Modelling and Force Tracking Control for Newly Type Configuration of Magneto-rheological Damper

M.S.F. Mansor[1, 2], H. Zamzuri[2], A.N.M. Jahari[2], A.A. Puad[1], F. Ahmad[3], and S.A. Mazlan[2]
[1]*Advanced Engineering and Strategy, Group of Engineering, Perusahaan Otomobil Nasional (PROTON) Sdn. Bhd.*
[2]*Vehicle System Engineering, Malaysia Japan International Institute of Technology, Universiti Teknologi Malaysia (UTM).*
[3]*Advanced Vehicle Technology Research Group, Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka.*
shuhaim@proton.com

***Abstract*—The objective of this paper is to model hysteresis behaviour of new MR damper configuration by using non-parametric model approaches. The approaches are non-parametric linearised data-driven (NPLDD) single input model, non-parametric linearised data-driven (NPLDD) double input model, and simple polynomial model. The modelling is developed to ensure the force of MR damper is tracked to any input force. The NPLDD model is developed based on look-up table while the polynomial model is developed based on curve fitting from the experimental results and consists of a pair of subsystems namely positive and negative acceleration which corresponds to the upper and lower curves. From the simulation results, the NPLDD double input model shows better performance in describing non-linear hysteresis behaviour of the MR damper compared with others. By using the NPLDD model, a force tracking based on PI controller has been developed. It is verified that the NPLDD model together with the PI control strategy has the capability to track the desired damping force well.**

***Index Terms*—Magneto-rheological Damper; NPLDD; Simple Polynomial Model; Hysteresis Behaviour; Force Tracking Control.**

I. INTRODUCTION

A damper is a device that dissipates energy in the form of heat. Energy is changed to heat by forcing a viscous fluid through an orifice. In a vehicle, energy from the road, rather than being transmitted to the vehicle, is changed into a temperature rise of the fluid inside of the damper. In this study, the damper is newly designed based on the configuration of magneto-rheological approach as a control element for damper characteristic. In order to achieve the design concept, MR fluid and controller to control the electric current are introduced instead of oil or gas that conventionally used in passive suspension. When the current is applied, the MR fluid will be exposed to the magnetic field, and thus the iron particle will be changed into the chain-like structure, as in Figure 1. The changes of iron particle in MR fluid will influence the changes of shear stress and viscosity of the fluid in less than 10 ms. As a result, the suspension will become more or less stiff [1].

This paper containing a brief explanation about the MR damper in section II, MR damper modelling by using NPLDD double and single input, and simple polynomial method in section III, MR damper model verification in section IV, force tracking control in section V, and conclusion in Section VI.

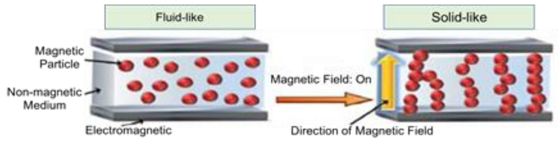

Figure 1: Iron particle of MR fluid [2]

II. MR DAMPER

The schematic of MR damper is shown in Figure 2. The design of newly MR damper consists of two cylinders where the air needs to fill in cylinder 2 to boost and maintain the output force of MR damper. Based on the valve design, the MR fluid can be manipulated to control the MR damper. The working principle of this MR damper is much similar to the existing damper in the market, except the damping characteristic can be controlled. At zero current, the MR damper is acting like a normal vehicle damper system. When sealed piston exhibits an external force, the sealed piston will traverse back and forth inside cylinder 1. If the sealed piston in cylinder 1 is compressed, the MR fluid will flow through MR valve to the accumulator and feed back to cylinder 1 again via bypass channel. If the piston in cylinder 1 is extended, the MR fluid will flow through MR valve from the accumulator and feed back to cylinder 2 via bypass channel.

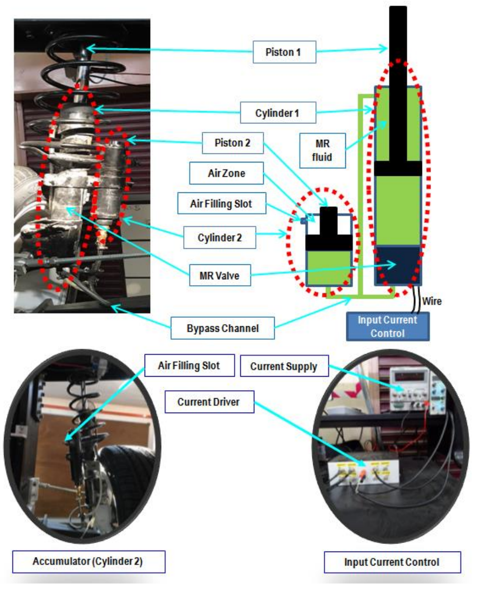

Figure 2: MR damper schematic diagram

The piston in cylinder 2 is used to separate the MR fluid and air. Here, there is one slot located at the top of cylinder 2 to be used to fill-in the air. The slot can be covered and tightened-up by a shielded screw. The air is used to accommodate the change in the MR fluid cylinder volume. As the piston rod in cylinder 1 compresses, the air compresses to compensate for the change in the volume available to the MR fluid. When the piston rod in cylinder 1 is extending, the air expands in order to avoid the creation of a vacuum. These working principles are applicable for all conditions even though the current varies.

III. MR DAMPER MODELLING

MR damper has high non-linear dynamic behaviour that needs appropriate control algorithm to ensure the effectiveness of the system [3, 4]. Hence, many researchers have conducted a comprehensive study to design the control method of MR damper [5]. Several models have been proposed in order to model the dynamic behaviour of the MR dampers. These include polynomial models [6, 7], a neural network model [8], and phenomenological models built on the Bouc-Wen hysteretic model [9].

MR damper can be modelled based on parametric and non-parametric approaches. Example of parametric approaches is Bingham model, Bouc-Wen model, non-linear viscoelastic-plastic model and others. While examples for the non-parametric approach is non-parametric linearised data-driven single input approach, non-parametric linearised data-driven double input approach, simple polynomial approach and others. The MR damper model development can be classified as an inner loop where the controller also needs to be designed for damping force tracking.

A. Non-parametric Linearised Data Driven

The first method of MR damper modelling is non-parametric linearised data-driven (NPLDD) model to capture the dynamic performance. This method is divided into NPLDD double input and NPLDD single input. NPLDD double input is developed based on experimental data that was mapped in a look-up table for a set of applied current and suspension relative velocity signals as the input.

On the other hand, the NPLDD single input is developed based on experimental data and consists of a pair of subsystem namely positive acceleration and negative relative acceleration of the damper. In each subsystem, the hard points of experimental data are mapped in the form of a look-up table for a set of applied current signals. The damper force is linearly interpolated if the current signal applied to the model lies between the specified input signals. Then, the output of the model is selected between the outputs of the two subsystems by a switch block based on real-time relative acceleration signal of the damper [10].

B. Simple Polynomial

To build an easy-for-implementation MR damper model for both simulation and real-time control systems, the proposed modelling approach is developed based on the experimental data.

This approach involves four main steps where for the first step, the investigation of force-velocity curve of MR damper is conducted via experimental works. The applied current is set to 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50, 0.55, 0.60, 0.65, 0.70, 0.75, 0.80, 0.85, 0.90, 0.95, and 1.00 Ampere. The cyclic motion is set to 0.1 Hz.

The second step is obtaining the hard points of experimental data from step one as illustrated in Figure 3. The hysteresis loop of each force-velocity curve is divided into two regions namely the positive acceleration (compression) and negative acceleration (extension) [11]. Then the third step as proposed by [6] fits both the compression and extension by the polynomial function expressed as:

$$F = \sum_{i=0}^{n} a_i v^i,\ n = 6 \qquad (1)$$

where F is the damper force, a_i is the experimental coefficient to be determined from the curve fitting and v is the damping velocity. In this work, the order of the polynomial for the damping force model is chosen by trial and error. After several investigations, it is observed that 6th order or higher order polynomials can capture the hysteresis behaviour of the MR damper. Considering computational time and implementation in real-time control of the damper, a 6th order polynomial is selected in this study.

In the last step, the output of the model namely the damper force is selected by a switch block. The switch block will pass through the output of positive acceleration subsystem if the acceleration of the damper is greater or equal to zero. Otherwise, the switch block will pass through the output of negative acceleration subsystem.

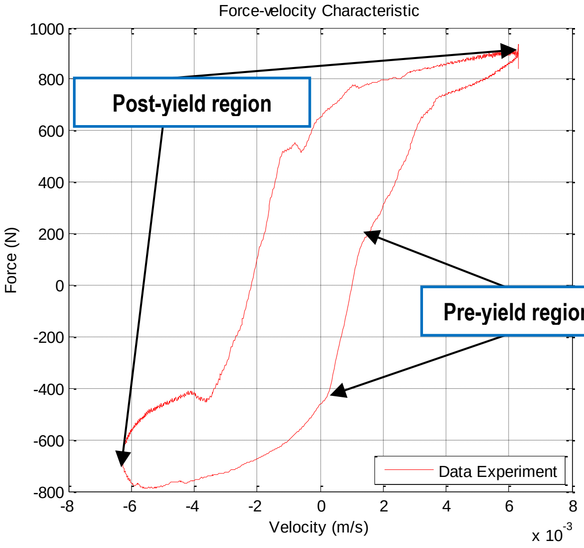

Figure 3: Hardpoints taken from the experimental result

IV. MR DAMPER MODEL VERIFICATION

The simulation was performed to explore the validity and the accuracy of the MR damper model in the MATLAB-SIMULINK environment. The response of the model compared among the three methods along with the experimental data of force-velocity characteristics as shown in Figure 4. During simulation study, the excitation frequency and magnitude were based on the experimental work which is 0.1 Hz and ± 0.06 m, respectively.

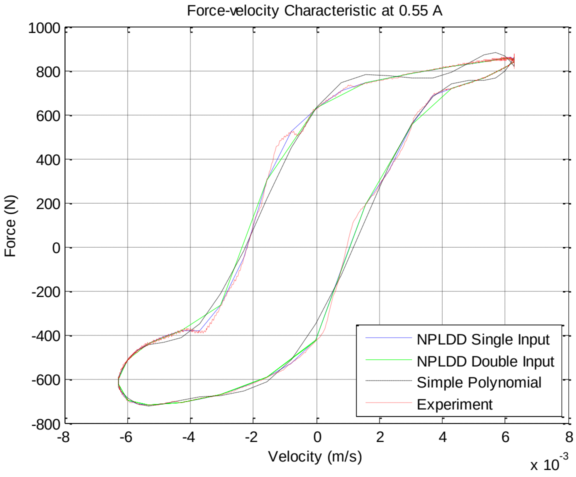

Figure 4: Force-velocity graph for different method of modelling at 0.55A

Figure 4 shows a force-velocity characteristic of the MR damper for different modelling methods. It can be seen that all models are reasonably good in predicting the experimental data in post-yield and pre-yield regions. However, the NPLDD model shows better performance compared to the simple polynomial model in predicting the behaviour of the experimental data.

To validate the effectiveness of the proposed model, the input current was varied to 0.05 A and 0.95 A at 0.1 Hz excitation frequency. The measured damping force obtained from experimental work and the predicted damping force from all entire models were compared and shown in Figures 5(a) and (b).

From the observation, it is clear that all models predict well the hysteresis behaviour at various input currents. Even that, the most precise model that follow experimental pattern is NPLDD single input with 98.8% degree of similarities while for a simple polynomial is 96.4%. Besides, it can be observed from Figures 4 and 5, the performance and magnitude of damping force for the proposed MR damper model increase when the input current is increased. As a conclusion, the proposed model especially NPLDD model can predict the damping force at a certain piston velocity under various conditions.

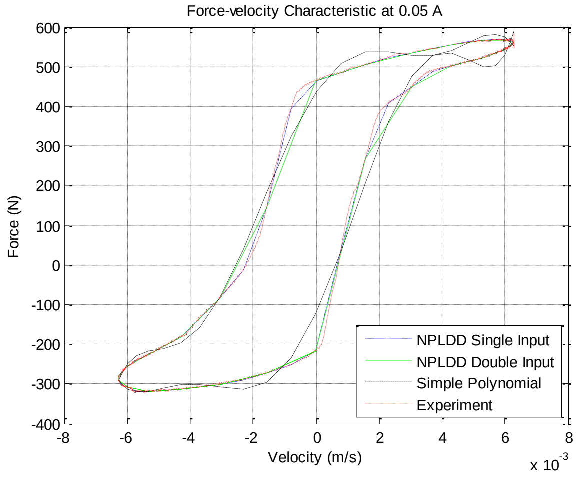

Figure 5(a): Force-velocity graph for different method of modelling at 0.05A

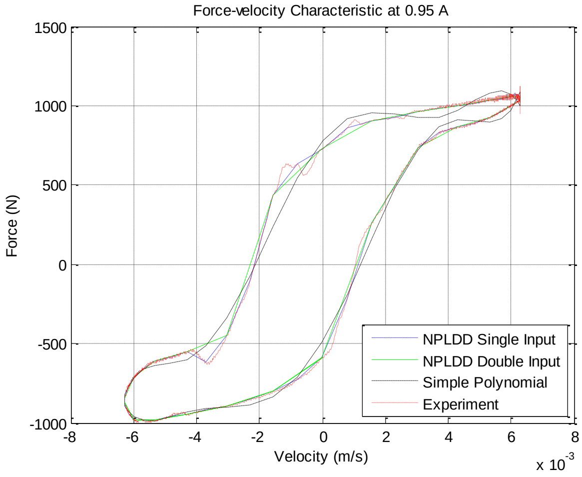

Figure 5(a): Force-velocity graph for different method of modelling at 0.95A

V. FORCE TRACKING CONTROL

Besides, having the similar behaviour as the real of MR damper, a good MR damper model must be easily controlled. In this section, a force-tracking control of the proposed MR damper model is performed in both simulation study and experimental works. The simulation study is executed in the MATLAB-SIMULINK environment for the sinusoidal, square, and saw-tooth function of desired force.

The structure of force tracking control of the proposed MR damper model using a proportional-integral (PI) controller are shown in Figure 6 which illustrates a closed-loop control system to achieve a desirable damping force. Related to tracking control, the PI controller has also been used for another application such as personal robot tracking system [12]. The PI controller is formulated as follows:

$$u(t) = K_p e(t) + K_i \int e(t) \tag{2}$$

$$e(t) = F_{des}(t) - F_{act}(t) \tag{3}$$

where F_{des} is the desired damping force, and F_{act} is the actual damping force.

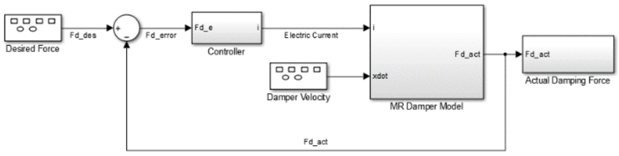

Figure 6: The structure of force tracking control of MR damper

In this simulation study, the parameters of K_p and K_i were chosen by trial and error method. The values of K_p and K_i are set to 1,500 and 100 respectively for NPLDD double input; K_p and K_i are set to 1.5 and 0.15 respectively for NPLDD single input, and K_p and K_i are set to 150 and 15 respectively for the simple polynomial.

Force tracking control is intended to check the tracking ability of the force tracking controller for a class of continuous and discontinuous functions. It is well known that the simulation results show the damping force controllability realised from the closed-loop controller. The simulation results under various functions of desired force are shown in Figures 7 to 9.

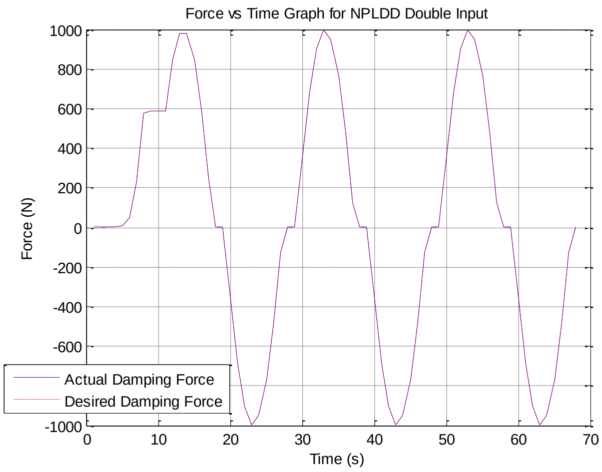

Figure 7(a): Force tracking control of NPLDD double input for sinusoidal

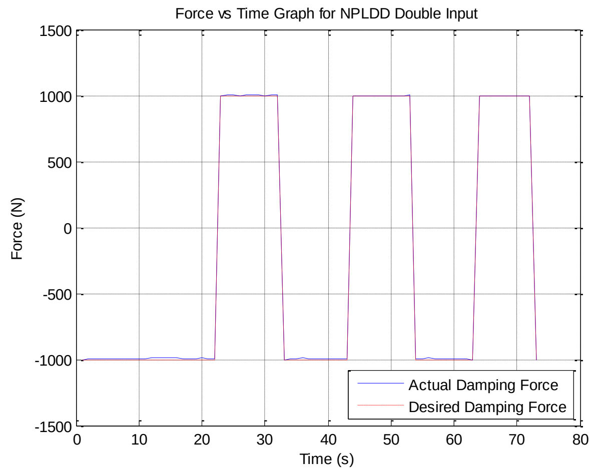

Figure 8(a): Force tracking control of NPLDD double input for square

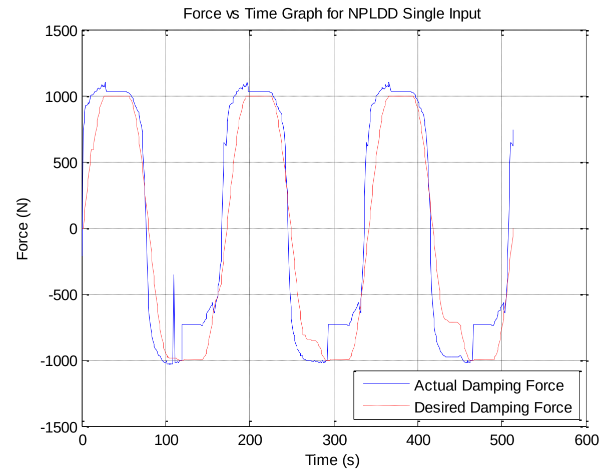

Figure 7(b): Force tracking control of NPLDD single input for sinusoidal

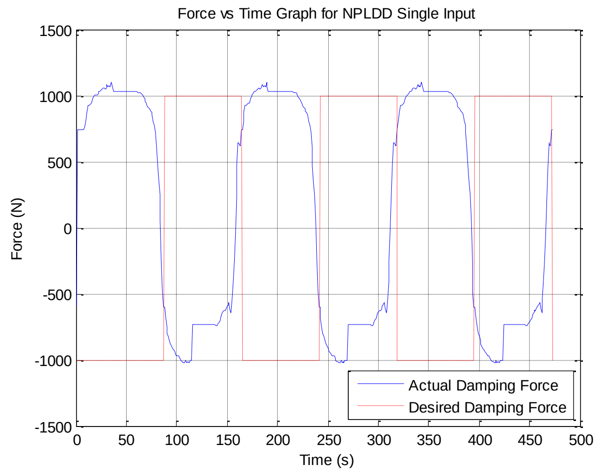

Figure 8(b): Force tracking control of NPLDD single input for square

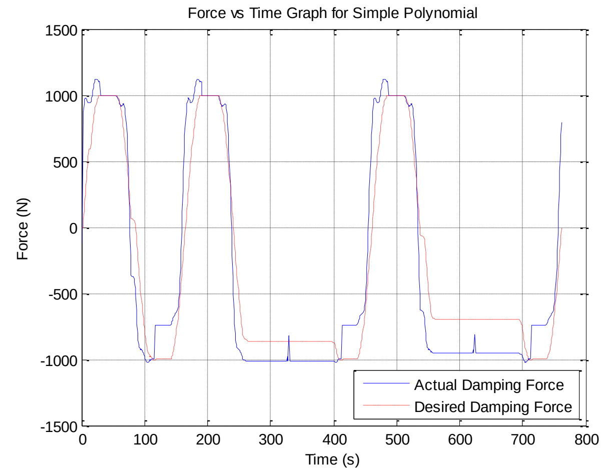

Figure 7(c): Force tracking control of simple polynomial for sinusoidal

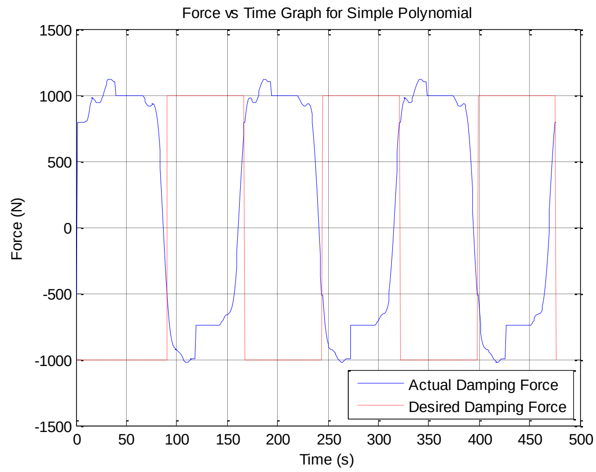

Figure 8(c): Force tracking control of simple polynomial for square

From Figure 7(a) – 7(c), it can be concluded that the NPLDD double input model of MR damper has a good capability in tracking the desired force in the whole range of the piston velocity. The other two models show that the actual damping force is slightly followed the desired force with unexpected noise.

From Figure 8(a) – 8(c), it can be concluded that the NPLDD double input model of MR damper has a good capability in tracking the desired force in the whole range of the piston velocity. Another two methods are not capable to track the desired force at all for both square and the saw-tooth input signal.

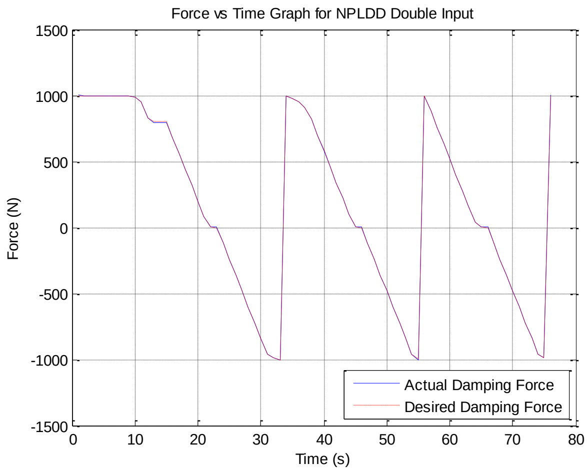

Figure 9(a): Force tracking control of NPLDD double input for saw-tooth

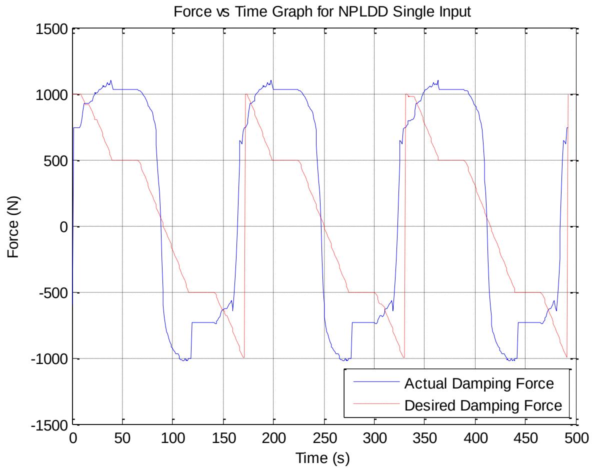

Figure 9(b): Force tracking control of NPLDD single input for saw-tooth

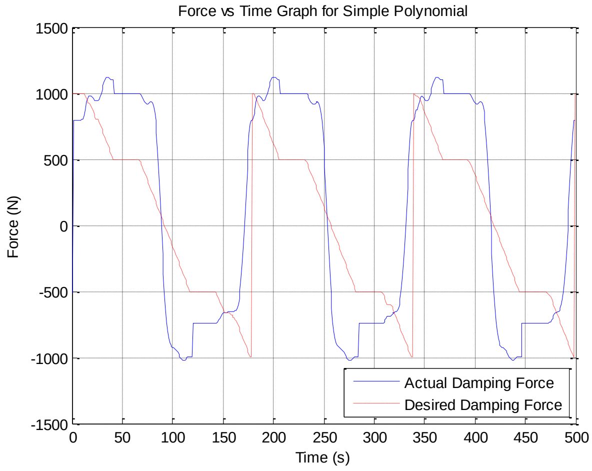

Figure 9(c): Force tracking control of simple polynomial for saw-tooth

From Figure 9(a) – 9(c), it can be concluded that the NPLDD double input model of MR damper has a good capability in tracking the desired force in the whole range of the piston velocity. Another two methods are not capable to track the desired force at all for both square and the saw-tooth input signal.

VI. CONCLUSION

The proposed NPLDD and simple polynomial model for damping force of MR damper have been investigated in this study. The measured experimental damping force was compared with the predicted ones the proposed model. It has been demonstrated that the proposed model agrees well the non-linear behaviour hysteresis behaviour of the MR damper in the form of force-velocity characteristics. The advantages of the proposed model are in the use of a simple algorithm and do not need a length numerical optimisation for parameter estimation. The best method that follows the hysteresis behaviour is NPLDD double input.

In addition, the controllability of the proposed model was investigated in both simulation and experimental works by realising a simple closed-loop control namely PI control. Since K_d is equal to zero, the PID was transformed to PI controller. Thus, the PI controller is sufficient to control the actual output to track to the desired input. From simulation study, it can be seen clearly that under several input functions, the NPLDD double input model tracks the desired damping force well. The others model is not capable to track the desired damping force for all the time.

ACKNOWLEDGEMENT

This research is supported by Perusahaan Otomobil Nasional Sdn. Bhd. (PROTON), Ministry of Higher Education and the Universiti Teknologi Malaysia (UTM) through the internal research grant Vot: 4C099 by Assoc. Prof. Ir. Dr. Saiful Amri Mazlan. The authors are grateful to the PROTON and UTM for supporting the present work.

Also, the authors are appreciative of PROTON Management, Razman Che Rose as Head of Advanced Engineering and Strategy for encouraging all engineers to write and submit a technical paper for knowledge sharing purpose. The author would like to thank Ir. Azmi Osman, Liza @ Sri Redzeki Mohd Anuar, and Dr. Nurulakmar Abu Husain for their effort of reviewing this paper.

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