

MAGNETO-RHEOLOGICAL (MR) DAMPER – PARAMETRIC MODELLING AND EXPERIMENTAL VALIDATION FOR LORD RD 8040-1

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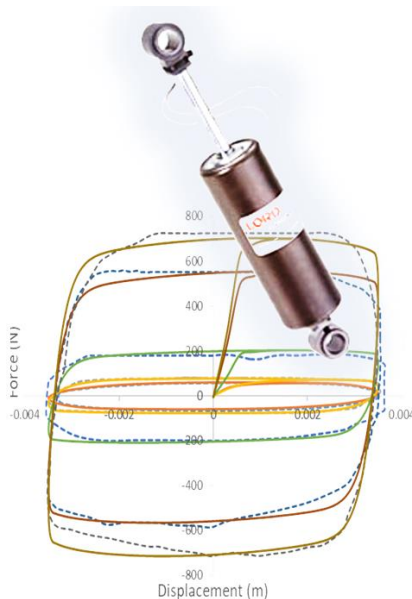
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Graphical abstract



Abstract

Magneto-rheological (MR) fluid technology has significantly developed during the past decades. The application of MR fluids has proliferated in various engineering fields with the development of MR fluid-based devices, especially MR fluid dampers. MR dampers are semi-active devices used for vibration reduction in many engineering applications. The MR dampers could offer an outstanding capability in semi-active vibration control due to excellent dynamical features such as fast response, low power consumption, and simple interfaces between electronic input and mechanical output. Modelling of MR damper is crucial in describing MR damper's behaviour. It is critical to comprehend the dynamic behaviour of these devices, as nonlinear hysteresis is a rather complex phenomenon. The Modified Bouc-Wen model represents the MR damper mathematically since this model is capable of performing as precisely as the non-parametric model. The Modified Bouc-Wen model parameters are damper dependent and must be defined for further simulation studies before utilising the damper. Validation of MR damper experimentally is one of the tasks required to confirm the parametric model performance. The specified parameters are believed to be worthwhile for this MR damper's use in further studies of real-time semi-active (SA) suspension systems. The small values of percentage difference for force (0.5-3.5%) indicate that the parameters implemented in the Modified Bouc-Wen model accurately portray the characteristics and behaviour of the MR damper.

Keywords: MR Damper, Modified Bouc-Wen model, semi-active (SA) system, experimental validation, Lord RD 8040-1

Abstrak

Teknologi bendalir magneto-rheologi (MR) pesat membangun sejak beberapa dekad yang lalu. Penggunaan bendalir MR juga berkembang pesat di pelbagai bidang kejuruteraan dengan pembangunan peranti berasaskan bendalir MR, terutama peredam bendalir MR. Peredam MR adalah peranti separa aktif yang digunakan untuk mengawal getaran dalam banyak aplikasi kejuruteraan. Peredam MR dapat menawarkan kemampuan yang luar biasa dalam kawalan getaran separa aktif kerana ciri dinamik yang sangat baik seperti tindak balas pantas, penggunaan kuasa yang rendah, dan antara muka yang mudah antara input elektronik dan output mekanikal. Pemodelan peredam MR sangat penting dalam menggambarkan tingkah laku peredam MR. Hanya penting untuk memahami tingkah laku dinamik peranti ini, kerana histeresis tak linear ialah fenomena yang kompleks. Model Bouc-Wen boleh ubah yang mewakili peredam MR secara matematik kerana model ini mampu menunjukkan prestasi yang tepat sama seperti model bukan parametrik. Parameter model Bouc-Wen diubahsuai bergantung pada peredam dan mesti ditentukan untuk kajian simulasi lebih lanjut sebelum menggunakan peredam. Pengesahan MR peredam secara eksperimen adalah salah satu tugas yang perlu untuk mengesahkan prestasi model parametrik. Parameter yang ditentukan dipercayai bermanfaat untuk penggunaan peredam MR ini dalam kajian

lanjutan untuk sistem ampaian separa aktif (SA) masa nyata. Nilai kecil peratusan perbezaan untuk daya (0.5-3.5%) menunjukkan bahawa parameter yang digunakan dalam model Modified Bouc-Wen menggambarkan dengan tepat ciri dan tingkah laku peredam MR.

Kata kunci: Peredam MR, model Bouc-Wen diubahsuai, sistem separa aktif (SA), pengesahan eksperimen, Lord RD 8040-1

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1.0 INTRODUCTION

Magneto-rheological (MR) damper is a prominent actuator among researchers when employing variable damping into the semi-active (SA) suspension system. It comes up with an excellent and possible method in eliminating the unwanted vibration motions. The MR damper uses a MR fluid, oil with metallic particles, and its damping ratio variation.

The popular research in MR damper involves MR damper modelling [1]–[3], MR fluid design and composition study [4]–[5], MR damper control [6]–[7], and MR damper behaviour [8]. Furthermore, MR damper is widely used in many engineering applications such as civil, automotive, bridge engineering, etc. In the automotive application, the MR damper control approach is the most commonly used to solve the suspension system's problems [9]–[15].

Implementing appropriate control strategies for the semi-active quarter car model requires an accurate MR damper model to achieve desirable control performance. MR damper modelling is an essential part of representing the observed behaviour of the MR damper. The behaviour of MR damper modelling can be clustered into two categories, namely parametric and non-parametric modellings. Bouc-Wen, Modified Bouc-Wen, Bingham, Dahl, Gamota-Filisko, Non-linear Viscoelastic-Plastic, Augmented Non-Linear Viscoelastic-Plastic, LuGre and algebraic are among of the parametric models investigated by previous scholars [1], [16], [17]. Meanwhile, non-parametric models such as the fuzzy, neural network, and neuro-fuzzy models learn from experimental data and require a set of input or output data [17], [18].

Briefly, parametric modelling defines the device as a collection of (linear and/or nonlinear) springs, dampers, and other physical elements. Meanwhile, non-parametric modelling deploys analytical expressions to characterise the properties of the modelled devices based on both testing data analysis and device operation principles. Modelling the MR damper using a parametric approach and validating it experimentally is one of the crucial tasks required to model an actuator before being implemented as a significant element in the semi-active suspension system controller verification.

In this paper, the Modified Bouc-Wen model is used to portray and describe the behaviour of MR damper Lord RD 8040-1 parametrically. Then, the model will be validated experimentally in terms of Force-Velocity, and Force-Displacement characteristics as well as in the time-force domain. These relationships are significant and essential to confirm that the suitable model with correct parameters was chosen to model the MR damper mathematically. Later, this validated parametric model will be used as a primary element in the MR damper representing an actuator for semi-active suspension system controller justification in real experimental work.

1.1 MR Damper Behaviour

The MR damper is intelligent in a carrier fluid that comprises tiny iron particles. The MR damper system; if the system requires stiff dampers, the magnetic field is applied, and the fluid immediately increases its viscosity. Instead, once the system provides soft damping, the magnetic fields spontaneously diminished.

This reveals that the MR damper's smart structure is an incredibly simple technology and can meet the suspension requirements to improve the systems, especially for the vehicle occupant's comfort. It may classify into three design types: the mono tube, twin tube, and double-ended MR damper. Because it can be mounted in different orientations as well as having a compact size, the mono tube MR damper is the most common. Overall overview design for each types of MR damper are shown in Figures 1 to 3.

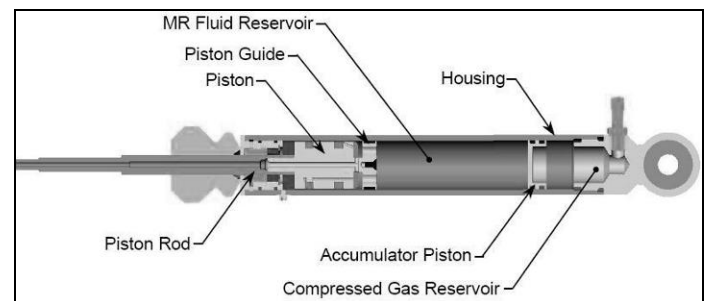


Figure 1 The mono tube MR Damper [19]

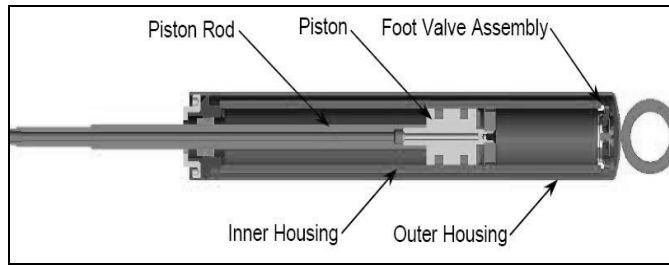


Figure 2 The twin tube MR Damper [19]

The MR damper usually has the fluid's pressure valve mode (driven flow). The pressure valve can be split into two components because of the viscous drag and pressure loss due to field-dependent yield stress.

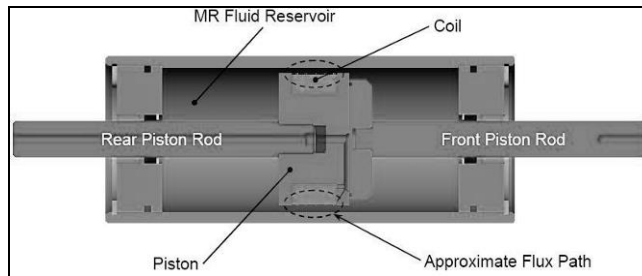


Figure 3 Double-ended MR Damper [19]

1.2 MR Fluid Composition

MR fluid is the suspension of particles that react magnetically to a liquid carrier. The existence of a magnetic field can regulate the rheological properties of MR fluids. The MR fluid has the potential to transform from a free-flowing liquid state to a solid form with minimal movement when subjected to magnetic fields. In MR fluid, the iron particles act like dipoles and continue to adjust along with the steady flux under the influence of a magnetic field [4].

Therefore, the magnetic field's intensity as shown in Figure 4 can be controlled by force or torque of application devices from this property. Dampers, clutches, brakes and transmissions are some examples of systems in which MR fluids have been used. As opposed to the MR damper, the tuning of conventional hydraulic dampers requires the physical modification of the different valves' settings inside the piston. Therefore, the conventional damper will have a constant setting during its lifespan and will consequently not function comprehensively under various road conditions. As a result, semi-active (SA) systems with MR dampers have attracted suspension researchers' attention for these reasons [20], [21], [22].

MR dampers not only benefit from their ability to provide the suspension with adjustable damping forces but also from a technological point of view inherently fail-safe devices. Depending on the off-state properties of the MR fluid inside, the MR damper can still function as a passive damping mechanism within specific performance parameters if the system is malfunction.

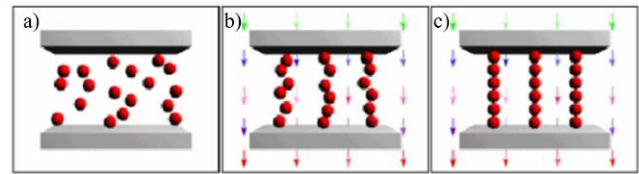


Figure 3 MR fluid behaviour (LORD Corporation 1997-2005) (a) No magnetic field (b) and (c) Increase in magnetic field [18]

1.3 MR Damper RD 8040-1

The MR damper RD 8040-1 produced by Lord Corporation, shown in Figure 5 is a short-stroke type damper, fast response with time, easy to use, and durable. The technical details of the MR damper Lord RD 8040-1 are given in Table 1. This mono-tube MR Damper type consists of a cylinder, a piston, an excitation coil, and the MR fluid, which moves steadily from a high-pressure chamber to a low-pressure chamber throughout the piston head.

By using a copper coil wrapped around the piston body, a magnetic field is applied in the flow direction, which is a component of the excitation current. The coil leads are extracted via the piston rod to provide the coil with the variable current to induce the variable magnetic field, which generates the variable damping effect.



Figure 4 MR Damper Lord RD 8040-1 [23]

Table 1 Technical properties of MR Damper Lord RD 8040-1 [24]

Properties	Value	Unit
Extended length	208	mm
Compressed length	153	mm
Body diameter	42.1	mm
Shaft diameter	10	mm
Input Voltage (DC)	12	V
Input Current		
Continuous	1	A
Intermittent	2	A
Coil resistant		
Ambient temperature	5	Ω
At 71 °C	7	Ω
Force (peak to peak)	>2447 (50 mms-1 at 1 A) <667 (200 mms-1 at 0 A)	N
Operating temperature	71	°C
Response time	< 15	ms

2.0 METHODOLOGY

2.1 Modelling Using Modified Bouc-Wen Model

This section discusses the method of modelling MR damper by using a parametric model. The Modified Bouc-Wen model introduced by Spencer is adopted to characterise the performance and behaviour MR damper Lord RD 8040-1 [25]. The structure diagram of MR damper with Modified Bouc-Wen model shown as Figure 6. The Modified Bouc-Wen model is the precise model compare to other MR damper parametric modelling models.

The development of an accurate and precise mathematical model of the MR damper plays a vital role in successfully implementing the semi-active attenuation of vibration [26]. The Modified Bouc-Wen model can simulate the effect of velocity and acceleration in all regions [27].

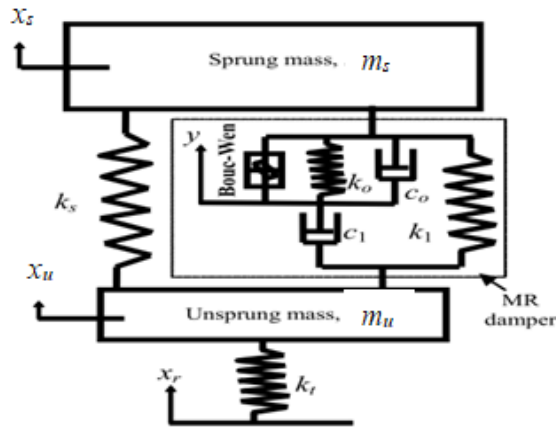


Figure 5 Semi-active (SA) MR Damper with Modified Bouc-Wen model [28]

The mathematical equation for the Modified Bouc-Wen model is given as Equations 1 to 8. The Modified Bouc-Wen model's equations will be used as a mathematical model to represent the behaviour of MR fluid damper in converting the voltage to the damper force.

The damping force in Modified Bouc Wen model can be expressed as

$$F = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) \quad (1)$$

or can be written as

$$F = c_1\dot{y} + k_1(x - x_0) \quad (2)$$

and z is an evolutionary variable given by

$$\dot{z} = -\gamma|\dot{x} - \dot{y}||z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \quad (3)$$

where

$$\dot{y} = \frac{1}{c_0 + c_1} [\alpha z + c_0\dot{x} + k_0(x - y)] \quad (4)$$

where:

- F = Total generated force
- c_0, c_1 = Viscous damping at larger & smaller velocity
- y = Internal displacement of MR damper
- γ, β, n = Hysteresis parameter
- k_1 = Stiffness represent accumulator
- k_0 = Stiffness at high velocity
- x_0 = Accumulator gas spring - Initial deflection
- η = a constant controlling the rate of change of a magnetic field to achieve the equilibrium of MR fluid
- α, A = Yield stress - MR fluid

The following linear relationships can be used to consider the damper force, F depends on the input voltage:

$$\alpha = \alpha_0 + \alpha_b u \quad (5)$$

$$c_0 = c_{0a} + c_{0b} u \quad (6)$$

$$c_1 = c_{1a} + c_{1b} u \quad (7)$$

Where v is given by the following differential equation:

$$\dot{u} = -\eta(v - u) \quad (8)$$

where v is the applied voltage to the current driver. The total of 14 parameters ($c_{0a}, c_{0b}, c_{1a}, c_{1b}, k_0, k_1, x_0, \alpha_a, \alpha_b, \gamma, n, \beta, \eta$, and A) have to be decided in Bouc-Wen Model to describe the hysteresis behaviour of MR damper accurately. The damping force generated by MR damper can be obtained using mathematical formulations as follows:

$$F_D = \left[\frac{18\eta l A_p^2}{\pi R_1 (R_2 - R_1)^3} + \frac{6\pi R_1 l \eta}{R_2 - R_1} \right] \dot{x}_p + \left[\frac{9l A_p}{R_2 - R_1} + 6\pi R_1 l \right] \tau_y \quad (9)$$

where:

- A_p = the working area of the piston
- η = the viscosity of MR fluid (in the absence of magnetic field)
- l = length of each damping duct
- R_2 = circular cylindrical orifice inner radius
- R_1 = orifice outer radius

In the MATLAB Simulink block diagram for MR Damper parametric modelling, the input for the Modified Bouc-Wen model will be voltage and 2.6 Hz sinusoidal input with 3.5 mm. The parameter for Modified Bouc-Wen model for Lord RD 8040-1 as

tabulated in Table 2 used in this simulation based on the well-established data conducted experimentally by the previous researcher [29], [30].

Parametric modelling requires different voltages (0-5 Volt) input supplied to the MR damper model. The model will produce the output in terms of Force, Displacement, and Velocity. But in order to choose a model that also works in magnetic fields, the parameter that changes with the voltage must be observed out beforehand. Therefore the relationship between input (voltage) and output (force) as specify in Equations 5 to 7 is considered.

Table 2 Parameter for Modified Bouc-Wen model [30]

Parameter	Value (Unit)	Parameter	Value (Unit)
α_a	1921.141 N/m	k_0	1940.405 N/m
α_b	5882.51 N/V.m	k_1	1.751268 N/m
C_{0a}	651.4718 N.s/m	A	155.32 m ⁻¹
C_{0b}	1043.7559 N.s/V.m	β	36332.07 m ⁻²
C_{1a}	2089.263 N.s/m	γ	36332.07 m ⁻²
C_{1b}	14384.918 N.s/V.m	η	60 s ⁻¹
x_0	0.00 m	n	2 s ⁻¹

2.2 Experimental Validation MR Damper Lord RD 8040-1

The experimental validation configuration for this research is in Figure 7. The rig consists of sinusoidal excitation, accelerometer, laser displacement, force sensor, MR damper Lord RD 8040-1, and NI-DAQ PCI 6259 hardware connected to MATLAB Simulink installed on PC.

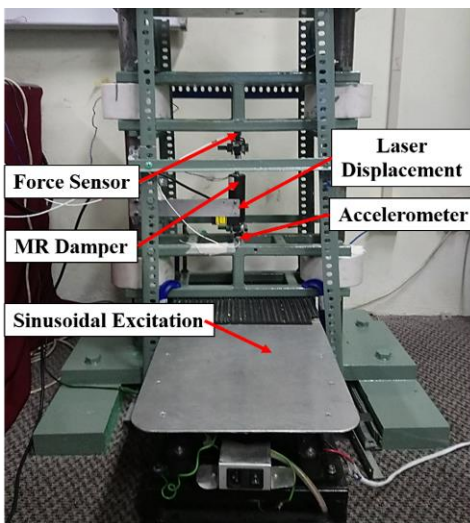


Figure 6 Validation rig for MR Damper Lord RD 8040-1

The data are gathered using Laser displacement, accelerometer, and force sensor. These sensors are attached to NI-DAQ PCI 6259 hardware that processes the incoming signals and transfers it to the MATLAB Simulink installed in the PC. A power supply and voltage-current converter are used to provide the MR damper Lord RD 8040-1 with the input voltage. The voltage-current driver applies the current to the MR damper's exciting coil according to the command voltage, which is determined by the MATLAB Simulink block for the Modified Bouc-Wen model.

Then, the magnetic field produced by the electromagnet influence the properties of the MR fluid, which consists of tiny magnetic particles in a non-conductive (magnetic inert) fluid base. Consequently, the magnitude of the electromagnet's input current determines the physical features of the MR dampers. Continuously variable damping in response to magnetic field strength is managed by increasing the MR fluid's yield strength. MR fluid flows through an orifice in the piston head from a high-pressure to a low-pressure chamber in the damper.

A small electromagnet in the piston head generates the magnetic field, which is perpendicular to the fluid flow. The upper head of the MR damper was the moveable end, while the lower head was incorporated with a force sensor for measuring the force applied to the MR damper. Five experimental tests were carried out with different voltage inputs for the MR damper (0 V, 0.5 V, 1.0 V, 1.5 V, 2.0 V, 2.5 V). The response of the MR damper due to a 2.6 Hz sinusoidal excitation with an amplitude of 35 mm was investigated for 6 constant voltages applied to the current driver of the MR damper. During the validation process, the current driver manufactured by Lord Corporation as illustrated in Figures 8 is adapted to convert voltage input from MATLAB Simulink to the MR damper Lord RD 8040-1. This step is necessary for the MR damper since the current will be the input for the Lord RD 8040-1 to operate.



Figure 7 Current driver by Lord Corporation

Force, displacement, and velocity measurements provided by the validation test rig were filtered and processed by MATLAB Simulink. Finally, the output from the MR damper in terms of Force, Velocity, Time, and Displacement will be collected. The working principle for the MR damper validation process can be referred to Figure 9. The relationship between Force-Displacement and Force-Velocity characteristics will be used to confirm that the selected model and parameter were correctly chosen to represent the MR fluid behaviour mathematically.

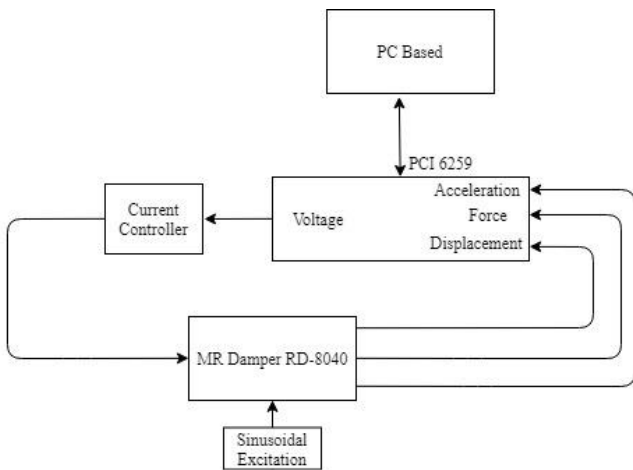


Figure 8 Working principle for MR damper validation process

3.0 RESULT AND DISCUSSION

3.1 Simulation Using Parametric Modelling

This section discusses the results obtained from the simulation works, which the parametric modelling using Modified Bouc-Wen model were performed in MATLAB Simulink environment. Then, the MR damper behaviour will be simulated in the form of Force-Velocity, Force-Displacement, and Force-Time relationships as depicted in Figures 10, 11 and 12, respectively.

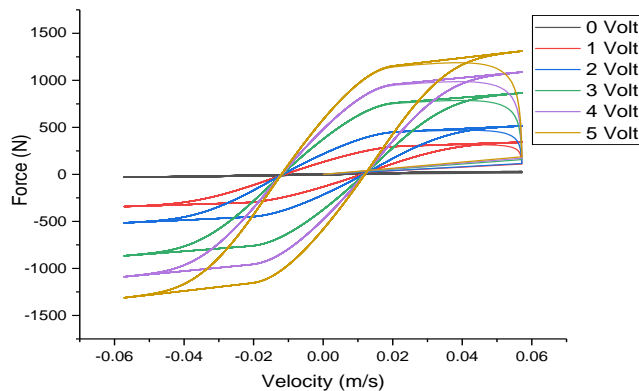


Figure 9 Force-Velocity relationship

In this task, different voltage input was applied to the Modified Bouc-Wen model to study the relationship behaviour of the Force-Velocity, Force-Displacement for any changes of input made to the MR damper model.

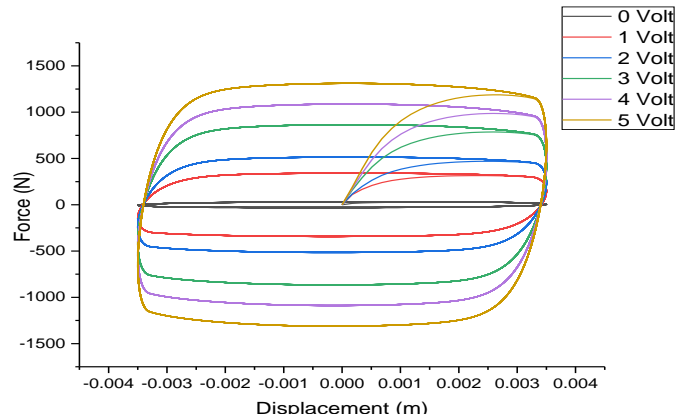


Figure 10 Force-Displacement relationship

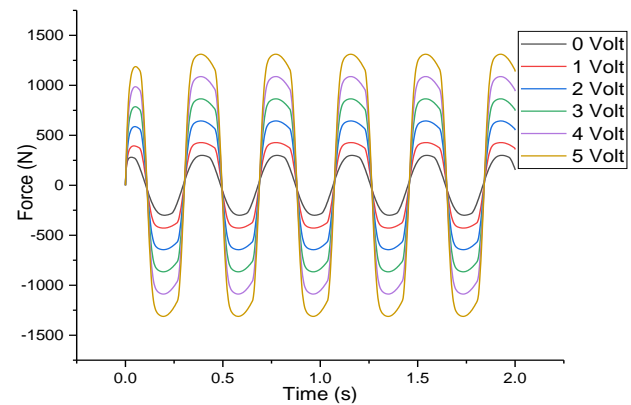


Figure 11 Force-Time relationship

3.2 Validation Of MR Damper

The validation process found that the MR damper model's characteristics using Modified Bouc-Wen reasonably close to the experimental results for the different voltage inputs. Figure 13 shows that the force predicted by the Modified Bouc-Wen model is in good agreement with the experimental results. In other words, the Modified Bouc-Wen model is a precise configuration compare to other parametric models since this model is capable of capturing the force-velocity and force-displacement hysteresis of the MR damper Lord RD 8040-1.

Then, the force prediction error of the magneto-rheological damper is another method to confirm the MR damper model has been selected with the correct model. The force prediction error is the difference between measured forces from the experimental work with force predicted by the MR damper model. Under the same applied voltage, an accurate and correct MR damper model will produce a predicted force as

close as possible with the measured force of experimental data. Figure 14 shown the force prediction error for the Modified Bouc-Wen model for different applied voltage signal (0, 0.5, 1.0, 1.5, 2 Volt). It can be concluded that the force prediction error has a tendency to increase with the increasing of applied voltage signals.

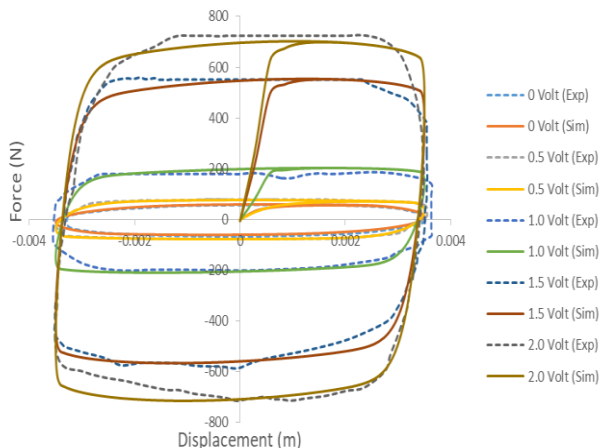


Figure 12 Validation of Force-Displacement relationship

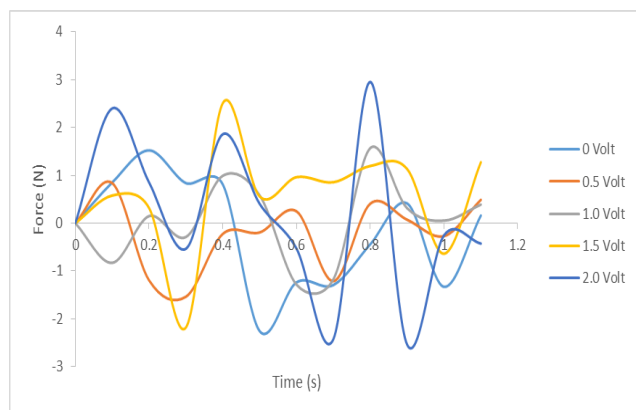


Figure 13 Force difference between simulation and experimental

The increase in prediction error can be justified in Table 3, demonstrating the MSE (simulation & experiment) and percentage difference for force when various voltages were applied to the MR damper. Equation 10 can be used to calculate the percentage difference for the force between simulation and experiment.

Table 3 MSE and Percentage difference

Force	Simulation (MSE)	Experiment (MSE)	Difference (%)
0 Volt	518.12	521.53	0.66
0.5 Volt	740.65	745.63	0.67
1.0 Volt	128.45	126.59	1.46
1.5 Volt	202.56	208.41	2.85
2.0 Volt	295.34	285.76	3.29

$$Diff = \left| \frac{Simulation - Exp}{\left(\frac{Simulation + Exp}{2} \right)} \right| \times 100\% \quad (10)$$

Due to the limitations of parametric modelling in accurately representing the entire behaviour of the MR damper, the percentage difference increased as the voltage increased.

4.0 CONCLUSION

The comparison between the parametric model and experimental data of MR damper Lord RD 8040-1 in the form of Force-Velocity and Force-Displacement is studied to choose the correct and suitable parameters for the Modified Bouc-Wen model. The Modified Bouc-Wen model's selected parameters are vital in defining and representing MR fluid behaviour mathematically. The validated Modified Bouc-Wen model is valuable as an actuator element in the semi-active suspension system controller. Although the parametric model is not good enough to compare with the non-parametric model, the Modified Bouc-Wen model with 14 parameters is the best model among the parametric models as an alternative method to replace the non-parametric model. Future studies could focus on modelling MR damper using a non-parametric approach that can portray in detail the characteristics and behaviour of MR damper Lord RD 8040-1.

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