MODELING MAGNETO-RHEOLOGICAL DAMPER USING ANFIS METHOD

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Report submitted in partial fulfillment of the requirements
for the award of Bachelor's Degree of Mechanical Engineering

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I certify that the project entitled "Modeling Magneto-Rheological using ANFIS method" is written by Mohd Ridzwan bin Hj Ramli. I have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for award of degree of Bachelor of Engineering. I herewith recommend that it be accepted in partial fulfillment of the requirements for the degree of bachelor of Mechanical Engineering.

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I hereby declare that I have checked this thesis and in my opinion this project is satisfactory in terms of scope and quality for the award of the degree of Bachelor's Degree of Mechanical Engineering.

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STUDENT'S DECLARATION

I declare that this thesis entitled "Modeling Magneto-Rheological Damper Using ANFIS Method" is the result of my own research except as cited in the references. The thesis has not been accepted for any bachelor's degree concurrently submitted in candidature of any other degrees.

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This work is sincerely dedicated to my beloved and precious one,

My father Hj Ramli bin Hj Husin,
My mother Hjh Pauziah bt Yusof,
My siblings Haslinda bt Hj Ramli,
Azizah bt Hj Ramli,
Zaihan bt Hj Ramli,
Lailatulakma bt Hj Ramli,
Hasnan b Hj Ramli,
And
Nur farhanah bt Hj Abd Kadir

Thank you to all my allies for all supports and encouragement through the process of finishing this work,
May Allah bless all of you

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Finally, a special thanks to my parents for their care and trust, and especially for the suffering that they have gone through in the earlier years so as to ensure an excellent education for me.

ABSTRACT

This thesis focused on the development Modeling Magneto-Rheological damper using Adaptive Neuro-Fuzzy Inference System (ANFIS) method. Magneto-Rheological (MR) damper is a semi-active control device and has been characterized by a set of non-linear differential equations which represent a model of the MR damper. By using this mathematical model, the force of the MR damper is directly solved to a given displacement and applied current. However, solving the non-linear equations describing the performance of the MR damper may be difficult or time consuming to predict a required voltage. One of the methods to model the MR damper is using (ANFIS).It is faster than the mathematical model for keeping the error small. ANFIS has been effectively applied to model complex systems because of its great training process.

ABSTRAK

Tesis ini tertumpu kepada Pemodelan pembangunan magneto-reologi peredam menggunakan Adaptive Neuro Fuzzy Sistem Inferens (ANFIS) method.Magneto-reologi (MR) peredam adalah alat kawalan semi-aktif dan telah dicirikan oleh satu set persamaan pembeza bukan linear yang mewakili model peredam MR. Dengan menggunakan model matematik ini, Daya peredam MR secara langsung diselesaikan dengan jarak dan arus elektrik yang diberikan. Walau bagaimanapun, penyelesaian persamaan bukan-linear yang menerangkan prestasi peredam MR mungkin sukar atau mengambil masa yang lama untuk meramalkan voltan yang diperlukan. Salah satu kaedah untuk memodelkan peredam MR menggunakan (ANFIS). Ia adalah lebih cepat daripada model matematik untuk mengekalkan ralat kecil. ANFIS telah berkesan digunakan untuk memodelkan sistem yang kompleks kerana proses latihan yang hebat.

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LIST OF SYMBOLS

F_{anfis}	-	ANFIS force
F_{actual}	-	Actual force from experimental
N	-	No of data
x	-	Body displacement
u	-	Wheel displacement

LIST OF ABBREVIATIONS

ANFIS	-	Adaptive Neuro-fuzzy inference system
MR	-	Magneto-Rheological
RMSE	-	Root Mean Square Error
MATLAB	-	Matrix Laboratory

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The purpose of this chapter is to present the project background and starting point for the progress in this project. The problem statements and objective of this project are discussed. The chapter end with the scopes of the project.

1.2 PROJECT BACKGROUND

In recent years, a family of fluids known as Magneto-rheological (MR) fluids has gained increased recognition for its many applications. During the late 1940's and early 1950's, there was a flurry of interest in MR devices (Jolly et al., 1998). This interest, however, soon died out, probably due to limitations in sealing technology and difficulties in preventing caking and particle sedimentation within the fluid. Magneto-rheological dampers of various applications have been and continue to be developed. Many structures, such as automotive vehicles, tall buildings, robotic manipulator arms and flexible spacecraft have already been designed using magneto-rheological damper. The most popular of these devices are MR damper, especially as automotive shock absorber. For instance, Lord Corporation has been developing MR fluids and devices since the early 1990's. In the mid 1990's, Lord Corporation began manufacturing an MR damper line called "Motion Master”. These dampers have found their way into truck seat suspensions and prosthetic legs. Shortly after, Lord developed a rotary MR brake for treadmill applications, as well as damper for automobile use (Lord, 1999). The automotive shock absorber has been shown to be a very important contributor to the ride and road handling of a vehicle. For ride comfort, shock absorber with a ‘soft’ setting are required to dissipate shock energy from the road, while a ‘hard’ setting is required for good vehicle handling. These conflicting characteristics of ride comfort and road holding is a major challenge to automotive shock absorber designer. Tuning of conventional hydraulic shock absorbers normally involves the physical adjustments of the settings of various valves located inside the piston. Also conventional absorbers will have a constant setting throughout their lifetime, and hence will not be able to operate satisfactorily in a wide range of road conditions. It is for these reasons that semi-active systems like MR dampers have attracted the attention of suspension designers and researchers. MR dampers are semi- active control devices that use MR fluids to produce controllable dampers. They potentially offer highly reliable operation and can be viewed as fail-safe in that they become passive dampers if the control hardware malfunction. The advantage of MR dampers over conventional dampers are that they are simple in construction, compromise between high frequency isolation and natural frequency isolation, they offer semi-active control, use very little power, have very quick response, has few moving parts, have a relax tolerances and direct interfacing with electronics. MR fluids are controllable fluids belonging to the class of active materials that have the unique ability to change dynamic yield stress when acted upon by an electric or magnetic field, while maintaining viscosity relatively constant. This property can be utilized in MR damper where the damping force is changed by changing the rheological properties of the fluid magnetically. The conclusions, advantages of Magneto rheological damper are the need very less control power, have simple construction, quick response to control signals and few moving parts.

1.3 PROBLEM STATEMENT

MR damper is a semi-active control device and has been characterized by a set of non-linear differential equations which represent a model of the MR damper. By using the mathematical model, the force of the MR damper is directly solved to a given displacement and applied current. However, given enough time and effort, it may be possible to perfectly model behaviour of a complex system through the use of traditional modelling techniques (Yen and Langari, 1999). One of the methods to model the MR damper is using Adaptive neuro-fuzzy inference system (ANFIS). ANFIS uses a hybrid learning algorithm that combines the backpropagation gradient descent and least square methods to create fuzzy inferences system whose membership functions are iteratively adjusted according to a given set of input and output data (Kyle and Paul, 2005). The ANFIS mathematical equation will be simulating into MATLAB program. It is faster than the traditional mathematical model for keeping the error small. ANFIS has been effectively applied to model complex systems because of its great training process.

1.4 OBJECTIVE

The primary objectives of this thesis is

I. To model the non linear of MR damper using ANFIS method.

II. To compare the result between experimental data and simulation using Root Mean Square Error (RMSE).

1.5 SCOPE

The scope for this thesis is

I. To understands MR damper characteristic

II. Modelling MR damper using ANFIS method.

III. Run code to obtain the data to analyzed using MATLAB

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is conducted to investigate the past research done in any areas that related in this project. This chapter starts with the meaning of each word in the project title. Previous researches are then reviewed and discussed briefly in order to understand more about projects and also gathering useful information.

2.2 MR Fluid

Magneto-rheological fluids are fluids that exhibit a change in rheological properties when a magnetic field is induced through the fluid (Jolly et al., 1998). In essence, the fluid's flow characteristics, namely apparent viscosity change. Jacob Rainbow, who worked for US National Bureau of Standards, first introduced MR fluids in the 1940s (Jolly et al., 1998). MR fluid consists of a liquid carrier, ferrous particles on the order of a few microns in diameter, and surfactant additives that are used to discourage particle settling. Three different carrier fluids are currently used, namely hydrocarbon-based oil, silicon oil, and water (Jolly et al., 1998). When exposed to a magnetic field, the ferrous particles that are dispersed throughout the fluid form magnetic dipoles. These magnetic dipoles align themselves along lines of magnetic flux, as shown in Figure 2.1

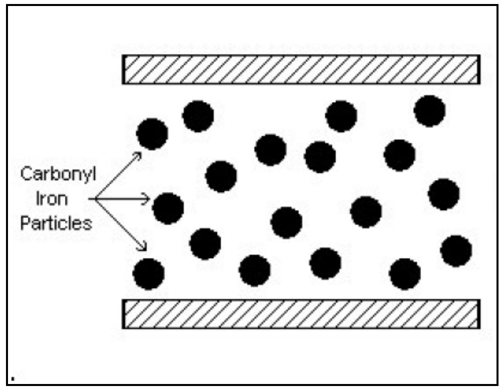

Figure 2.1 Off-state MR fluid particle

Source: John (2003)

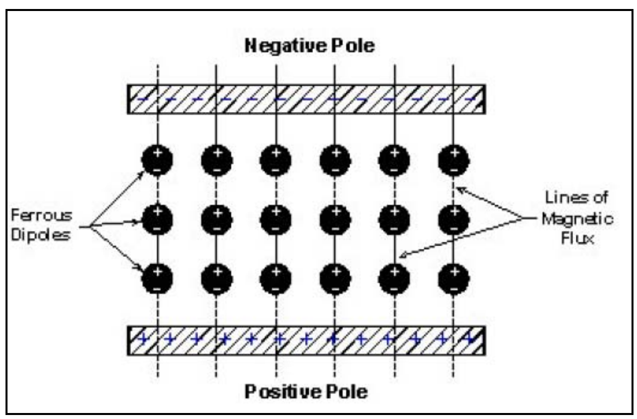

Figure 2.2 Aligning in applied magnetic field

Source: John (2003)

The dipoles align parallel to the induced magnetic flux lines to form chain-like structure of iron particle between the north and South Pole (Lord, 1999). On a larger scale, this reordering of ferrous dipole particles can be visualized as a very large number of microscopic beads that are threaded onto a very thin string as is shown in Figure 2.3. One can picture this thin string stretching from one magnetic pole to the other and perpendicular to each paramagnetic pole surface.

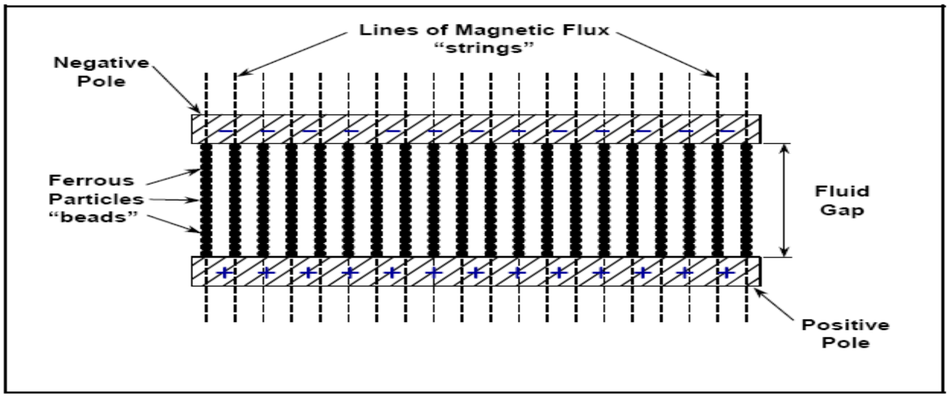

Figure 2.3 String and beads analogy of activated MR fluid

Source: John (2003)

An MR fluid is used in of three modes of operation, these being valve mode, shear mode and squeeze mode. A device that uses squeeze mode has a thin film (on the order of 0.020 inch) of MR fluid that is sandwiched between paramagnetic pole surfaces (Poyner, 2001).

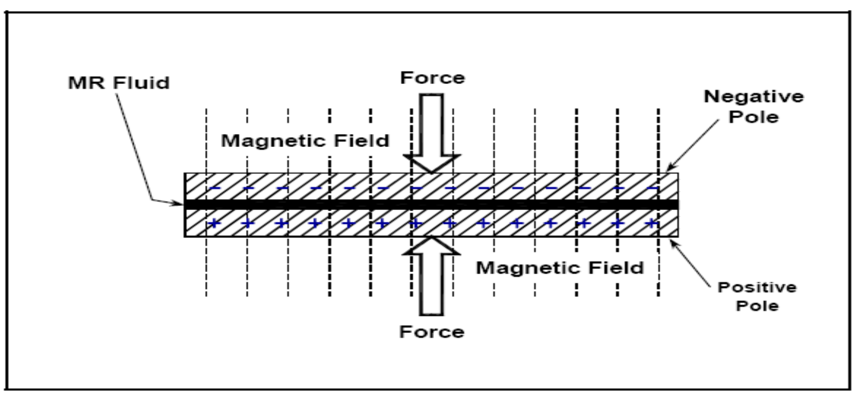

Figure 2.4 MR fluid used in squeeze mode

Source: Poyner (2001)

As depicted in Figure 2.5, MR fluid device is said to operate in shear mode when a thin layer (≈ 0.005 to 0.015 inch) of MR fluid is sandwiched between two paramagnetic moving surfaces. The shear mode is useful primarily for dampers that are not required to produce large forces or for compact clutches and brakes.

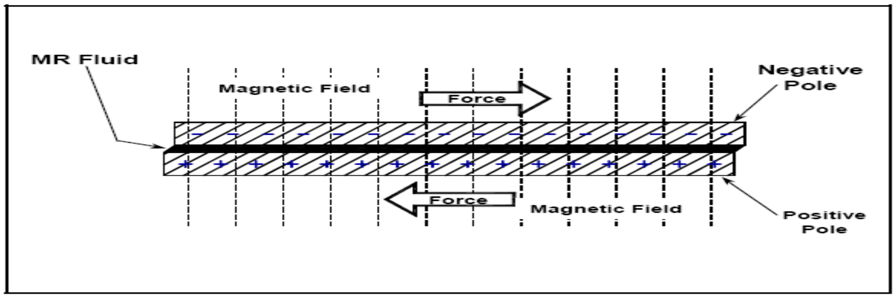

Figure 2.5 MR fluid used in shear mode

Source: Poyner (2001)

The last mode of MR damper operation, valve mode, is the most widely used of the three modes. An MR device is said to operate in valve mode when the MR fluid is used to impede the flow of MR fluid from one reservoir to another, as is shown in Figure 5.6. With the exception of a single hybrid MR damper design, all of the dampers used in this project operate in the valve mode.

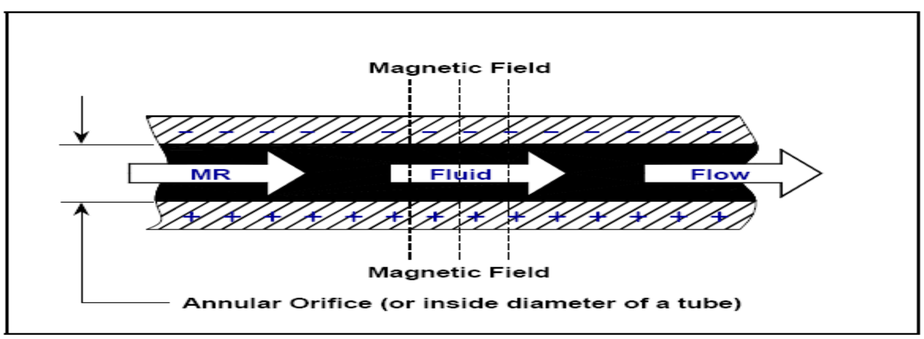

Figure 2.6 MR fluid used in valve mode

Source: Poyner (2001)

The advantages of MR fluid technology relative to conventional and electro-mechanical solutions are summarised as follows (Metered, 2010):

- Quick response time (less than 10 milliseconds).
- Consistent efficacy across extreme temperature variations.
- Continuously variable control damping.
- High dissipative force that is less dependent on velocity compared to passive dampers.
- Greater energy density.
- Inherent system stability (no active forces generated).
- Minimal power usage (typically 12V , 1 A. max. current that can fail-safe to battery backup, which can, in turn, fail-safe to passive damping mode).

MR fluids are quite similar to Electro rheological (ER) fluids in composition. MR and ER fluids contain carbonyl iron on the order of a few microns in size. From table 2.1 MR fluids demonstrate very high yield strength of 20 to 50 times the strength of ER fluids. Furthermore, because the magnetic polarization mechanism is unaffected by temperature, the performance of MR based devices is relatively insensitive to temperature over a broad temperature range (including the range for automotive use) (Marin et al., 2004). MR fluids can operate at temperature from -40 to 150^{o} C with only slight variation in the yield stress (Carlson et al., 1994), in contrast to ER fluids (restricted to a range of 10 to 90 ^{o} C) .MR fluids are significantly less sensitive to impurities or contaminants such as are commonly encountered during manufacturing and usage (Wang and Liao, 2005).MR technology can provide flexible control capabilities in designs that are far less complicated and more reliable than those based on ER technology (Dyke, 1996) . Moreover, as can be seen from Table 2.1, in contrast to ER fluids, MR fluids can be readily operated from a low voltage (*e.g.*, ~12–24V), current-driven power supply outputting only ~1–2 amps. From the data MR fluids are more effective for use in controllable fluid dampers considered to ER fluids.

Table 2.1 Properties of MR and ER fluid

Property	MR Fluid	ER Fluid
Max.yield stress	50 to 100 Kpa	2 to 5 Kpa
Max . Field	~250 KA/m	~4 KV/mm
Plastic viscosity	0.1 to 1.0 Pa.s	0.1 to 1.0 Pa.s
Operable temperature range	-40 to 1500 C	+10 to 90 ^{0}C
Stability	unaffected by most impurities	cannot tolerate impurities
Response time	ms	ms
Density	3 to 4g/cm3	1 to 2 g/cm
Dynamic Viscosity	5x10-11 s/Pa	5x10-8 s/Pa
Max.energy density	0.1 J/cm	0.001 J/cm
Power supply (typical)	2 to 25V	2000 to 5000V

Source: Metered (2010)

2.3 Types of suspension

Suspension is the term given to the system of springs, shock absorber and linkages that connects a vehicle to it wheels. The purpose of suspension systems is developed to increase handling quality and comfort. This condition can be achieved by continuously keeping the degree of stability of the vehicle to the road surface when the vehicle is driven to every direction. The suspension system also will distribute the vehicle weight distribution evenly to reduce the impact when accelerating, braking or cornering. The suspension also protects the vehicle and any cargo or luggage from damage and wear. The design of front and rear suspension of a car may be different. Generally there are three type of suspension which is passive, semi active and fully active suspension. . This suspension system categorizing depends on the external power input and/or the control bandwidth into the system (Appleyad and Wellstead, 1995).

2.3.1 Passive suspension system

A passive suspension system is one which the characteristics of the components (springs and dampers) are fixed. An early design for automobile suspension systems focused on unconstrained optimization for passive suspension system which indicates the desirability of low suspension stiffness, reduced un-sprung mass, and optimum damping ratio for the best controllability (Thompson, 1976). The spring is chosen based solely on the weight of the vehicle, while the damper is the component that defines the suspensions placement on the compromise curve. Passive suspension design is a compromise between vehicles handling and ride comfort, as shown in Figure 2.7.

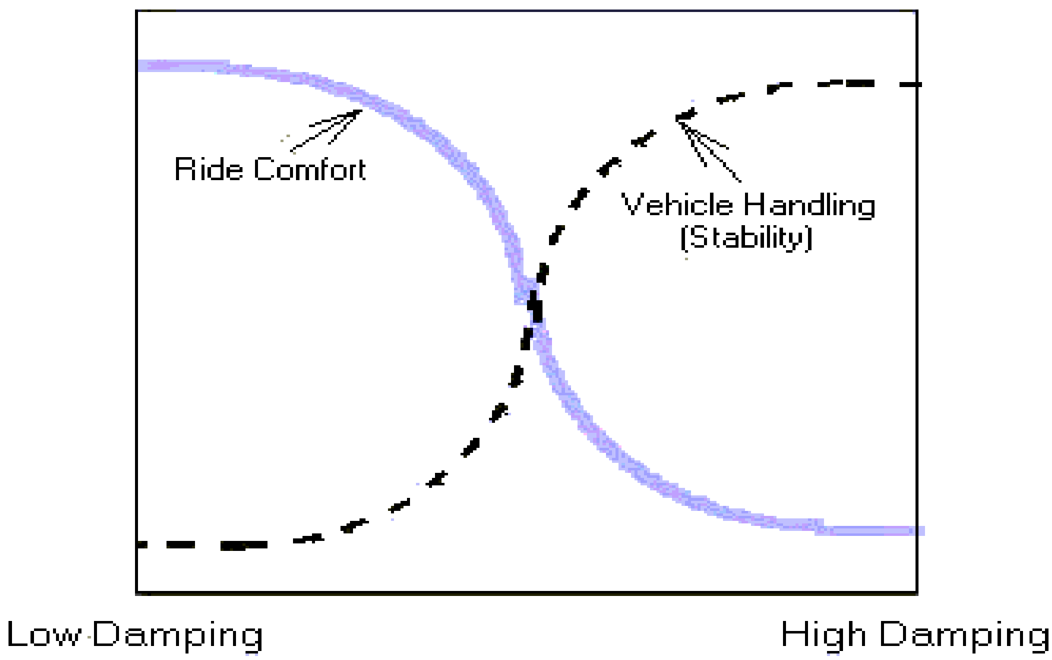

Figure 2.7: Damping Compromise for Passive Dampers

A heavily damped suspension will yield good vehicle handling, but also transfers much of the road input to the vehicle body. When the vehicle is traveling at low speed on a rough road or at high speed in a straight line, this will be perceived as a harsh ride. The vehicle operators may find the harsh ride objectionable, or it may damage cargo. A lightly damped suspension will yield a more comfortable ride, but can significantly reduce the stability of the vehicle in turns, lane change maneuvers, or in negotiating an exit ramp. Good design of a passive suspension can to some extent optimize ride and stability, but cannot eliminate this compromise. Passive suspension system representation diagram is shown in Figure 2.8.

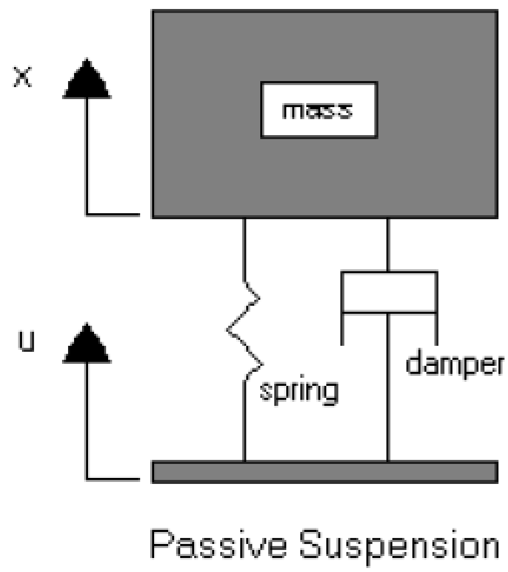

Figure 2.8: Passive suspension system

Source: Karnopp (1995)

2.3.2 Active suspension system.

Conventional suspension design is inherently a compromise, primarily between ride quality and road handling. In addition to this compromise, passive suspension system performance deviates greatly as vehicle mass varies. Active suspension techniques seek to improve both ride and handling over a wider range of operating conditions. The potential of active suspension systems had been developed using control techniques established during the space race of the 1950 and 1960 (Karnopp and Trikha, 1969). In active suspension, the damper is replaced by a force actuator. The advantage the force actuator can generate a force in any direction, while a passive damper can only dissipate energy (Emmanuel, 2003). A good control scheme can result in a much better compromise between ride comfort and vehicle stability compared to passive suspension (Alleyne and Hendrick, 1995). Active suspension can also easily reduce the pitch and the roll of the vehicle. However, active suspensions have many disadvantages and are too expensive for wide spread commercial use because of their complexity and large power requirements. Also, a failure of the force actuator could make the vehicle very unstable and therefore dangerous to drive. Active suspension system representation in diagram is shown in figure 2.9.

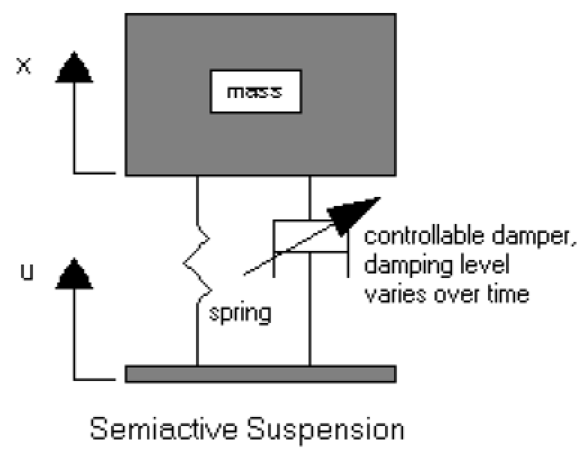

Figure 2.9: Active suspension system

Source: Karnopp (1995)

2.3.3 Semi-Active suspension system.

The idea of semi-active suspension control was introduced in the early 1970's in the form of variable damping. Since then, variable damping schemes have been the predominant form of semi-active suspension control. In early semi-active suspension system, regulating of the damping force can be achieved by utilizing the control damper under closed loop control, such is only capable of dissipating energy (Williams, 1994). In semi-active suspension, the passive dampers are replaced with dampers capable of changing their characteristics. A semi-active damper uses external power only to adjust the damping level, and operate an embedded controller and set of sensors. The controller determines the level of damping based on a control strategy and automatically adjusts the damper to achieve that damping. The main advantage of a semi-active system is that it requires far less energy than fully active control. In addition, semi-active systems are usually far less complex than fully active systems (Emmanuel, 2003).Semi-active suspension system representation in diagram is shown in figure 2.10.

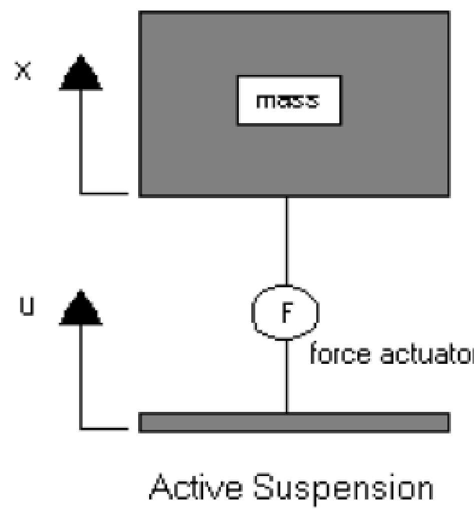

Figure 2.10: Semi-active suspension system

Source: Karnopp (1995)

2.4 MR Damper Types

MR dampers are perhaps one of the most common applications for MR fluids. The fluid's adjustable apparent viscosities make it ideal for use in damper for vibration control. There are three main types of MR dampers. These are the mono tube, the twin tube, and the double ended MR damper. The three design type reflects methods of adjusting the fluid volume to account for the volume of the damper shaft. Mono tube is the most common since it can be installed in any orientation and is compact in size.

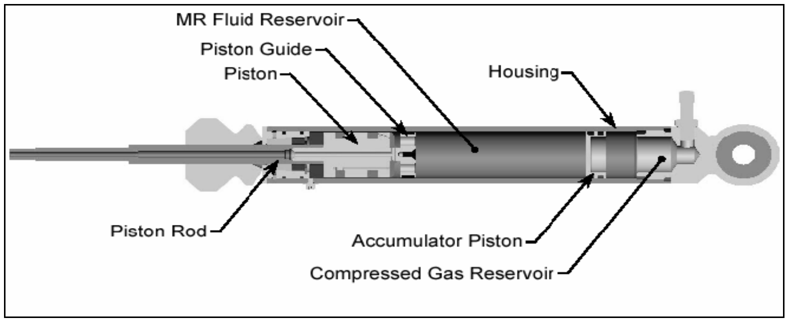

Figure 2.11 Monotube MR damper

Source: John (2003)

The twin tube MR damper uses two fluid reservoirs to negotiate the changing volume of MR fluid. In this configuration the damper has inner and outer housing. As the piston rod enters the inner housing, the extra volume of MR fluid displaced by the piston rod is forced from the inner housing to the outer housing via the foot valve. When the piston rod retracts, MR fluid flows back into the inner housing, therefore preventing the creation of vacuum in the inner housing and cavitations of the damper. This damper must be mounted with the foot valve at the bottom to ensure no cavitations (Lampe, 1998).

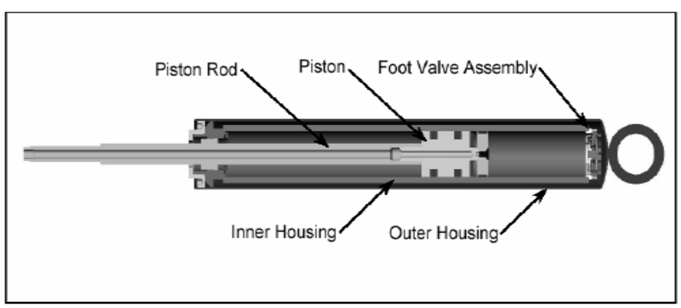

Figure 2.12 Twin tube MR dampers

Source: John (2003)

The final type of MR damper is called a double-ended damper since a piston rod of equal diameter protrudes from both ends of the damper housing. Since there is no change in the double-ended damper does not require an accumulator mechanism. Double- ended MR damper have been used for bicycle applications (Ahmadian, 1999), gun recoil application (Ahmadian and Poyner, 1999) and for controlling building sway motion caused by wind gusts and earthquakes (Dyke et al, 1996).

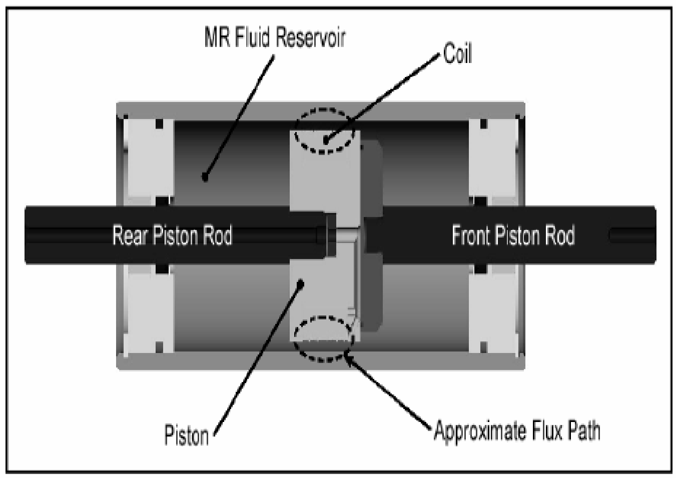

Figure 2.13 Double-ended MR dampers

Source: Poyner (2001)

2.5 Modelling of MR Fluid damper

The MR damper is a semi-active control device and described as nonlinear differential equation (Eltanawie, 2010). By nonlinear is meant that the output is a nonlinear function of the inputs. In the case of the forward (or direct) dynamics, the output is the force and the inputs are the electrical input (voltage or current applied to the electromagnet) and the mechanical input (displacement of the damper corresponding velocity, or acceleration) (Metered, 2010). Two types of modeling MR damper is parametric model and nonparametric model. Parametric models require assumptions regarding the structure of the mechanical model that simulates the behavior (Wang and Liao, 2005). Parametric models such as Bingham's model, extended Bingham, and Bouc-Wen, which numerically tractable and has been used extensively for modeling hysteretic systems (Poyner, 2001). Non-parametric models do not make any assumption on the underlying input/output relationship of the system being modeling. Non-parametric models do not make any assumptions on the underlying input/output relationship of the system being modeling. An elevated amount of input/output data has to be used to identify the system, enabling the subsequent reliable prediction of the system's response to arbitrary inputs within the range of the training data. Several techniques are used for emulating non-parametric models such as neutral networks, fuzzy logic, neuro-fuzzy and polynomial models. Wang and Liao (2005) proposed a forward MR damper model, which consists of a recurrent neutral-network in which the output is delayed and fed back to the input layer.

2.6 Adaptive Neuro-fuzzy inference system (ANFIS)

The ANFIS approach learns the rules and membership functions from data. ANFIS is an adaptive network. An adaptive network is network of nodes and directional links (Jang, 1993). Associated with the network is a learning rule - for example back propagation. It's called adaptive because some, or all, of the nodes have parameters which affect the output of the node. These networks are learning a relationship between inputs and outputs. The architecture of a two input-two rule ANFIS, as shown in Figure 2.14.

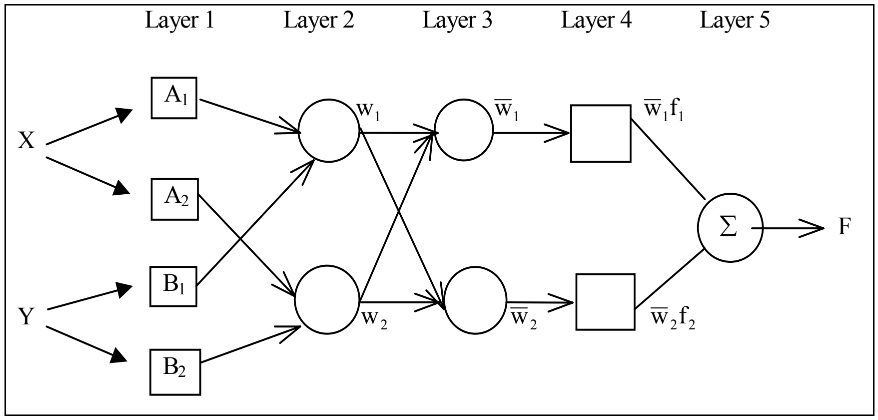

Figure 2.14 ANFIS architecture

Source: Eltantawie (2010)

The ANFIS has five layers (Jang, 1993). The circular nodes represent nodes that are fixed whereas the square nodes are nodes that have parameters to be learnt.

Layer 1

The output of each node is:

$$O_{1,i} = \mu_{A_i}(x) \qquad for\ i = 1,2$$

$$O_{1,i} = \mu_{B_{i-2}}(y) \qquad for\ i = 3,4 \tag{2.1}$$

The $O_{1,i}(x)$ is essentially the membership grade for x and y .The membership functions could be anything but for illustration purposes we will use the bell shaped function given by:

$$\mu_A(x) = \frac{1}{1 + \left| \frac{x - c_i}{a_i} \right|^{2b_i}} \tag{2.2}$$

Where a_i, b_i, c_i parameters to be learn. These are the premise parameters.

Layer 2

Every node in this layer is fixed. This is where the t-norm is used to 'AND' the membership grades - for example the product:

$$O_{2,i} = w_i = \mu_{A_i}(x)\mu_{B_i}(y), \quad i = 1,2 \tag{2.3}$$

Layer 3

Layer 3 contains fixed nodes which calculate the ratio of the firing strengths of the rules:

$$O_{3,i} = \overline{w}_i = \frac{w_i}{w_1 + w_2} \tag{2.4}$$

Layer 4

The nodes in this layer are adaptive and perform the consequent of the rules:

$$O_{4,i} = \overline{w_i} f_i = \overline{w_i}(p_i x + q_i y + r_i) \tag{2.5}$$

The parameters in this layer (p_i, q_i, r_i) are to be determined and are referred to as the consequent parameters.

Layer 5

There is a single node here that computes the overall output:

$$O_{5,i} = \sum_i \overline{w_i} f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \tag{2.6}$$

This then is how, typically, the input vector is fed through the network layer by layer. We now consider how the ANFIS learns the premise and consequent parameters for the membership functions and the rules.

2.7 Back-propagation

Back-propagation is a common method of training artificial neural networks to minimize the objective function. Arthur and Ho (1969) described it as a multi-stage dynamic system optimization method. Any network structure can be trained with back-propagation when desired output patterns exist and each function has been used to calculate the actual output patterns is differentiable. As with conventional gradient decent, back-propagation works by each modifiable weight, calculating the gradient of error function with respect to the weight and then adjusting it accordingly (Boden, 2001). Back-propagation learning algorithm can be divided into two phases: propagation and weight update (Werbos, 1994).

Phase 1: Propagation

Propagation involves the following steps:

1. Forward propagation of a training pattern's input through the neural network in order to generate the propagation's output activations.
2. Backward propagation of the propagation's output activations through the neural network using the training pattern's target in order to generate the deltas of all output and hidden neurons.

Phase 2: Weight update

Weight-synapse follows the following steps:

1. Multiply its output delta and input activation to get the gradient of the weight.
2. Bring the weight in the opposite direction of the gradient by subtracting a ratio of it from the weight.

This ratio influences the speed and quality of learning; it is called the learning rate. The sign of the gradient of a weight indicates where the error is increasing; this weight must be updated in the opposite direction.

2.8 Root Mean Square Error (RMSE)

RMSE is a frequently used measure of the differences between values predicted by a model or an estimator and the values actually observed. To construct the RMSE, first need to determine the residuals. Residuals are the difference between the actual values and the predicted values. The actual values are actual force (F_{act}) and predicted values are simulation force (F_{anfis}).Next step is squaring the residuals, averaging the squares, and taking the square root gives the RMSE. Where N is no of data.

$$\sqrt{\frac{\sum_{i=1}^{n}(F_{actual}-F_{anfis})^2}{N}} \tag{2.7}$$

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discussed in detailed about the method use for modeling the MR damper using ANFIS method. This chapter begins with a brief explanation of the step involved in this project and followed by a methodology flowchart as the summary. The processes of each step that involved in this project are then is described and discussed thoroughly in this chapter.

3.2 Methodology Process

This project starts the project background, problem statement, objective and the scope of the project is discussed with supervisor in order to understand overall of the project.

After understand the project process, experimental to get MR damper data is started. The data collected are the displacement across the damper and the force applied to MR damper. The collected data will be used to compare with the simulation using ANFIS method.

The next process is understands the Adaptive neuro-fuzzy inference system and it architecture. The ANFIS equation will be coding in the MATLAB and produced MR damper Simulink diagram. The simulation result will be compared with the experimental result.

After completing all the process needed, the result of the simulation will be analyzed and discussed. The Final step is writing the final report of the project. The summary of all methodology above can be referring from a flow chart which is shown in Figure 3.1.

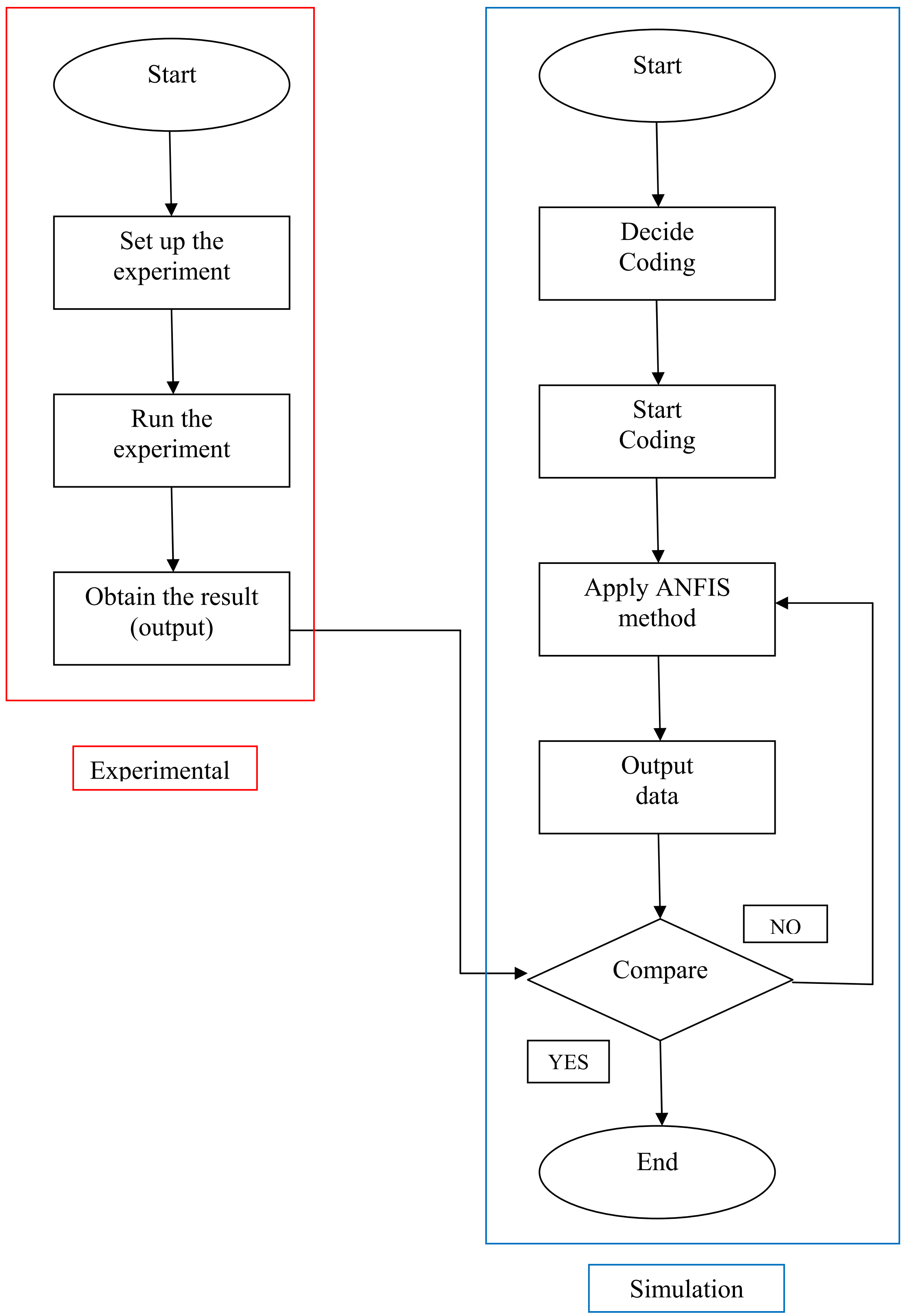

Figure 3.1: Flow Chart of methodology

3.3 Experimental MR damper

This experiment is done to obtain the required data to establish the ANFIS model. The data collected are the displacement across the damper and the force applied to the MR damper. Figure 3.2 shows the experiment setup.

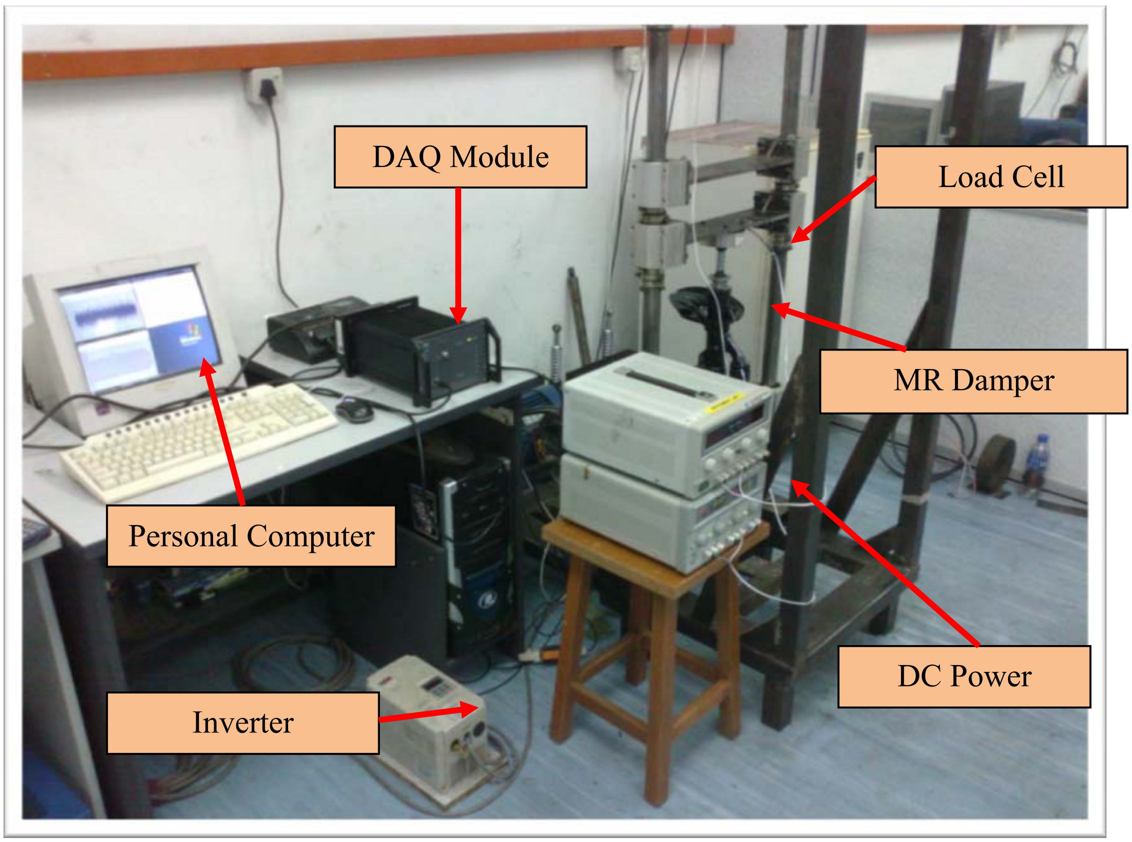

Figure 3.2**:** Equipment for Identification of MR Damper

This experiment is done by using tensile testing machine. This machine has the upper and lower head which will grip the damper to be unmovable. The upper head is connected to a load cell. This load cell will allow the operator to measure the force applied to MR damper. The lower head which is moveable was operated by a hydraulic actuator that can read generated displacement signal. An accelerometer is attached to the test machine to measure the displacement of the damper. A direct current (DC) power supply is use to provide the current to flow through the MR damper. The data acquisition (DAQ) module act as the interface between the personal computer and signals from the MR damper. The personal computer will record the data.

3.4 Modeling and simulation software

The software that used to create the Simulink diagram and running the simulation is MATLAB. MATLAB stand for Matrix Laboratory. The very first version on MATLAB, written at the University of New Mexico and Stanford University in the late 1970s was intended for use in Matrix theory, Linear algebra and Numerical analysis. Later and with the addition of several toolboxes the capabilities of MATLAB were expended and today it is very powerful tool at the hand of an engineer (Matlab, 2003). Typical uses of MATLAB include:

- Math and computation
- Algorithm development
- Modeling, simulation and prototyping
- Data analysis, exploration and visualization
- Scientific and engineering graphics
- Application development, including graphical user interface building.

For the project, Simulink from MATLAB is used to model the block diagram of MR damper. The equation will be converted into block diagram by using MATLAB Simulink library block function. Modeling must be precisely following required equations in order to avoid error thus giving the correct results during the simulation. Figure 3.3 shows the MATLAB interface and Figure 3.4 shows the MATLAB Simulink Library.

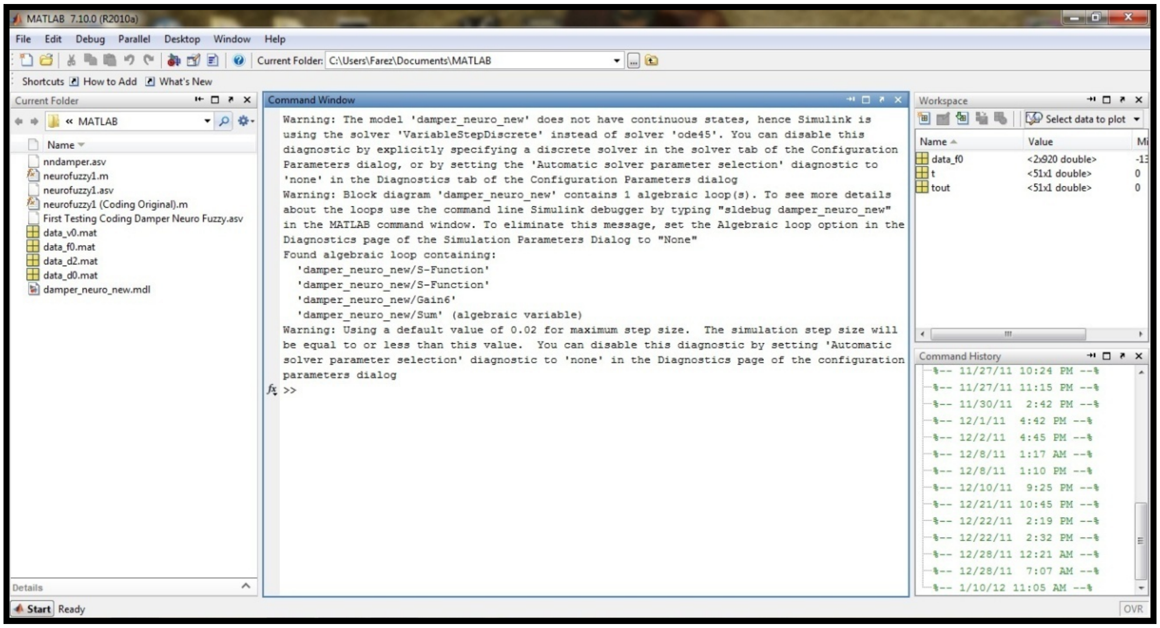

Figure 3.3**:** MATLAB interface

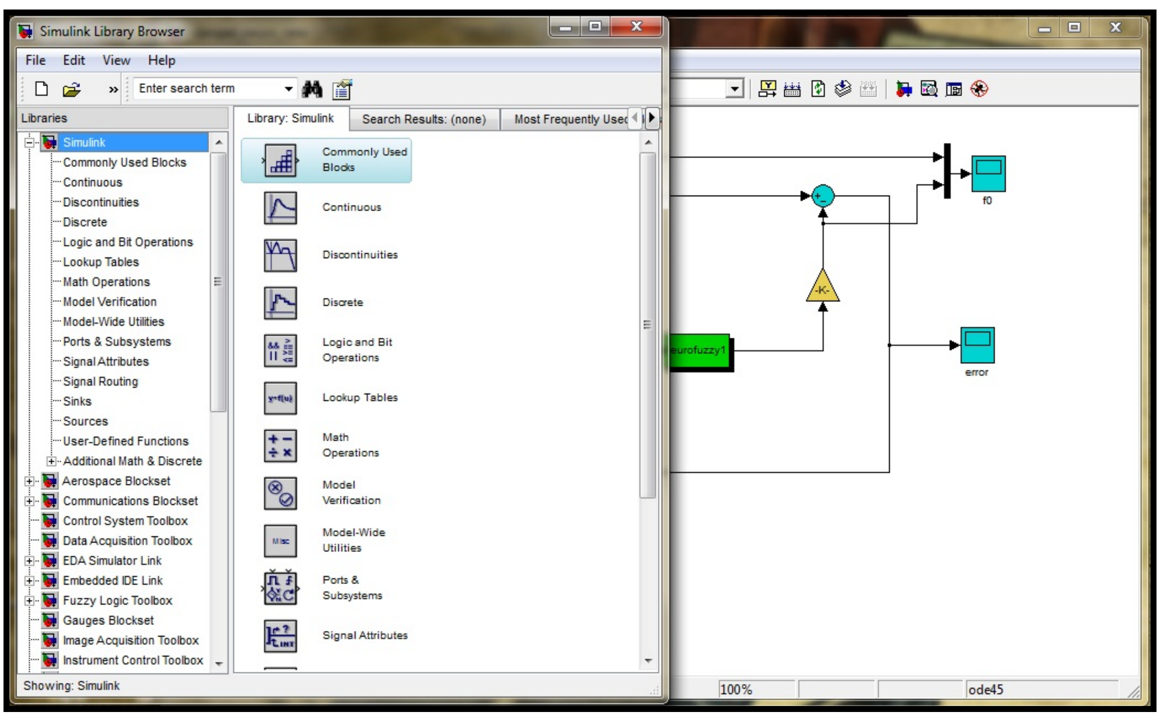

Figure 3.4**:** MATLAB Simulink library

3.5 Overview of ANFIS system

The inputs for this simulation are the displacement across the damper and the force applied to the MR damper. There are three input nodes and one output node. The output is the damping force of the current moment. The displacement is denoted by data_d0.mat while the force is denoted by data_f0.mat. The output will be compared with the experimental output. There are some delays must be included in this simulation to obtain the desired data faster. The data model by adaptive ANFIS inference system will be compare with the experimental data. The ANFIS method is used to generate the mathematical model of this MR damper. The Simulink diagram showed in Figure 3.5.

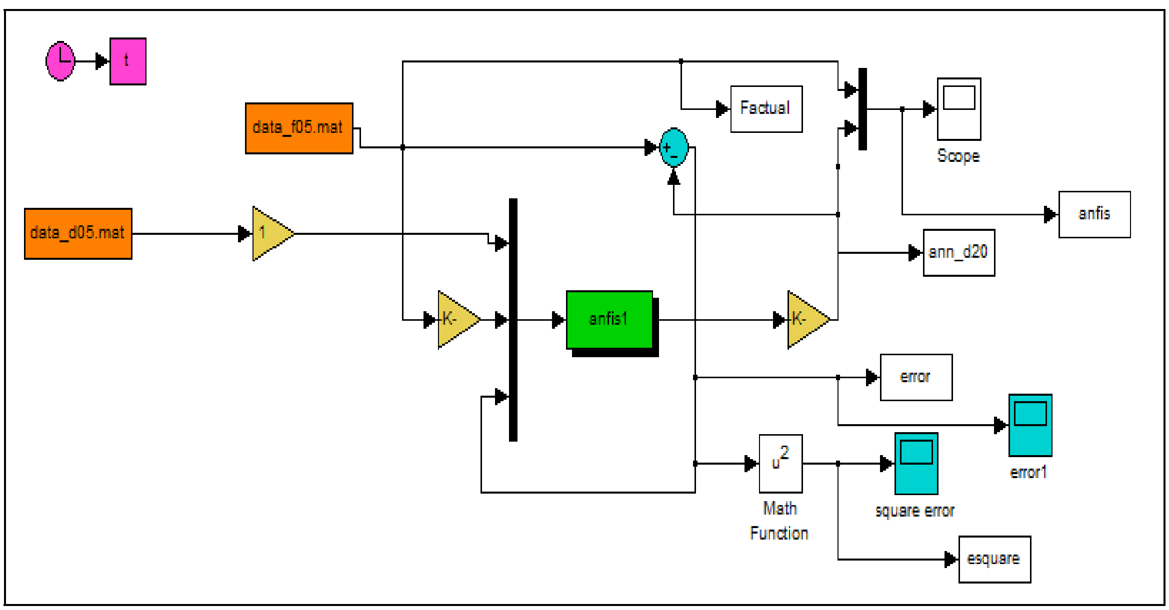

Figure 3.5: Simulink diagram for ANFIS

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

In this chapter, all findings and result are showed and discussed .The result of experimental MR damper is showed first and discussed. The result of simulation using ANFIS are previewed to see whether the response of simulation is similar with the experimental results. Next is using RMSE to measure the difference error values between simulation and experimental result.

4.2 Experimental and Simulations result

Simulation starts with make a coding for ANFIS method. ANFIS equation (equation 2.2 – 2.6) will be simulating into MATLAB program. After done developing the coding, in the command part “simsizes (sizes)” as a weight and “sys = md1upadate” shown in Figure 4.1 and Figure 4.2 need to fine tuned range around -1 and 1 to find the similar experimental force graph .

```
sys = simsizes(sizes);
str = [];
x0=[0.01 0.001 0.01 0 0.1 0.1 0.01 0 0.1 0.001 1 0 1 0.001 0.0001 0 0 0 0 0 0.0001 1 0.00001 0 0.000001 1 0.0001 0];%(update 18)
ts  =[-1 0];                   % inherited sample time
```

Figure 4.1: Weight need to tune.

```
function sys = mdlUpdate(t,x,u)
   % A = 0.000000000000000001; % d0 f0
    A = 0.000001; % d05 f05
```

Figure 4.2: Learning rate need to tune

Result and analysis of the data were made for both simulation and experimental method. On the experimental side, fives different current 0A, 1A, 1.5A & 2A were injected to the damper and a device called Data Acquistion (DAQ) will collect two data such as Force (*N*) and Acceleration (*m*) produce by the damper .As for the acceleration result, before the data is transfer to the DAQ device it is initial taken from a device called "Accelerometer" that were put at the bottom of the damper. Acceleration data that were collected is manually integrated to get a displacement (*m*) data because the primary data that is needed for the experimental part is Force (*N*) and Displacement (*m*). In simulation part, ANFIS method is conducted by using both data Force (*N*) and Displacement (*m*) that were obtaining from experimental part and the result from the simulation is use to calculate RMSE using the equation below .

$$\sqrt{\frac{\sum_{i=1}^{n}(F_{actual} - F_{anfis})^2}{N}} \tag{4.0}$$

where,

$$(F_{actual} - F_{anfis})^2 = U^2 \tag{4.1}$$

thus,

$$\sqrt{\frac{U^2}{N}} \tag{4.2}$$

With respect to the estimated parameter U^2 is defined as the actual forces subtract to ANFIS force and *N* is defined as the total numbers of error.

4.3 Experimental and Simulations result for 0A current

Force and displacement graph result from the experimental showed in Figure 4.3 and 4.4 when 0A current is applied to the damper.

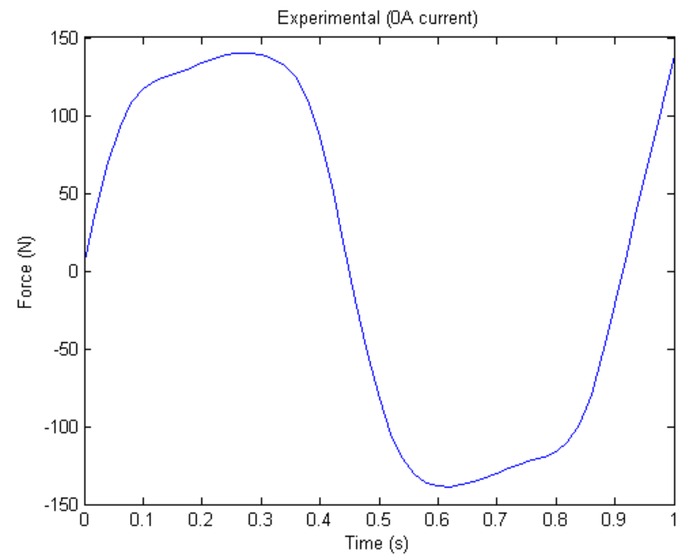

Figure 4.3: Experimental graph for 0A current.

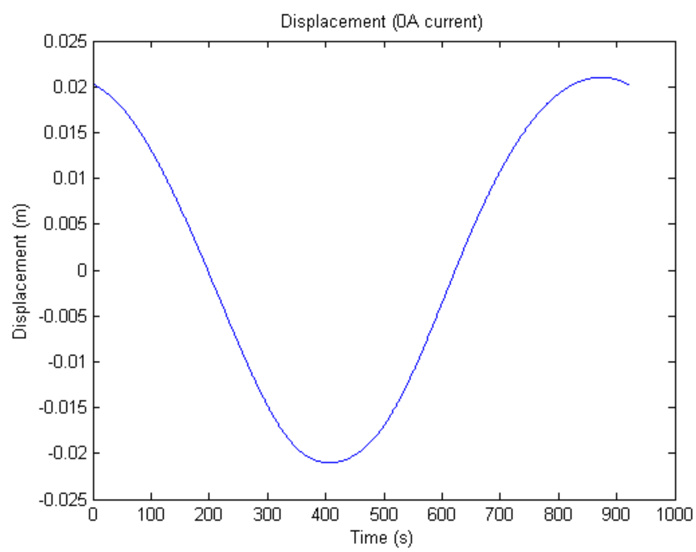

Figure 4.4: Displacement graph for 0A current

In simulation side, data from the experimental were use and the current is also set to 0A at the simulation block diagram (Figure 4.5), thus resulting the same output as the experimental method shown in Figure 4.4. But in simulation, the primary result that need to be obtained is the graph of errors (Figure 4.6) between experimental and simulation so that RMSE can be calculated.

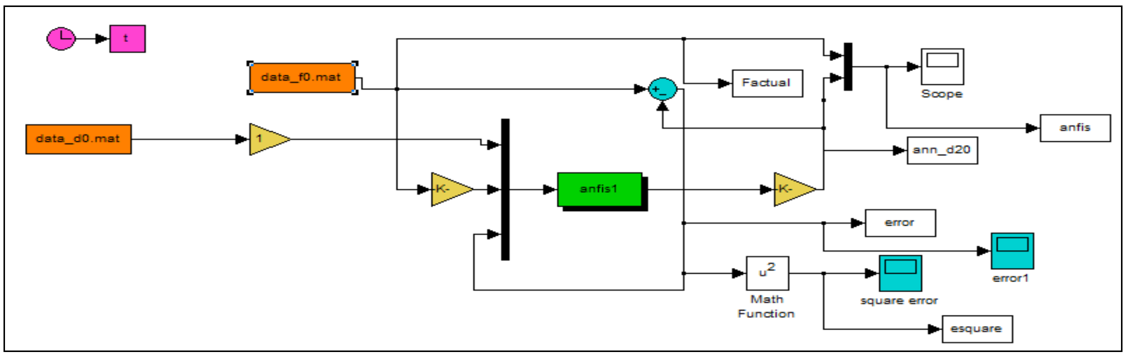

Figure 4.5: Simulation block diagram using experimental data and 0A current

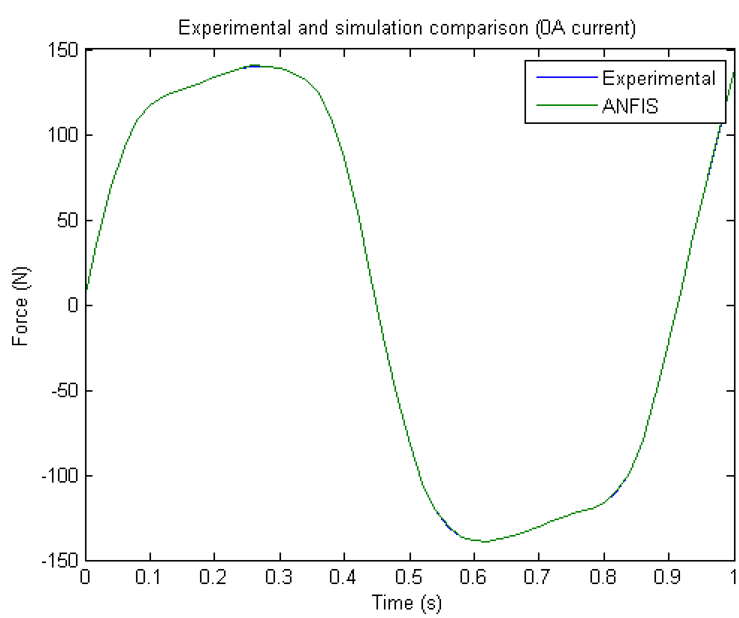

Figure 4.6: Simulation and experimental graph for 0A current

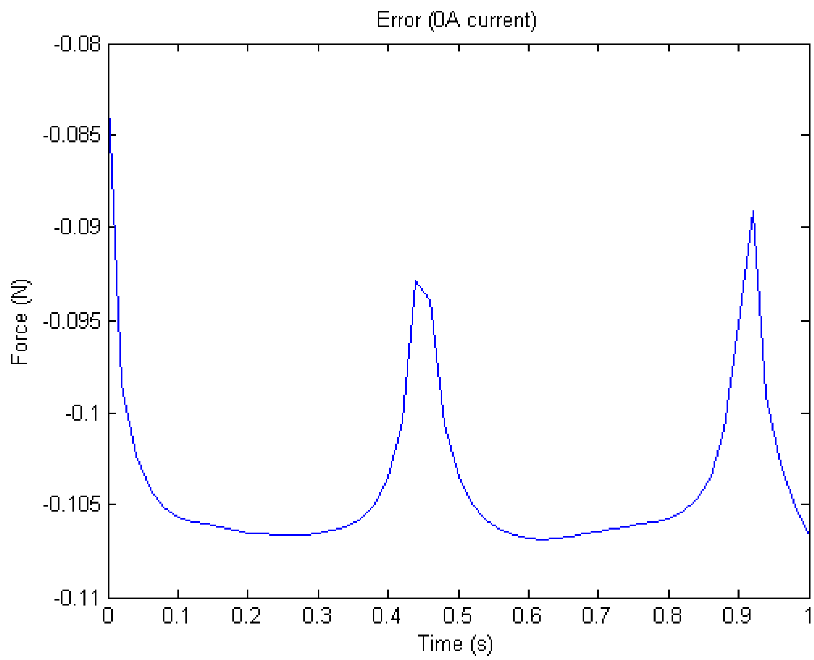

Figure 4.7: Error graph for experimental and simulation

After getting the result of error between both experimental and simulation, base on the RMSE equation (4.2) all of the values is submitted and calculated.

$$\text{RMSE} = \sqrt{\frac{U^2}{N}} = \sqrt{\frac{0.54918}{51}}$$

$$\text{RMSE} = 0.10377$$

Thus the RMSE for 0A current is 0.10377.

4.4 Experimental and Simulations result for 0.5A current

The result of the force and displacement graph shown in Figure 4.8 and Figure 4.9 occur when 0.5A current is applied to the damper.

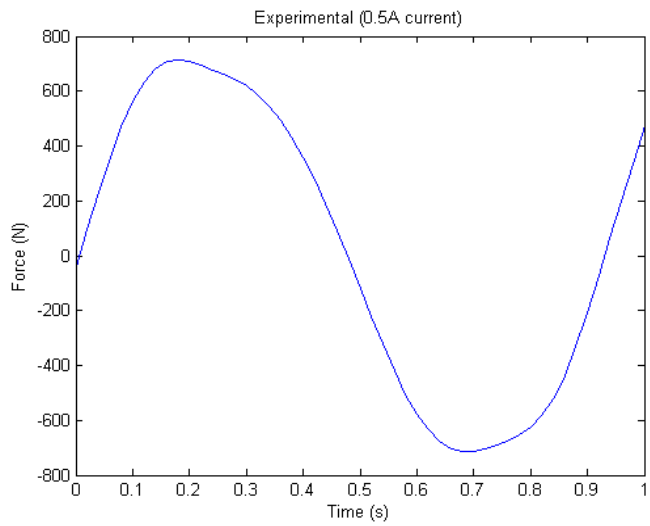

Figure 4.8: Experimental graph for 0.5A current

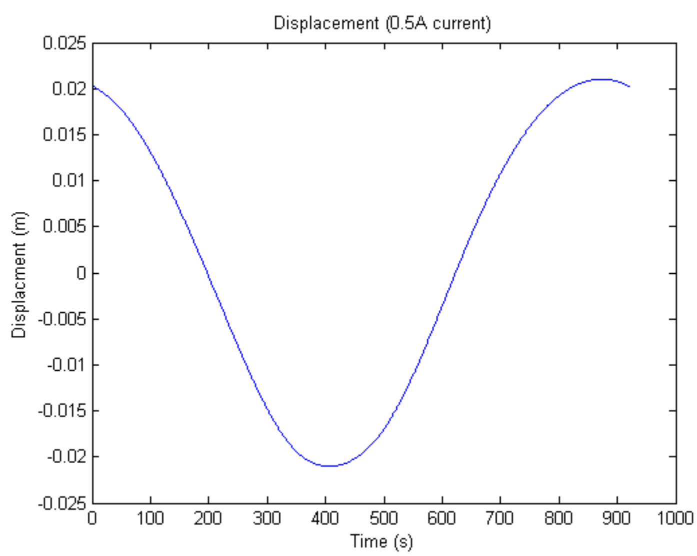

Figure 4.9: Displacement graph for 0.5A current

In simulation side, data from the experimental were use and the current is also set to 0.5A at the simulation block diagram (Figure 4.10), thus resulting the same output as the experimental method shown in Figure 4.11. Similarly in simulation at 0A, the primary result that need to be obtained is the graph of errors (Figure 4.12) between experimental and simulation so that RMSE can be calculated.

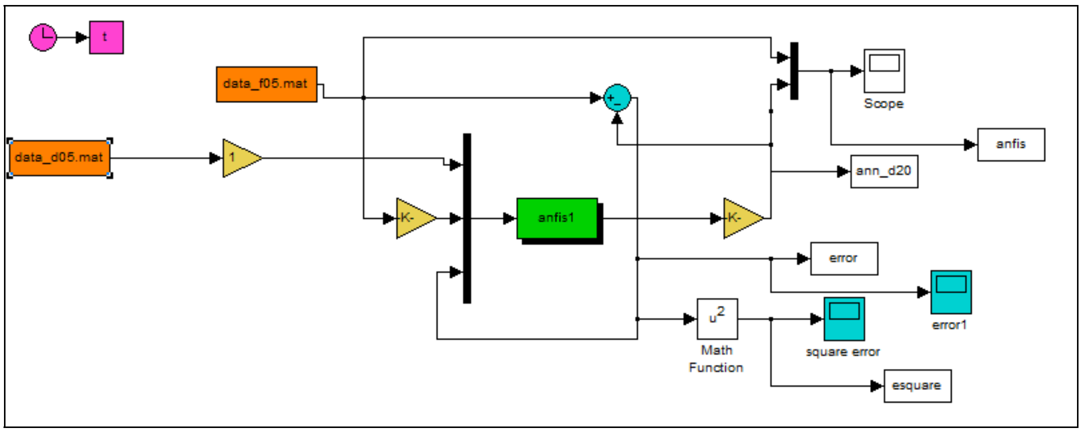

Figure 4.10: Simulation block diagram using experimental data and 0.5A current

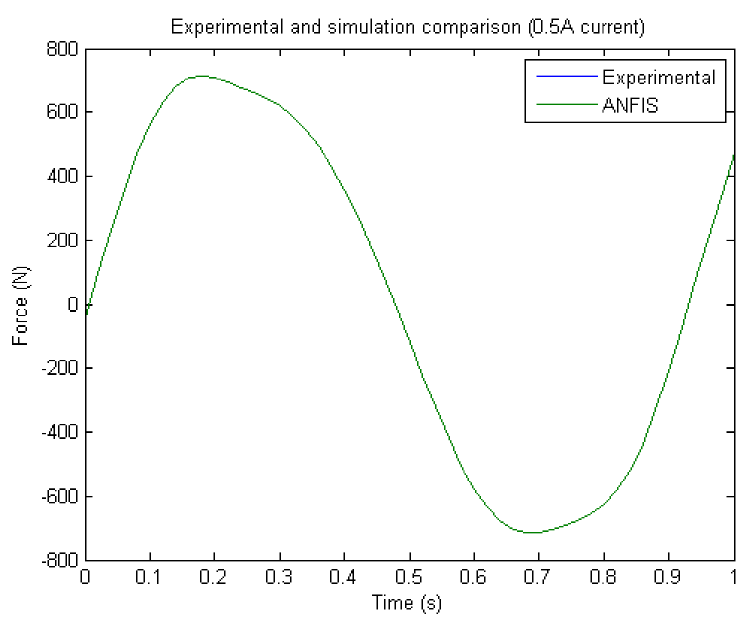

Figure 4.11: Simulation and experimental graph for 0.5A current

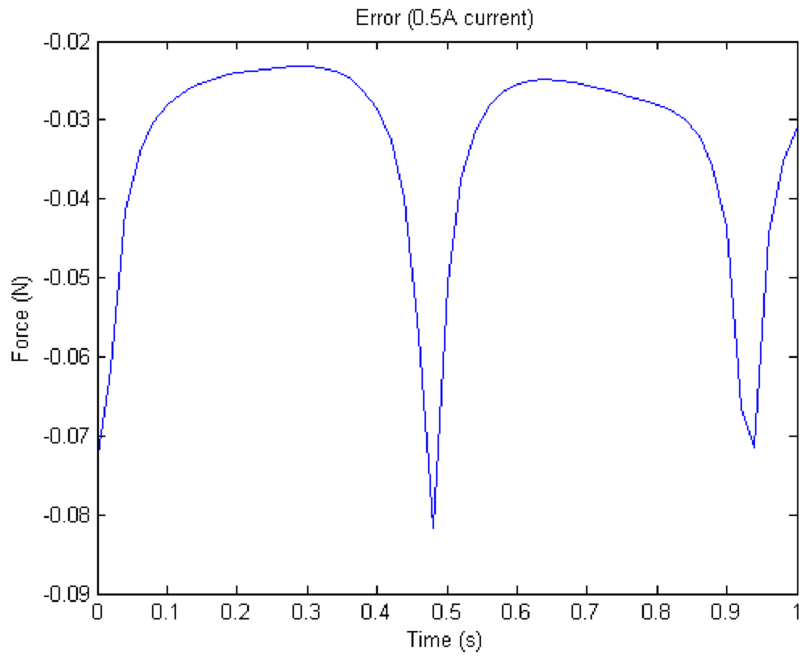

Figure 4.12: Error graph for experimental and simulation

After getting the result of error between both experimental and simulation, base on the RMSE equation (4.2) all of the values is submitted and calculated.

$$\text{RMSE} = \sqrt{\frac{U^2}{N}} = \sqrt{\frac{0.069039}{51}}$$

$$\text{RMSE} = 0.03679$$

Thus the RMSE for 0.5A current is 0.03679.

4.5 Experimental and Simulations result for 1A current

The result of the force and displacement graph shown in Figure 4.13 and Figure 4.14 occur when 1A current is applied to the damper.

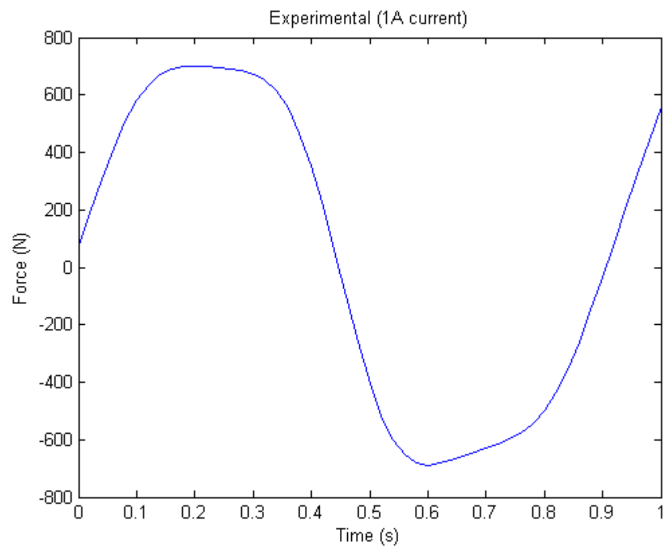

Figure 4.13: Experimental graph for 1A current

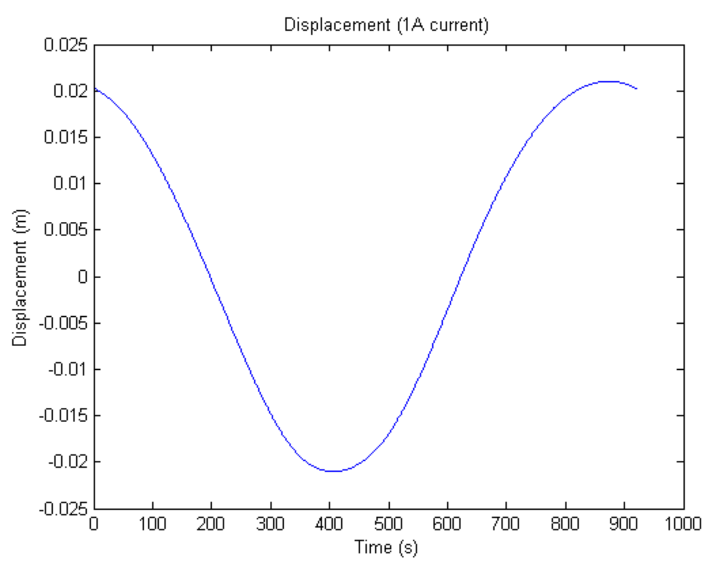

Figure 4.14: Displacement graph for 1A current

In simulation side, data from the experimental were use and the current is also set to 1A at the simulation block diagram (Figure 4.15), thus resulting the same output as the experimental method shown in Figure 4.16. Similarly in simulation at 0.5A, the primary result that need to be obtained is the graph of errors (Figure 4.17) between experimental and simulation so that RMSE can be calculated.

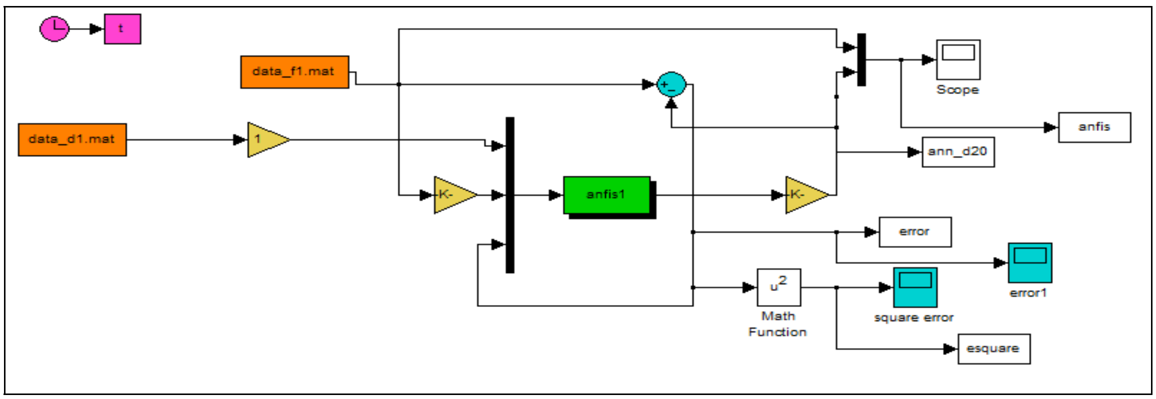

Figure 4.15: Simulation block diagram using experimental data and 1A current

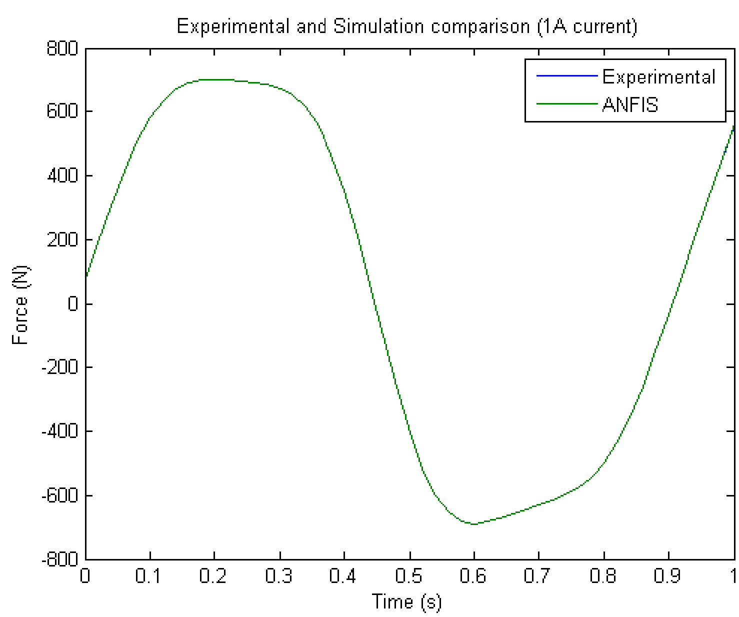

Figure 4.16: Simulation and experimental graph for 1A current

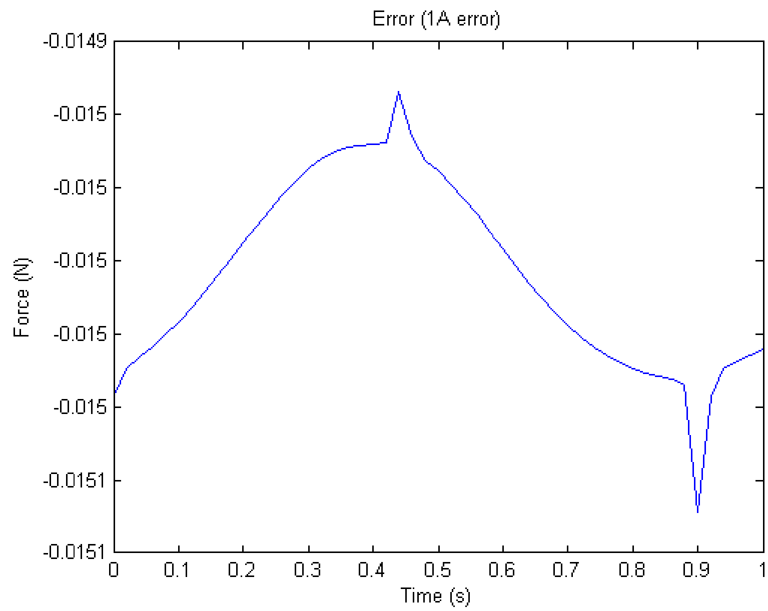

Figure 4.17: Error graph for experimental and simulation

After getting the result of error between both experimental and simulation, base on the RMSE equation (4.2) all of the values is submitted and calculated.

$$\text{RMSE} = \sqrt{\frac{U^2}{N}} = \sqrt{\frac{0.01148}{51}}$$

$$\text{RMSE} = 0.01500$$

Thus the RMSE for 1A current is 0.01500.

4.6 Experimental and simulation for 1.5A current

The result of the force and displacement graph shown in Figure 4.18 and Figure 4.19 occur when 1.5A current is applied to the damper.

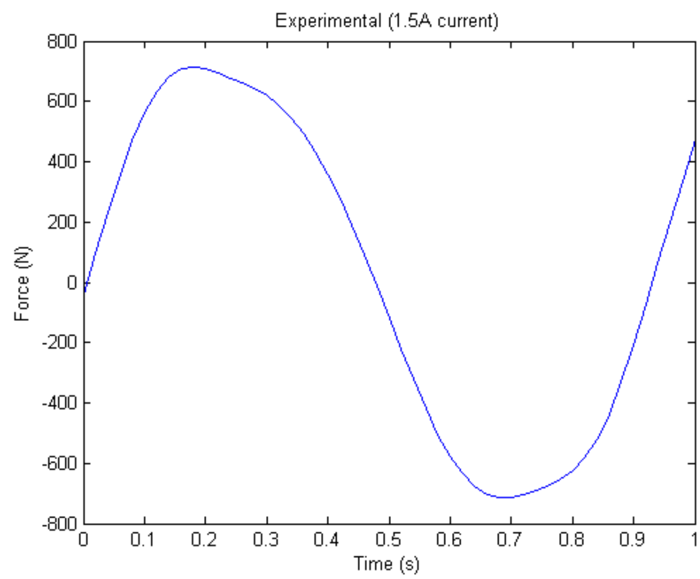

Figure 4.18: Experimental graph for 1.5A current

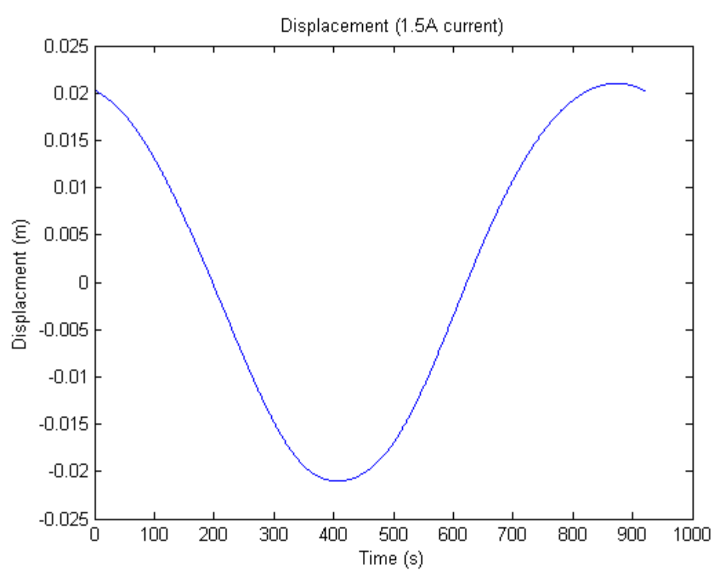

Figure 4.19: Displacement graph for 1.5A current

In simulation side, data from the experimental were use and the current is also set to 1.5A at the simulation block diagram (Figure 4.20), thus resulting the same output as the experimental method shown in Figure 4.21. Similarly in simulation at 1A, the primary result that need to be obtained is the graph of errors (Figure 4.22) between experimental and simulation so that RMSE can be calculated.

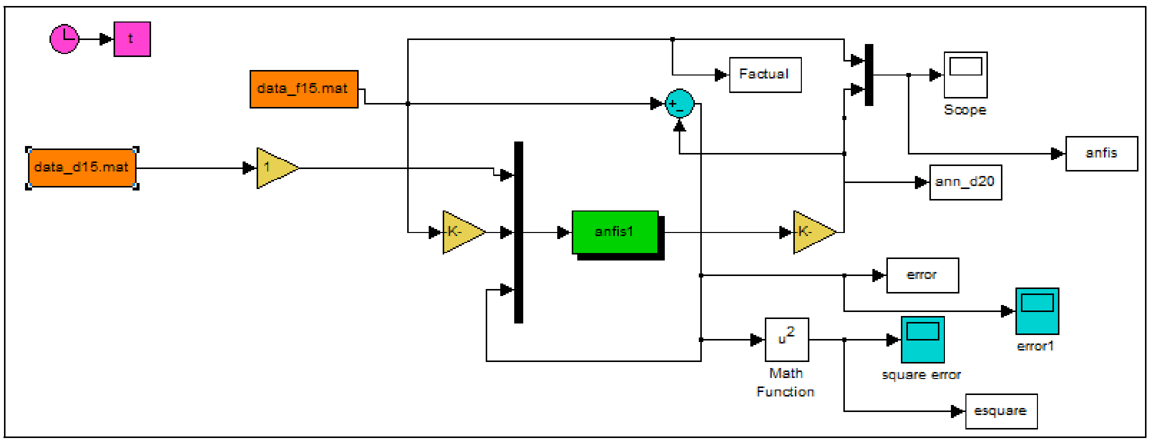

Figure 4.20: Simulation block diagram using experimental data and 1.5A current

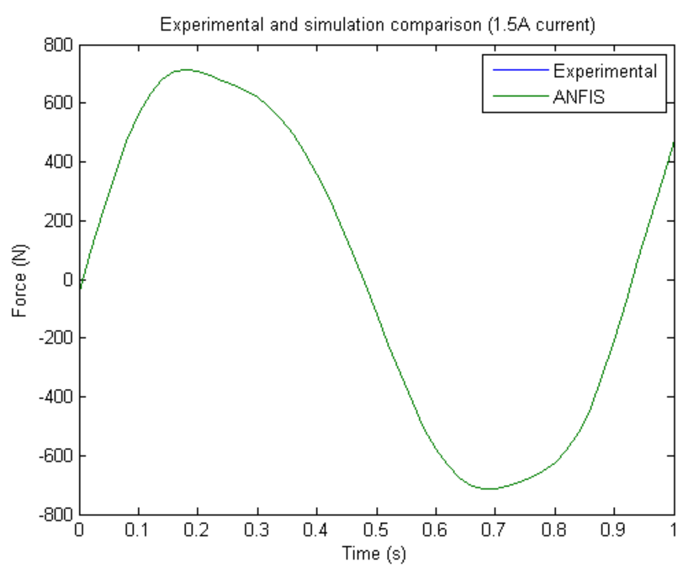

Figure 4.21: Simulation and experimental graph for 1.5A current

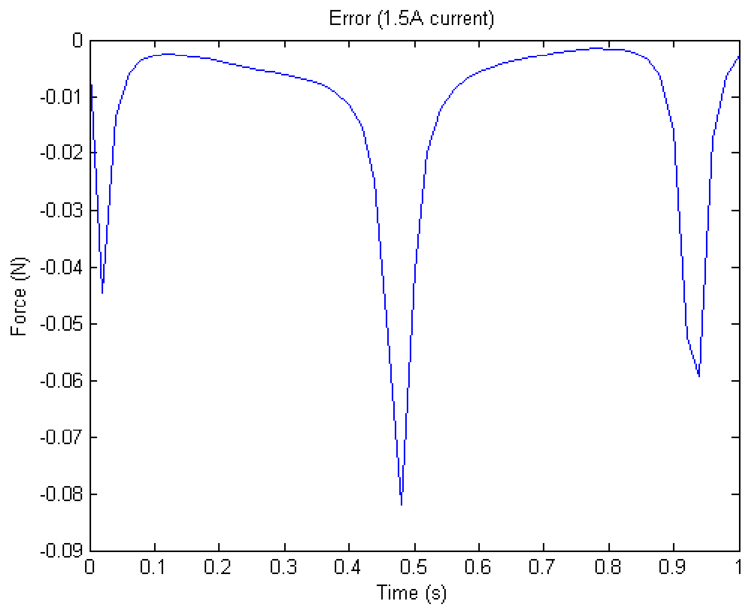

Figure: 4.22: Error graph for experimental and simulation

After getting the result of error between both experimental and simulation, base on the RMSE equation (4.2) all of the values is submitted and calculated.

$$\text{RMSE} = \sqrt{\frac{U^2}{N}} = \sqrt{\frac{0.0225}{51}}$$

RMSE = 0.02101

Thus the RMSE for 1.5A current is 0.02101.

4.7 Experimental and simulation for 2A current

The result of the force and displacement graph shown in Figure 4.22 and Figure 4.23 occur when 2A current is applied to the damper.

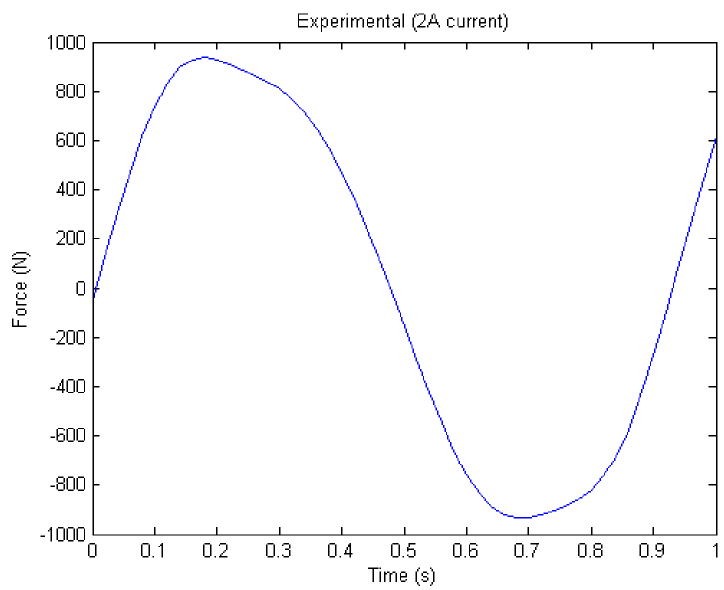

Figure 4.23: Experimental graph for 2A current

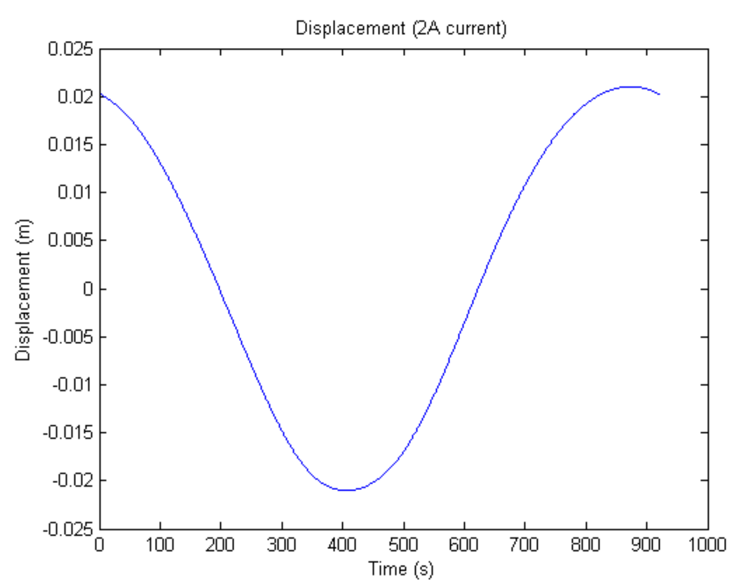

Figure 4.24: Displacement graph for 2A current

In simulation side, data from the experimental were use and the current is also set to 2A at the simulation block diagram (Figure 4.24), thus resulting the same output as the experimental method shown in Figure 4.25. Similarly in simulation at 1.5A, the primary result that need to be obtained is the graph of errors (Figure 4.26) between experimental and simulation so that RMSE can be calculated.

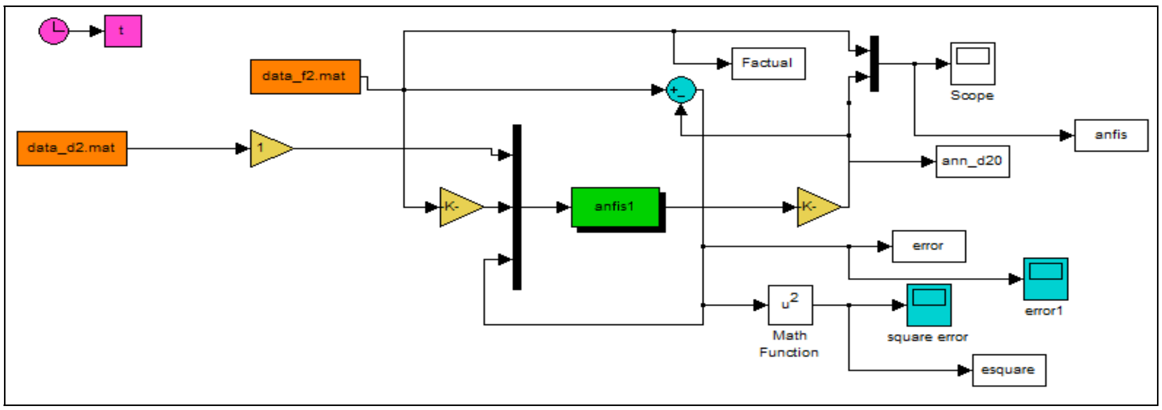

Figure 4.25: Simulation block diagram using experimental data and 2A current.

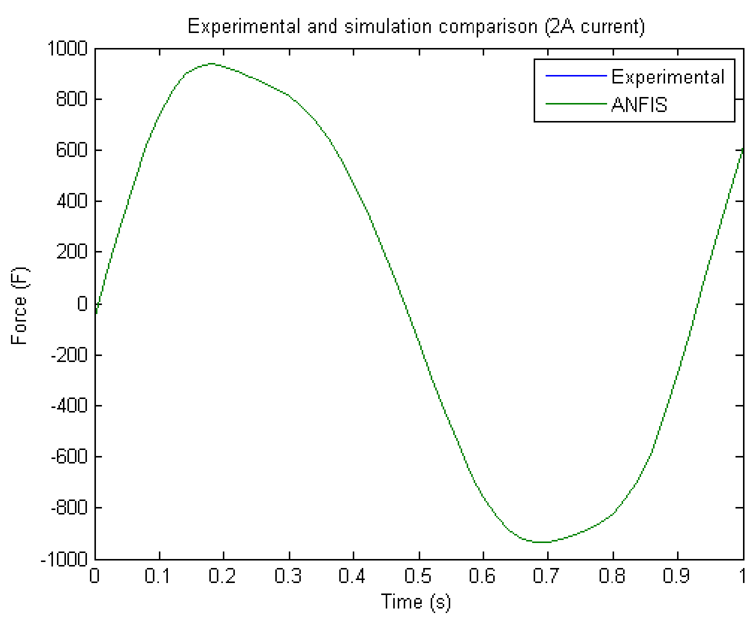

Figure 4.26: Simulation and experimental graph for 2A current

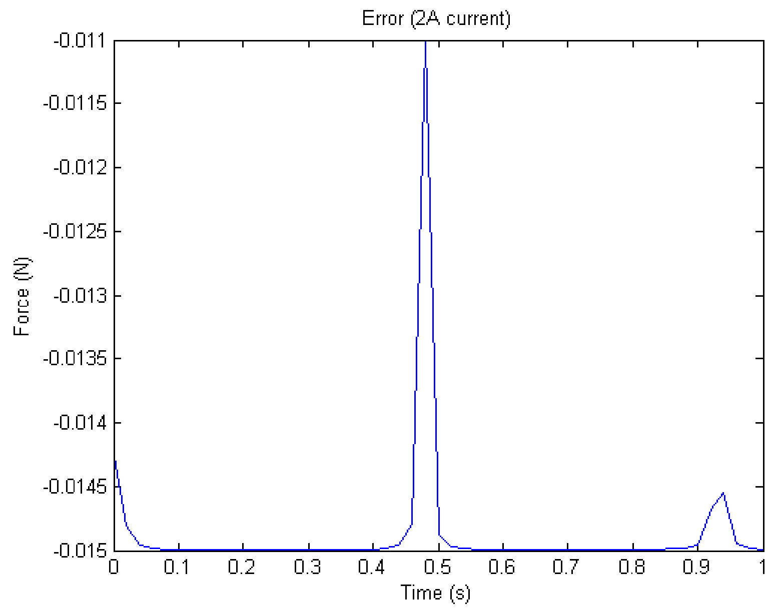

Figure 4.27: Error graph for experimental and simulation

After getting the result of error between both experimental and simulation, base on the RMSE equation (4.2) all of the values is submitted and calculated

$$\text{RMSE} = \sqrt{\frac{n^2}{N}} = \sqrt{\frac{0.011296}{51}}$$

$$\text{RMSE} = 0.01488$$

Thus the RMSE for 2A current is 0.01488.

Concluding the overall RMSE between experimental and simulation result for 0A, 0.5A, 1A, 1.5A and 2A current can be shown in Table 4.1

Table 4.1: Overall RMSE result for experimental and simulation method

Current (Ampere)	RMSE
0	0.10377
0.5	0.03679
1	0.01500
1.5	0.02101
2	0.01488

In summary, the simulation proves that the MR damper can be modeling using ANFIS method. Compared the MR damper force from experimental and simulation with present RMSE show the effectiveness using ANFIS in modeling MR damper. It is shown that among of fives current were used to test this experiment, 2A current that have the lowest value of RMSE. Another 4 data it need to been fine tuned as been discussed in section 4.2, to get better RMSE result.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

The purpose of this chapter is to summarize the work that has been completed for this thesis. In addition, the result of testing will be discussed with respect to the research objective set in chapter 1. This chapter will conclude with several suggestions for future work that should be pursued in this area research.

5.2 Conclusion

The MR damper is a versatile device, which can be used in many applications. The identification of MR dampers is definitely difficult due to its nonlinear dynamics. The benefit using ANFIS is that combines advantages of artificial neural network and fuzzy logic to deliver excellent modeling competency for complex and nonlinear equation. Given identical sets of input, execution speed of the fully trained ANFIS is approximately 10^3 times faster than the mathematical model (Kyle and Paul, 2005). In this project, the objective is archived where the MR damper has been modeling using ANFIS method. Validation results from chapter 4 shows that the proposed ANFIS model can predict the damping force accurately and small RMSE like 1A results get 0.01500. It has been shown that with ANFIS, a multiple input or single output can be created that accurately characterizes dynamics behavior of a MR damper. ANFIS model can be used as a design tool by engineers and researchers to further exploit benefits of semi-active control system.

5.3 Future recommendations

There are several future recommendations for this project to improve the modeling a MR damper as below.

1. Continuation of work on ANFIS: continue fine tune the weight and learning rate using ANFIS to get better result for the RMSE.

2. Method for tune: find and use certain method to get appropriate value of weight and learning rate.

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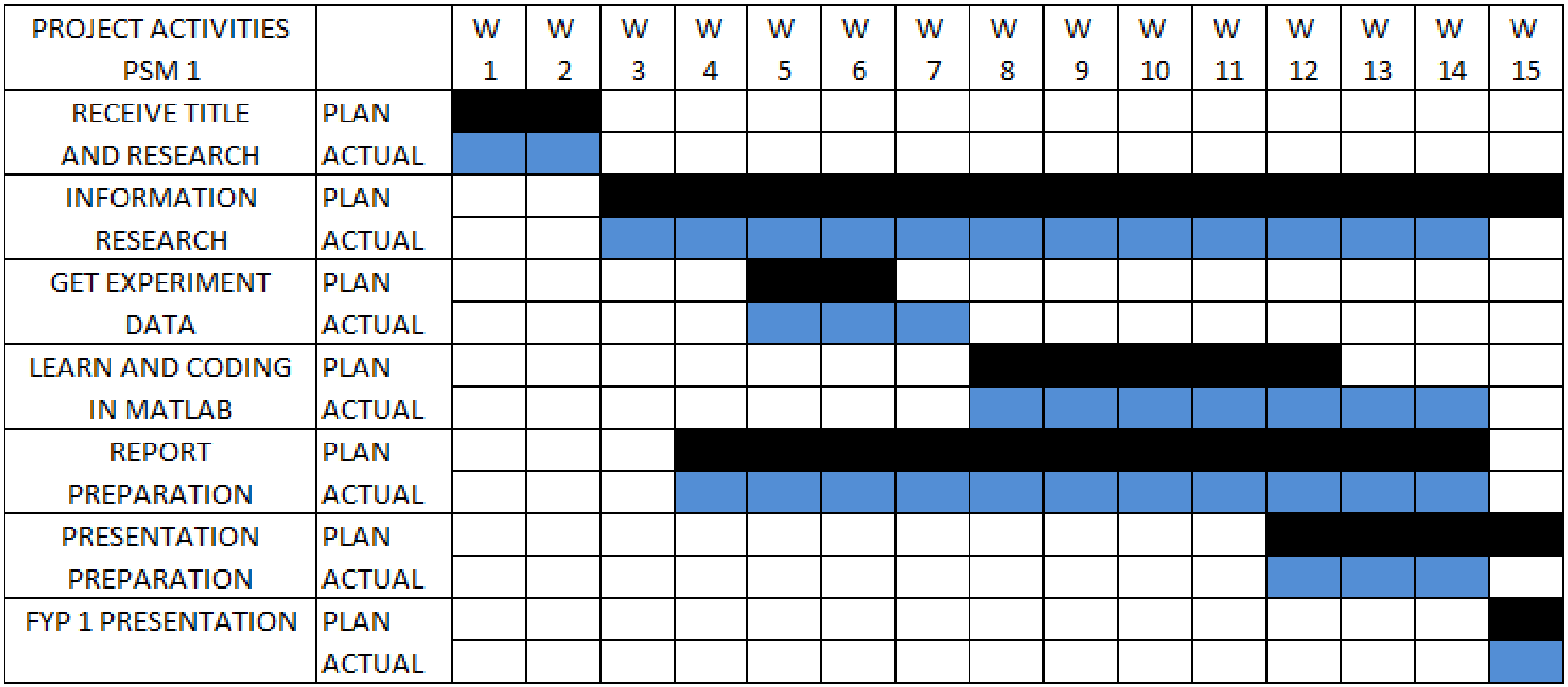
APPENDIX

APPENDIX A1

Gantt chart/ project schedule for FYP 1



APPENDIX A2

Gantt chart/ project schedule for FYP 2

PROJECT ACTIVITIES PSM 2		W 1	W 2	W 3	W 4	W 5	W 6	W 7	W 8	W 9	W 10	W 11	W 12	W 13	W 14
DISCUSS PROJECT FLOW	PLAN														
	ACTUAL														
GET EXPERIMENT DATA	PLAN														
	ACTUAL														
CODING MATLAB	PLAN														
	ACTUAL														
RESULT ANALYSIS	PLAN														
	ACTUAL														
REPORT PREPARATION	PLAN														
	ACTUAL														
PRESENTATION PREPARATION	PLAN														
	ACTUAL														
FYP 2 PRESENTATION	PLAN														
	ACTUAL														