal, saw-tooth and square function. The performance of force tracking control of MR damper evaluated by synchronizing the actual force produce by MR damper as close as possible with the desired force. Bouc-Wen model have been chosen as MR damper to undergo the force-tracking control based on the simulation result of comparing between Bouc-Wen model and Modified Bouc-Wen model. Force-tracking control of MR damper model for this thesis is performed using a simple continuous state control. To generate approximately the corresponding desired control force *Fd,* the command signal is selected and described by the MATLAB Simulink block diagram as shown in Figure 3.20.

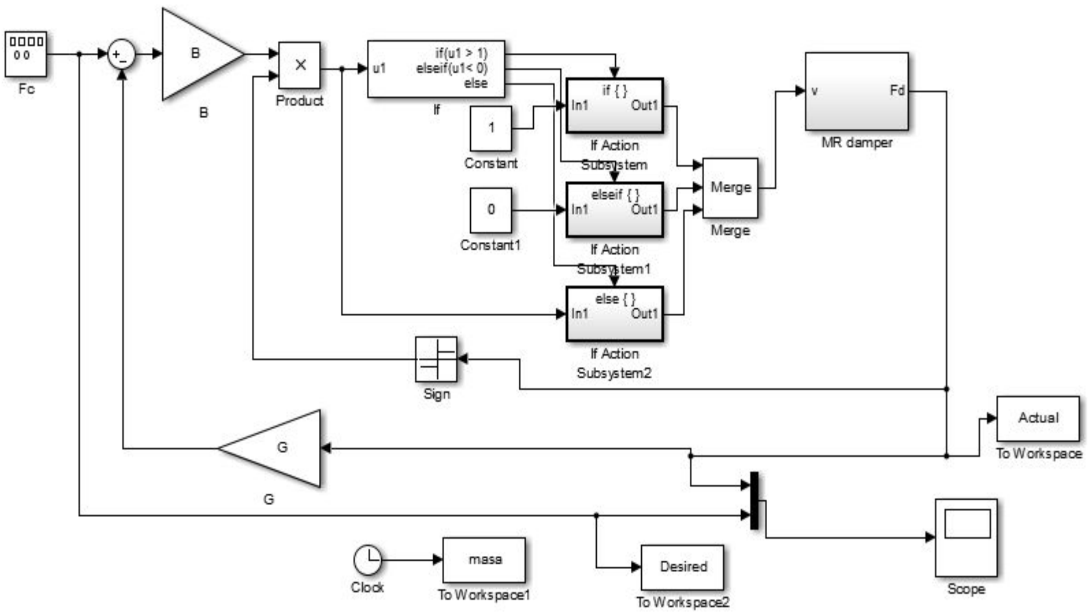

Figure 3.21 Force tracking control of MR damper

In planning this system, the particular damping force of MR damper is feedback with a feedback gain G and compared with the specified force. The ensuing error is scaled employing a proportional gain B. The controller perform is enabled only the direction of damping force and therefore the error are within the same direction. If the specified force and the damper rate have totally different sign and set the command current signal to zero. Between the allowable maximum and minimum currents, the corrected control signal is then saturated. The value of gain B and gain G are determined by using trial and error method. The algorithm for selecting command signal can be stated as below Equation (3.1) where *Fd* is the actual damping force and *Fc* is the desired damping force.

$$\begin{aligned} &if \quad B(Fc-GFd)\, sign\,(Fd) > Imax \;\; then \quad i=Imax \\ &if \quad B(Fc-GFd)\, sign\,(Fd) > Imin \;\; then \quad i=Imin \\ &\quad else \quad i=B(Fc-GFd)\, sign\,(Fd) \end{aligned} \tag{3.1}$$

3.7 Summary

Chapter 3 present the methodology of this project which begin with collecting data from related resources to develop the mathematical model for Bouc-Wen and Modified Bouc-Wen model. The mathematical model of this parametric model was applied to generate the Simulink model for both MR dampers which Bouc-Wen and Modified Bouc-Wen. Next, the parameter of Bouc-Wen and Modified Bouc-Wen model was identified, then loaded to the Simulink model to come out with result of this model and the result will be analyze. After the result of comparison between Bouc-Wen model and Modified Bouc-Wen model has been analyzed, the study of simulation for force tracking control of MR damper conducted using continuous state control and the result will be presented in Chapter 4.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

In this chapter, the result of comparison between Bouc-Wen and Modified Bouc-Wen model will be presented based on mathematical model of this parametric model. Next, the effect of MR damper when applied current and the result of force tracking control of MR damper will be covered in this chapter.

4.1.1 Result for Bouc-Wen and Modified Bouc-Wen model

This section presenting the result that was obtained from MATLAB Simulink model by applying the parameter identification based on table 3.1 in Chapter 3. These results showed favorable result with compared to the past experiment that conducted by previous researcher. The strategy used has thus been shown to be accurate and precise system identification method and ready to estimate the damping force under any desired combination of current and frequency of the excitation. Based Figure 4.1, 4.2 and 4.3, the result of Bouc-Wen model and Modified Bouc-Wen model was demonstrated using MATLAB Simulink. Parameter used for both models are for cable-stayed bridged of 50 N to 200 N.

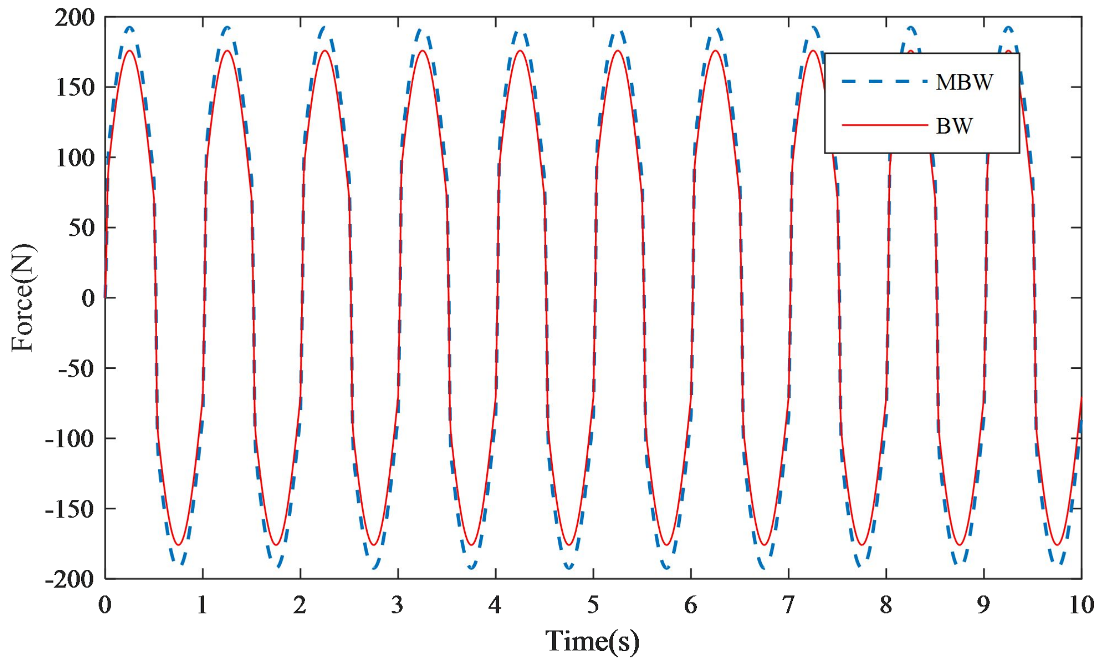

Figure 4.1 Graph of Force (N) against Time (s) for BW and MBW model

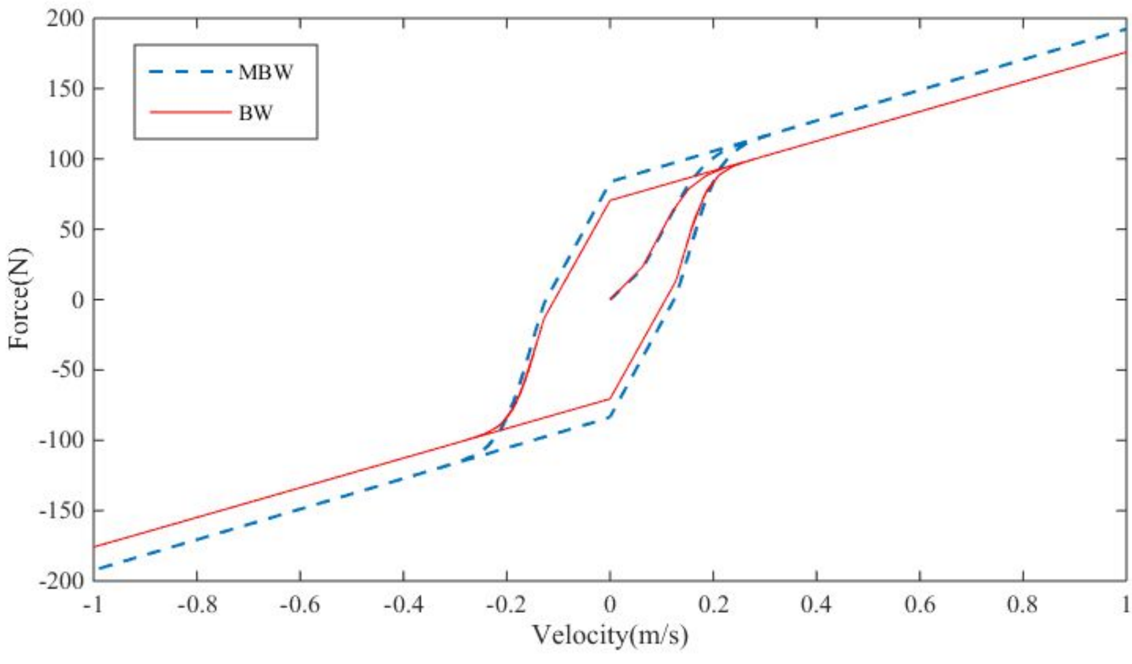

Figure 4.2 Graph of Force (N) against Velocity (m/s) for BW and MBW

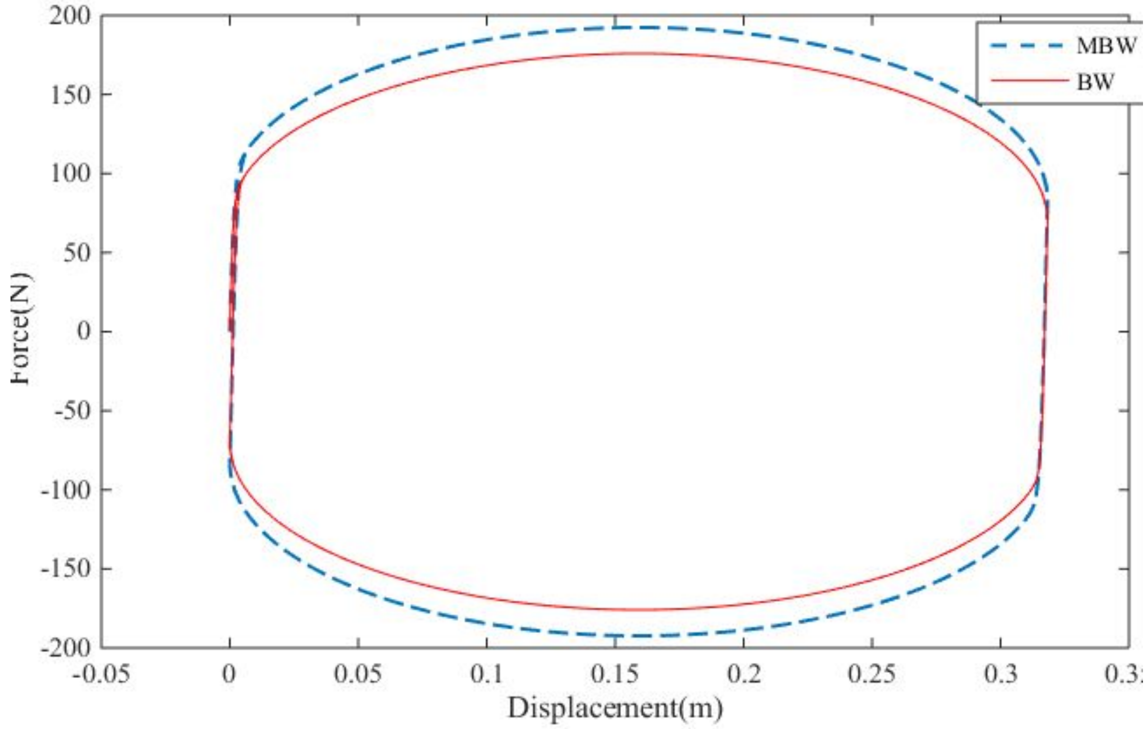

Figure 4.3 Graph of Force (N) against Displacement (m) for BW and MBW

Based on graph comparison between Bouc-Wen model and Modified Bouc-Wen model shown in Figure 4.1 to Figure 4.3, it can be seen that the performance of Bouc-Wen model and Modified Bouc-Wen almost does not show huge differences in force-time, force-displacement and force-velocity characteristics.

4.2 The Effect of Applied Current to MR Damper

In this section the result of MR damper when current is applied, obtained according to various amount of current applied which is from 0A to 5A. Based on result of force-time, force-velocity and force-displacement shown in Figure 4.4 to Figure 4.6. By applying current 0A to 5A, in range of displacement from 0 to 0.314m the force also increased as shown in Figure 4.4. The hysteresis behavior of MR damper model become bigger when higher magnitude of current was applied as shown in Figure 4.5.

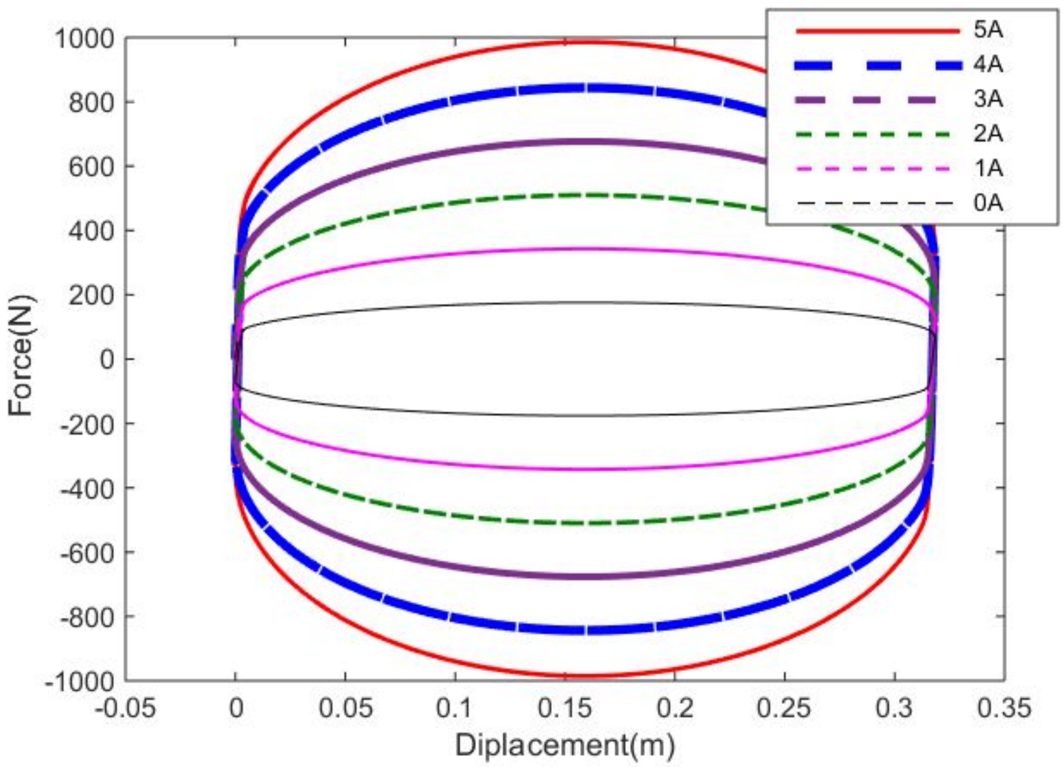

Figure 4.4 Graph of Force (N) against Displacement (m) for different magnitude of current

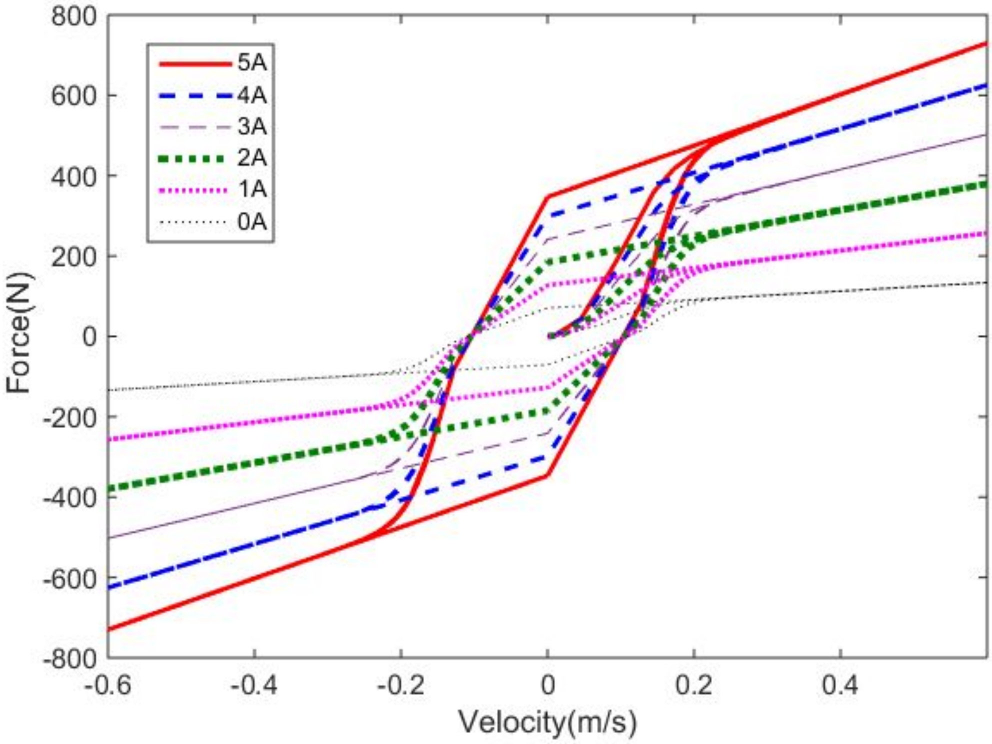

Figure 4.5 Graph of Force (N) against Velocity (m/s) for different magnitude of current

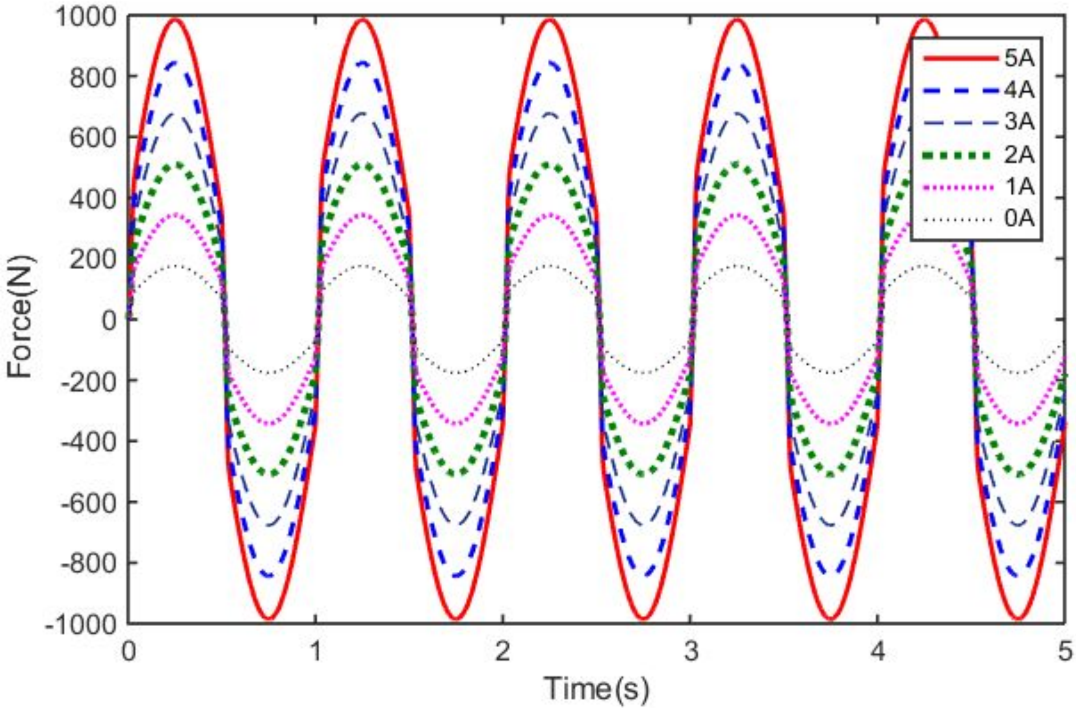

Figure 4.6 Graph of Force (N) against Time (s) for different magnitude of current

Table 4.1 Peak force of MR damper for different magnitude of current

Current, I (A)	**Peak Force (N)**
0A	175.9N
1A	342.7N
2A	509.6N
3A	676N
4A	843.4N
5A	960.1N

The simulation result of the peak force for MR damper when applied current at various magnitude of current shown in Table 4.1. This result was taken and analyzed from three different type of graph which is force-time, force-velocity and force-displacement characteristic. From the result in Table 4.1, it can conclude that as the current applied increase, the corresponding damping force of MR damper is also increase. Figure 4.6 for force-time characteristic shows that the peak force gradually increases as the current applied is increased. In particular, when the current is applied to the MR damper, the viscosity of fluid in MR damper will increase. When the viscosity of fluid in MR damper is increase, the damping force of MR damper will also increase and that explained why peak force in the graph from Figure 4.6 increase as the current increased.

4.3 Force Tracking Control of MR damper

This section will be presented the force tracking control of MR damper model using continuous state feedback controller for square, sinusoidal and sawtooth function of target force. The force tracking control are conducted for maximum current only which the peak force for maximum current is approximately 950N.

In this simulation for sinusoidal function the parameters of feedback gain B are set at 0.0009 and for the proportional gain G is set at -0.173. Based on Figure 4.7, it can be seen that the force tracking control of MR damper for sinusoidal function of target force is excellent because the actual force value is followed the line of desired force closely but when the actual damping force reached to 0 N, the actual force line does not follow the desired force line closely. The peak value for the desired force is 947.8 N and the peak value for actual force is 954 N.

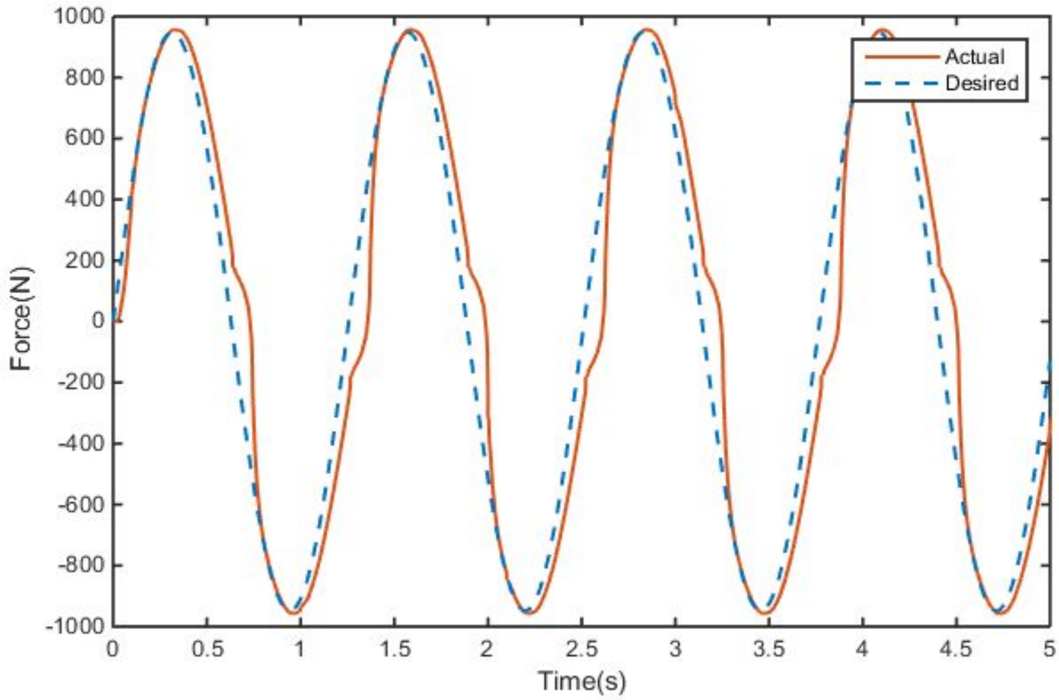

Figure 4.7 Sinusoidal function

Next, it can be seen that the Figure 4.8 present the force tracking control of MR damper for square function of target force is good as the sinusoidal function and the line of actual force keep follow closely to the desired force especially at peak 948 N. For square function simulation, the value gain B is set to -10 and the value of proportional gain G is set to 100.

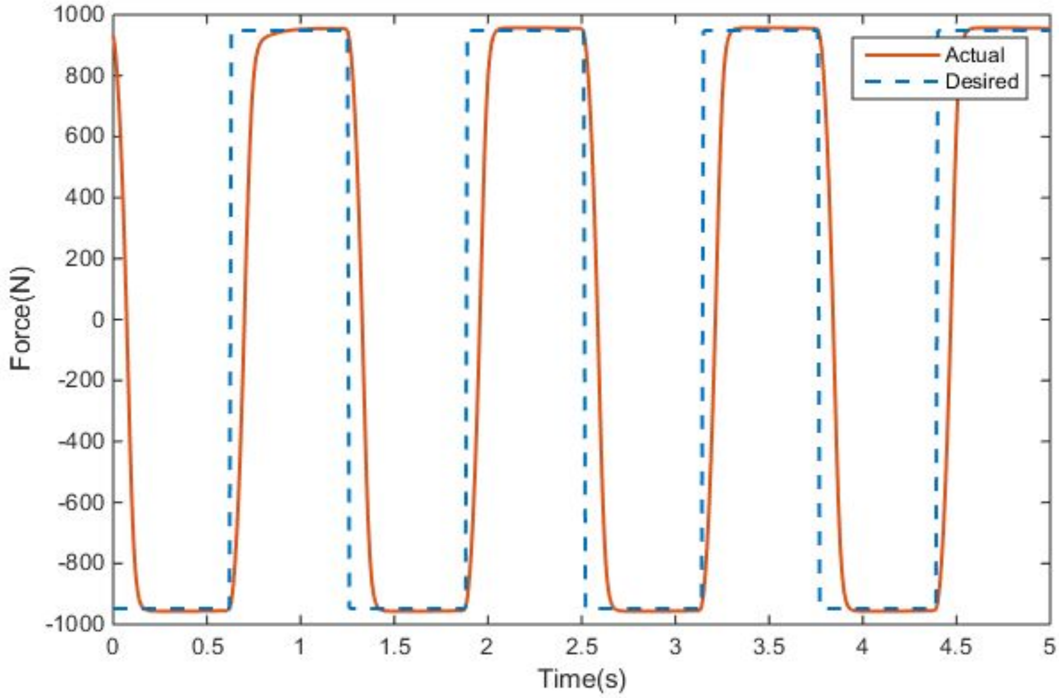

Figure 4.8 Square function

However, the simulation results of tracking force on sawtooth function at various peak forces that are shown in Figure 4.9 are in good performance although it is rather difficult to closely follow the desired force especially at the peak force value of desired force above 800 N. The peak for the actual force is 835.5 N and the peak for the desired force is 942.9 N. For this sawtooth simulation the value of gain B is set to 0.00485019 and the proportional gain G is set to 0.55.

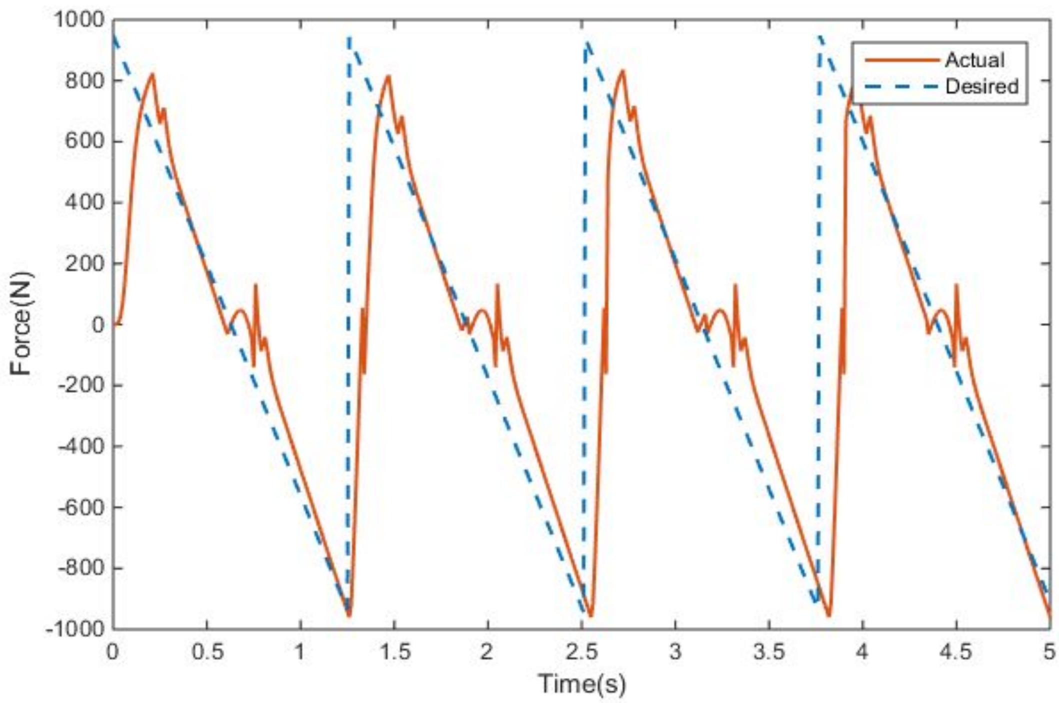

Figure 4.9 Sawtooth function

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This chapter is divided into two sections. The first section summarizes the result of the research performed and for the second section is present the recommendations of this thesis for future work. There are two main objectives for this study that was highlighted in Chapter 1 which is to analyze MR damper model based on parametric modeling method and to design the force tracking control of MR damper. This chapter will discuss how are the objective was achieved.

5.1 Conclusion

For the conclusion of the studies represent in this paper intended to provide a deeper insight into the behavior of semi-active device which is MR dampers and their potential application in a railway vehicle suspension system. The mathemtical model for parametric model of Bouc-Wen and Modifed Bouc-Wen model has been completely investigated based on previous researcher. Those mathematical model has been used in order to create the Simulink model for BW and MBW model in MATLAB Simulink. The result obtained from BW and MBW model has been compared using MATLAB Simulink model by using force of 50 N to 200 N. The effect of applied current to the MR damper have been performed and investigated that show the current and damping force is increase simultaneously. The modelling for force tracking control of MR damper has been particularly highlighted in Chapter 3. The result of force tracking control has been presented in Chapter 4 that show the actual force produced by MR damper is able to follow closely the desired force under three different input function at maximum peak force. Therefore, all of the objective for this study is achieved.

5.2 Recommendation

The hysteretic behavior of this Bouc-Wen model based on the characteristic of their parameter. In future work recommend is to conduct the study for the behavior of non-parametric model such polynomial and neural network which need to conduct the experiment first and then the simulation analysis. For force tracking control, in future are needed to conduct some experiment for validate the MR damper model to simulate the actual force produce by MR damper using different amount of current and frequency.

REFERENCES

Atray, V. S. and P. N. Roschke (2003). "Design, fabrication, testing, and fuzzy modeling of a large magnetorheological damper for vibration control in a railcar". Proceedings of the 2003 IEEE/ASME Joint Rail Conference, 2003..IEEE, 2003.

Carlson, J. D. and M. R. Jolly (2000). "MR Fluid, Foam and Elastomer Devices." Mechatronics 10(4–5): 555-569.

Choi, S.-B., et al. (2000). "Vibration Control of a MR Seat Damper for Commercial Vehicles." Journal of Intelligent Material Systems and Structures 11(12): 936-944.

Guo, D., et al. (2004). "Neural network control for a semi-active vehicle suspension with a magnetorheological damper." **10**(3): 461-471.

Guo, S., et al. (2006). "Dynamic modeling of magnetorheological damper behaviors." Journal of Intelligent material system and structure 17(1): 3-14.

Hudha, K., et al. (2011). "Lateral suspension control of railway vehicle using semi-active magnetorheological damper". Intelligent Vehicles Symposium (IV), 2011 IEEE, IEEE.

İ, Ş., et al. (2010). "Comparison of some existing parametric models for magnetorheological fluid dampers." Smart Materials and Structures 19(3): 035012..

Ismail, M., et al. (2009). "The Hysteresis Bouc-Wen Model, a Survey." Archives of Computational Methods in Engineering 16(2): 161-188.

Kwak, M. K., et al. (2014). "Hardware-in-the-loop simulation experiment for semi-active vibration control of lateral vibrations of railway vehicle by magneto-rheological fluid damper." Vehicle System Dynamics 52(7): 891-908.

Kwok, N. M., et al. (2006). "A novel hysteretic model for magnetorheological fluid dampers and parameter identification using particle swarm optimization." Sensors and Actuators A: Physical 132(2): 441-451.

Lai, C. Y. and W. H. Liao (2016). "Vibration Control of a Suspension System via a Magnetorheological Fluid Damper." Modal Analysis 8(4): 527-547.

Lam, A. H.-F. and W.-H. J. I. J. o. V. D. Liao (2003). "Semi-active control of automotive suspension systems with magneto-rheological dampers." International Journal of Vehicle Design 33(1-3): 50-75.

Lee, H. G., et al. (2011). "Performance Evaluation of a Quarter-Vehicle MR Suspension System with Different Tire Pressure." International Journal of Precision Engineering and Manufacturing 12(2)(2): 203-210.

Liao, W., et al. (2003). "Semiactive vibration control of train suspension systems via magnetorheological dampers." Journal of Intelligent material systems and structures 14(3): 161-172.

Metered, H., et al. (2010). "The experimental identification of magnetorheological dampers and evaluation of their controllers." Mechanical Systems and Signal Processing 24(4): 976-994.

Nicholas, C. R. and M. W. Norman (2004). "Volume-constrained optimization of magnetorheological and electrorheological valves and dampers." Smart Materials and Structures 13(6): 1303.

Oh, J.-S., et al. (2016). "Vibration control of a semi-active railway vehicle suspension with magneto-rheological dampers." Advances in Mechanical Engineering 8(4), p. 1687814016643638

Peel, D. J., et al. (1996). "Dynamic modelling of an ER vibration damper for vehicle suspension applications." Smart Materials and Structures 5(5): 591

Ronghui, Z., et al. (2010). LQG control for the integrated tilt and active lateral secondary suspension in high speed railway vehicles. Control and Automation (ICCA), 2010 8th IEEE International Conference on.

Şahin, İ., Engin, T., & Çeşmeci, Ş. (2010). Comparison of some existing parametric models for magnetorheological fluid dampers. Smart materials and structures, 19(3), 035012.

Sapiński, B., et al. (2003). "Analysis of parametric models of MR linear damper." Journal of Theoretical and Applied Mechanics 41(2): 215-240.

Shin, Y.-J., et al. (2014). "H∞ control of railway vehicle suspension with MR damper using scaled roller rig." Smart Materials and Structures 23(9).

Sims, N. D., et al. (2003). "A unified modelling and model updating procedure for electrorheological and magnetorheological vibration dampers." Smart materials and structures 13(1): 100.

Spencers, J. B. F., et al. (1997). "Phenomenological Model of Magnetorheological Damper." Journal of Engineering Mechanics. 123(3): 9.

Talatahari, S., et al. (2012). "Parameter identification of Bouc-Wen model for MR fluid dampers using adaptive charged system search optimization." Journal of Mechanical Science and Technology 26(8): 2523-2534.

Van Kasteel, R., et al. (2003). "A New Shock Absorber Model with an Application in Vehicle Dynamics Studies." SAE International: 305-311

Wang, D. H. and W. H. Liao (2005). "Modeling and Control of Magnetorheological Fluid Dampers using Neural Networks." Smart Materials and Structures 14: 111-126.

Zamzuri, H., et al. (2007). LQG with Fuzzy Correction Mechanism in Tilting Railway Vehicle Control Design. The 3rd IFAC Workshop on Advanced Fuzzy and Neural Control, University of Valenciennes et du Hainaut Cambrésis, France. 40(21): 7-12

Zapateiro, M., et al. (2009). "Semiactive Backstepping Control for Vibration Reduction in a Structure with Magnetorheological Damper Subject to Seismic Motions." Journal of Intelligent Material Systems and Structures 20(17): 2037-2053.

Zong, L.-H., et al. (2013). "Semi-active H∞ control of high-speed railway vehicle suspension with magnetorheological dampers." Vehicle System Dynamics 51(5): 600-626..

Zribi, M. and M. J. M. A. Karkoub (2004). "Robust control of a car suspension system using magnetorheological dampers." Modal Analysis 10(4): 507-524.

APPENDICES

Trial and Error Method

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Waveform	No	B	G		Waveform	No	B	G		Waveform	No	B	G
2	Square	1	0	0		Sawtooth	1	0.0012	-0.09		Sinusoidal	1	0.0001	-0.173
3	Square	2	10	-1		Sawtooth	2	0.0013	-0.08		Sinusoidal	2	0.0002	-0.12
4	Square	3	20	-2		Sawtooth	3	0.0014	-0.07		Sinusoidal	3	0.0003	-0.13
5	Square	4	30	-3		Sawtooth	4	0.0015	-0.06		Sinusoidal	4	0.0004	-0.14
6	Square	5	40	-4		Sawtooth	5	0.0016	-0.05		Sinusoidal	5	0.0005	-0.15
7	Square	6	50	-5		Sawtooth	6	0.0017	-0.04		Sinusoidal	6	0.0006	-0.16
8	Square	7	60	-6		Sawtooth	7	0.0018	-0.03		Sinusoidal	7	0.0007	-0.17
9	Square	8	70	-7		Sawtooth	8	0.0019	-0.02		Sinusoidal	8	0.0008	-0.171
10	Square	9	80	-8		Sawtooth	9	0.002	-0.01		Sinusoidal	9	0.0009	-0.172
11	Square	10	90	-9		Sawtooth	10	0.001	0.01		Sinusoidal	10	0.0009	-0.173
12	Square	11	100	-10		Sawtooth	11	0.0015	0.016		Sinusoidal			
13	Square	12	-10	100		Sawtooth	12	0.0011	0.02		Sinusoidal			
14	Square	13				Sawtooth	13	0.0011	0.001		Sinusoidal			
15	Square	14				Sawtooth	14	0.0013	0.18		Sinusoidal			
16	Square	15				Sawtooth	15	0.0033	0.1		Sinusoidal			
17	Square	16				Sawtooth	16	0.0011	0.25		Sinusoidal			
18	Square	17				Sawtooth	17	0.0015	0.3		Sinusoidal			
19	Square	18				Sawtooth	18	0.004851	0.55		Sinusoidal			
20	Square	19				Sawtooth	19	0.00485019	0.55		Sinusoidal			
21	Square	20				Sawtooth	20	0.00695	0.945		Sinusoidal			
22														
23														
24														

GANTT CHART (PSM I)

No	Task	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1	Approval from supervisor and register for project title														
2	Brainstorming and discussion about the detail of this project with supervisor														
3	Planning when to meet and briefing about PSM 1 activities														
4	Do research and study about the MR damper model														
5	In form of table, list out 56 references for literature review														
6	Do research and study about the mathematical model of Bouc-Wen and Modified Bouc-Wen														
7	Prepare progress report and submit														
8	Prepare Chapter 2: Literature Review														
9	Prepare Chapter 3: Methodology														
10	Compilation of PSM 1: Final report														
11	Presentation Session for PSM 1														
12	Submit PSM 1 final report														

GANTT CHART (PSM II)

No	Task	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
1	Discussion about comments and mistakes in PSM 1 report														
2	Brainstorming to solve and do the correction of the report.														
3	Present progress to the supervisor														
4	Do research and study about controller														
5	List out references in form of table for literature review														
6	Prepare progress report and submit														
7	Prepare Chapter 4: Result and Discussion														
8	Prepare Chapter 5: Conclusion														
9	Do the improvement and revision Chapter 1 until Chapter 3														
10	Compilation of PSM 2: Final report														
11	Presentation Session for PSM 2														
12	Submit PSM 2 final report														