Simulation and Experimental Studies on the Behavior of a Magnetorheological Damper under Impact Loading

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***Abstract*— This paper is aimed to model behavior of a magnetorheological (MR) damper under impact loading through polynomial approach. The polynomial model is developed based on curve fitting from experimental results and consists of a three regions namely fluid locking, positive and negative acceleration regions. The experimental results which have been performed using impact test apparatus are evaluated in the form of transmitted force in velocity domain. The simulation results of the proposed polynomial model are then compared with the experimental results. Results show that the proposed polynomial model is follow the experimental data in three regions has been study namely fluid locking, positive and negative accelerations.**

Keywords- magnetorheological damper; polynomial model; fluid locking; impact loading

I. INTRODUCTION

Magnetorheological (MR) fluids fall into a class of smart fluids which rheological properties (elasticity, plasticity, or viscosity) change in the presence of a magnetic field. In the presence of a magnetic field, the particles align and form linear chains parallel to the field direction. With a properly designed magnetic circuit, the apparent yield stress of the MR fluid will change within milliseconds [3]. A significant amount of work on developing electromagnetic circuits for damper coil has lead to design an electromagnetic systems that require low voltages and exhibit fast response times [12].

An MR damper is relatively a recent damping device, in which the magnitude of the resisting force acting upon a mechanical structure can be adjusted in real time [11]. Generally, there are two ways in modeling of MR damper namely parametric and non-parametric modeling [8, 13, 14]. In parametric modeling, the behavior of MR damper is represented by a set of mathematical equations that relates the state variables and the resisting force produced by MR damper [5]. On the other hand, non-parametric models of MR damper known as black box model are developed by using approximation functions to estimate the trend of experimental data in the form of force versus velocity or force versus displacement characteristics [2].

Previous studies on shock reduction are actively accomplished using smart fluid which has reversible properties with applied magnetic fields. Lee *et al*. (2002) investigated a magnetorheological (MR) damper to reduce shock transmitted to a helicopter including its dynamics model and controller strategy [9]. MR damper application for shock reduction in weapon mechanism has also studied by Ahmadian *et al*. (2002) [1]. Song *et al*. (2004) proposed the shock damper to reduce impact by means of acceleration decrement of the damper [12]. Other application was the use of MR damper in driver seat for shock attenuation. Investigation on the potential benefits of MR damper in reducing the incidence and severity of end-stop impacts of a low natural frequency was performed by McManus et al. (2001) [10]. However, the previously mentioned studies did not investigate specifically in modeling the MR damper characteristics under impact loading.

The contribution of this work is to study behavior of the MR damper under impact condition and develop its mathematical model which can be integrated with a control system by using non parametric method. In order to achieve the aim, a type of MR damper is tested using impact test apparatus developed in Autotronics Laboratory, UTeM. Thus, its behavior is investigated in both experimental and simulation studies. The experimental results are evaluated in terms of the transmitted force versus damper velocity and the transmitted force versus damper displacement. A polynomial approach is used to model the MR damper behavior under impact loading based on its experimental results and then simulated using well-known mathematics software namely SIMULINK-MATLAB.

This paper is organized as follows: The first section discusses some previous works on the use of the MR damper and some techniques on MR damper modeling; the second

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section describes the experimental works for obtaining the data of MR damper test under impact loads; the third section explains the algorithm of the proposed modeling approach; the fourth section shows the simulation results, validation of the model with experimental data, and the last section consists of some discussion and recommendation for future study.

II. MR DAMPER CONFIGURATION AND EXPERIMENTAL SETUP

The rheological response of MR fluids results dipole alignment of ferrous particles by the application of magnetic field. The interaction between the resulting induced dipoles causes the particles to form columnar structures, parallel to the applied field. These chain-like structures restrict the motion of the fluid, thereby increasing the viscous characteristics of the damper. By adjusting the current within an allowable range, the resisting force to motion of the MR damper increases or decreases in a non-linear fashion. A schematic of a typical MR damper is illustrated in Fig. 1.

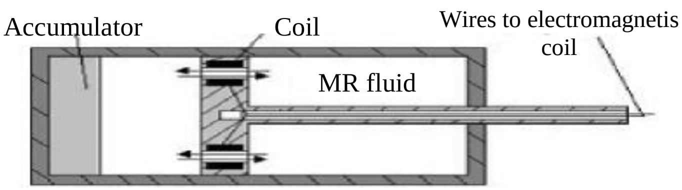


Figure 1. Schematic of MR damper

The MR damper used in this study is RD-8040-1, which was manufactured by Lord Corporation. The damper consists of a piston, magnetic circuit, accumulator, and pressurized gas inside an accumulator and MR fluid. The length of the damper is 21 cm in its extended position and has 5 cm of stroke. The maximum current can be applied to the electromagnet coils in the magnetic choke is 2 Amp and the coil resistance is 2 ohm.

The experimental work was carried out in the Autotronic Laboratory, Department of Automotive, Universiti Teknikal Malaysia Melaka (UTeM) using a impact test rig developed by the Smart Material and Automotive Control Group, UTeM. The impact test rig consists of a wire transducer to measure the relative displacement and relative velocity of the damper and load cell to measure the damper force. The Integrated Measurement and Control (IMC) device provides signal processing of the transducers and excitation signals of the slider crank actuator systemThe setup of the impact test rig is shown in Fig. 2, which is mainly composed of pendulum as the external force, MR damper and vehicle model.

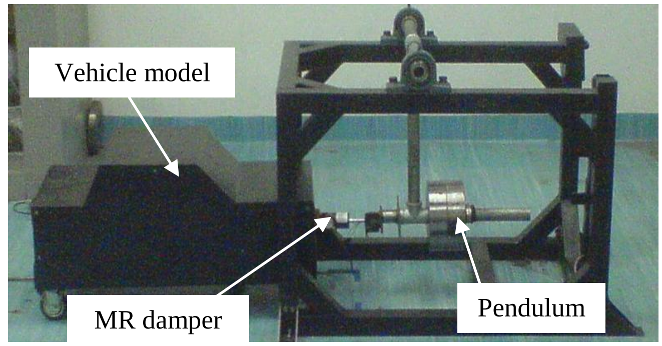


Figure 2. Impact loading test rig

III. MR DAMPER MODELING

In order to build an easy implementation of MR damper model for both simulation and real time control systems, the proposed model should be develop based on the experimental data. Fig. 3 shows a hard point in damper velocity and transmitted force versus time during impact load.

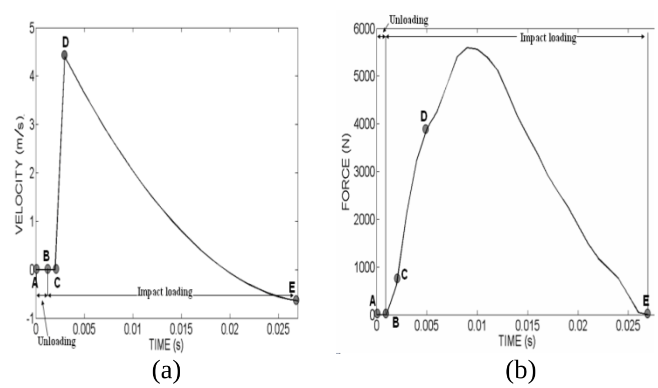


Figure 3: Hard point for: (a) damper velocity versus time (b) force transmitted versus time

Unloading boundary is defined as a term that is used to describe the pendulum in not in collision with the MR damper. The time for the unloading boundary is 0 to 0.001s. After 0.001s, the pendulum starts to collide with the MR damper. The impact loading boundary is defined as the time contact (t_c) between pendulum and MR damper during collision or impact. In this boundary, it is introduced three terms namely a fluid locking region, positive acceleration and negative acceleration region of MR damper during as shown in Table 1.

In order to build an MR damper model for both simulation and real-time control systems, the proposed modeling approach is developed based on the experimental data and consists of four main. In the first step, experimental works on investigating the force versus time and velocity versus time curve of MR damper behavior are performed for a set of constant values of applied current namely 0, 0.5, 1, 1.5, 2 Ampere and the mass of pendulum is set 25 kg as the impact load for MR damper. The second step is obtaining the hard points for fluid locking region of experimental data from step one as illustrated in Fig. 4. In the fluid locking region, the hard point for force and velocity is between times 0.001 to 0.002s. Then the third step is fitting the curve by the polynomial function for the hard points in this region.. But the force that transmitted of MR damper is fitting by a polynomial function with the first order or linearization curve of polynomial that shown in Fig. 4.

Table 1. Impact loading region

	Impact loading region		
	Fluid locking	Positive acceleration	Negative acceleration
Hard point	B to C	C to D	D to E
Time (s)	0.001< t < 0.002	0.002< t < 0.005	0.005< t < t_c

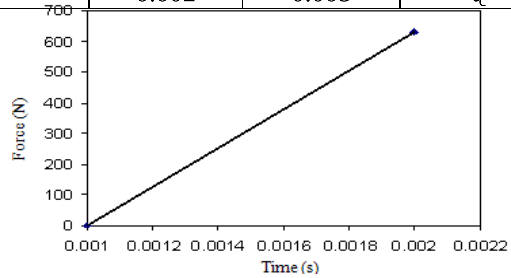


Figure 4: Linearization curve that obtain the hard point in force versus time for fluid locking region.

The function of the polynomial for the transmitted force and velocity of the damper in the fluid locking region expressed as follow;

$$f_d = \sum_{i=0}^{n} a_i\, t^i\,, n = 1 \qquad \text{if } 0.001 \le t \le 0.002 \qquad (1)$$

$$v_d = 0 \qquad \text{if } 0.001 \le t \le 0.002 \qquad (2)$$

where f_d is the transmitted force, a_i is the experimental coefficient to be determined from the curve fitting and t is the time during the impact.

The fourth step is linearization of the coefficient a_i for each curve. In this step, the coefficient of a_i is linearly approximated with respect to the input current [7]. The linearization of the coefficient a_i is governed as follows:

$$a_i = b_i + c_i I \qquad (3)$$

After substituting Eq.(1) into Eq.(3), the damping force can be expressed as follows,

$$f_d = \sum_{i}^{n} (b_i + c_i I) t^i\,,\ n = 1 \text{ where } 0.001 \le t \le 0.002 \qquad (4)$$

The coefficients of b_i and c_i are obtained from the slope and the intercept of the plots as shown in Fig. 5. From the investigation, the coefficients of a_i, b_i and c_i are not responsive to the magnitude of the applied current. The values of b_i and c_i used in this study are listed in Table 2.

In the positive acceleration region, the proposed modeling approach is developed based on the experimental data and has similar step of modeling with fluid locking region that has been described before.

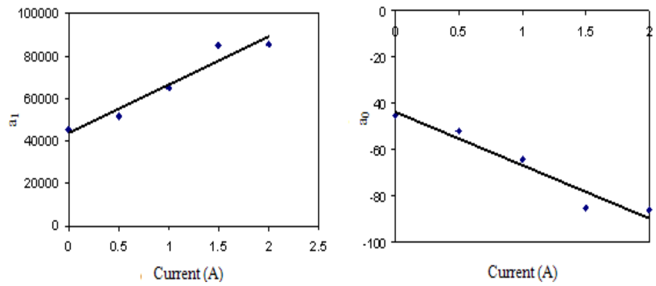


Figure 5: The linear regression of the coefficients a_i correspond to the input current for fluid locking region

Table 2: Coefficients of polynomial model for transmitted force in fluid locking region

Fluid Locking			
Parameter	**Value**	**Parameter**	**Value**
b_0	-43.654	c_0	-22.668
b_1	43564	c_1	22668

The hard points force versus time and velocity versus time in this region for experimental data is illustrated in Fig. 6. It can be clearly stated the hard point in positive acceleration region for force and velocity is between times 0.002 to 0.005s. This is because from this range of times the velocity of the damper starts to increase and goes to the maximum velocity at time 0.005 s. When the velocity increases, the acceleration of the damper will be positive value and this region is label as positive acceleration region. At this region the force that transmitted of MR damper is fitting by a polynomial function with the second order curve of polynomial that shown in Fig. 6. The function of transmitted force is expressed as follow;

$$f_d = \sum_{i}^{n} d_i t^i\,,\ n = 2 \text{ if } 0.002 < t \le 0.005 \qquad (5)$$

By fitting the hard points in the velocity versus time with polynomial function that shown in Fig. 6, the third order of polynomial is chosen to fit it. The function of velocity of the damper is expressed as follow;

$$v_d = \sum_{i}^{n} g_i t^i\,,\ n = 3 \text{ if } 0.002 < t \le 0.005 \qquad (6)$$

Where v_d is velocity of the damper, d_i and g_i are the experimental coefficient to be determined from the curve fitting.

Then the linearization of the coefficients d_i for the transmitted force and g_i for velocity of the damper will be done for each curve. In this step, the both coefficients are linearly approximated with respect to the input current as shown in Fig. 7 and 8.

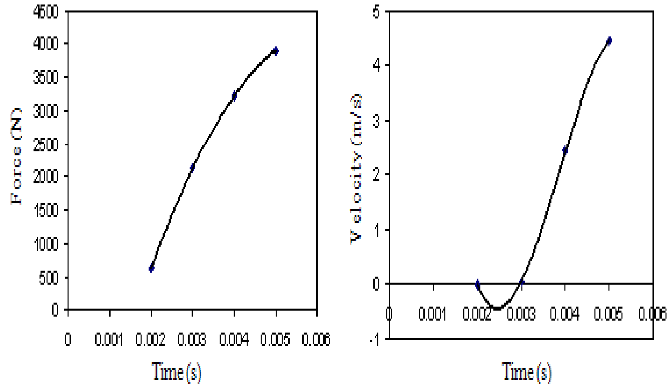


Figure 6: 2nd order and 3rd order polynomial curve that obtain the hard point in force and damper velocity versus time for positive acceleration region.

The linearization of the coefficient for the transmitted force, d_i and velocity of the damper, g_i are governed as follows:

$$d_i = e_i + f_i I \,, \quad i = 0, 1, 2 \qquad (7)$$

$$g_i = h_i + p_i I \,, \quad i = 0, 1, 2, 3 \qquad (8)$$

After substituting Eq.(7) into Eq.(5), the damping force can be expressed as follows,

$$f_d = \sum_i^n (e_i + f_i I) t^i \,, \; n = 2 \quad \text{if} \quad 0.002 < t \leq 0.005 \qquad (9)$$

Then substituting Eq.(8) into Eq.(6), the velocity of the damper is shown below,

$$v_d = \sum_i^n (h_i + p_i I) t^i \,, \; n = 3 \;\; \text{if} \;\; 0.002 < t \leq 0.005 \qquad (10)$$

The coefficients of e_i and f_i are also obtained from the slope and the intercept of the plots as shown in Fig. 7 and the coefficients of h_i and p_i also obtained from the slope and the intercept of the plots that described in Fig. 8. The values of e_i and f_i used in this study are listed in Table 3 and the values of h_i and p_i are shown in Table 4.

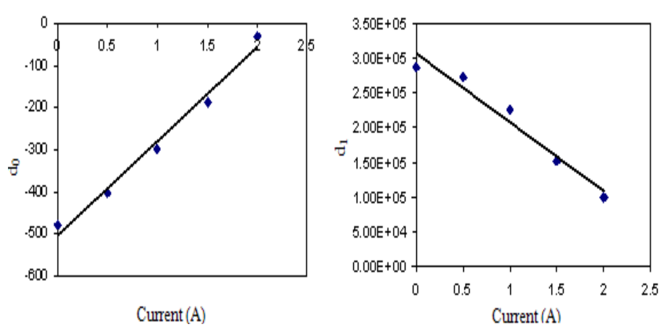


Figure 7: The linear regression of the coefficients d_i in force versus time polynomial curve correspond to the input current for positive acceleration region

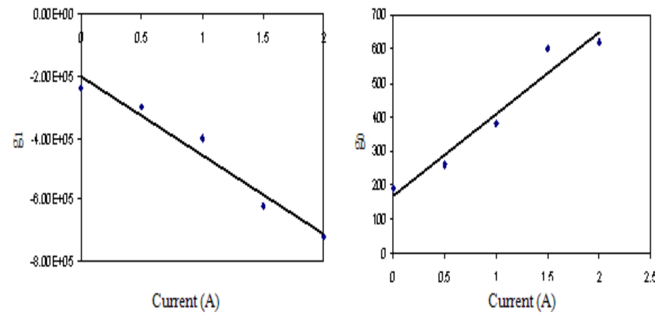


Figure 8: The linear regression of the coefficients g_i in velocity versus time polynomial curve correspond to the input current for positive acceleration region

In the negative acceleration region, the proposed modeling approach is developed based on the experimental data. The hard points force versus time and velocity versus time in this region for experimental data is illustrated in Fig. 9.

Table 3: Coefficients of the polynomial model for transmitted force in positive acceleration region

Positive Acceleration			
Parameter	**Value**	**Parameter**	**Value**
e_0	-499.6864	f_0	146.729
e_1	3.005×10^5	f_1	-9.67×10^4
e_2	-2.749×10^7	f_2	1.359×10^7

Table 4: Coefficients of the polynomial model for velocity damper in positive acceleration region

Positive Acceleration			
Parameter	**Value**	**Parameter**	**Value**
h_0	181.776	p_0	243.096
h_1	-2.066×10^5	p_1	-2.342×10^5
h_2	8.464×10^7	p_2	8.874×10^7
h_3	6.182×10^9	p_3	-6.288×10^9

Based on the Fig. 9, the hard point in negative acceleration region for force and velocity is between times 0.005 to time contact, t_c. In this range of times the velocity of the damper starts to decrease from the maximum velocity at time 0.005s to zero velocity. At this region the force that transmitted by the MR damper is fitting with the fourth order polynomial curve that shown in Fig. 9. The function of the transmitted force is expressed as follow;

$$f_d = \sum_i^n j_i t^i \,, \; n = 4 \quad \text{if} \quad 0.005 < t \leq t_c \qquad (11)$$

By fitting the hard points in the velocity versus time with polynomial function, the third order of polynomial is chosen to fit it. The function of velocity of the damper is expressed as follow;

$$v_d = \sum_i^n m_i t^i \,, \; n = 3 \;\; \text{if} \;\; 0.005 < t \leq t_c \qquad (12)$$

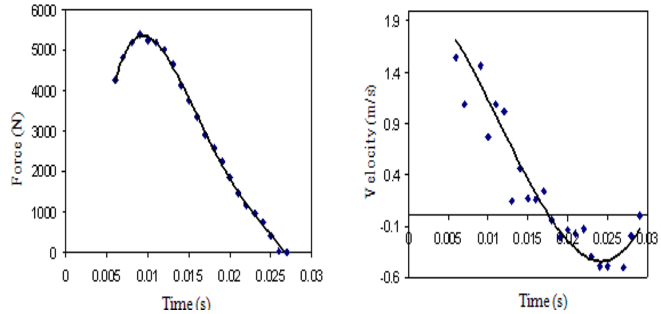


Figure 9: 4th order and 3rd order polynomial curve that obtain the hard point in force and velocity damper versus time for negative acceleration region.

Then the linearization of the coefficients j_i for the transmitted force and m_i for velocity of the damper will be done for each curve as shown in Fig. 10 and 11. The linearization of coefficients is governed as follows:

$$j_i = k_i + q_i I \;, \quad i = 0, 1, 2, 3, 4 \qquad (13)$$

$$m_i = n_i + r_i I \;, \quad i = 0, 1, 2, 3 \qquad (14)$$

After substituting Eq.(13) into Eq.(11), the damping force can be expressed as follows,

$$f_d = \sum_i^n (k_i + q_i I) t^i \;, \; n = 4 \;\; \text{if} \;\; 0.005 < t \leq t_c \qquad (15)$$

Then substituting Eq.(14) into Eq.(12), the velocity of the damper is shown below,

$$v_d = \sum_i^n (n_i + r_i I) t^i \;, \; n = 3 \;\; \text{if} \;\; 0.005 < t \leq t_c \qquad (16)$$

The coefficients of k_i and q_i are obtained from the slope and the intercept of the plots as shown in Fig. 10 and the coefficients of n_i and r_i also obtained from the slope and the intercept of the plots that described in Fig. 11. The values of k_i and q_i used in this study are listed in Table 5 and the values of n_i and r_i are shown in Table 6.

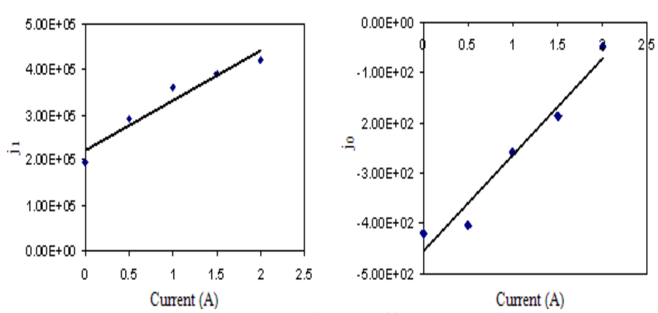


Figure 10: The linear regression of the coefficients j_i in force versus time polynomial curve correspond to the input current for negative acceleration region

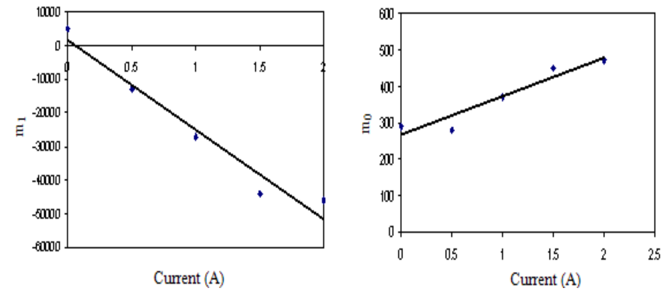


Figure 11: The linear regression of the coefficients m_i in velocity versus time polynomial curve correspond to the input current for negative acceleration region

Table 5: Coefficients of the polynomial model for transmitted force in negative acceleration region

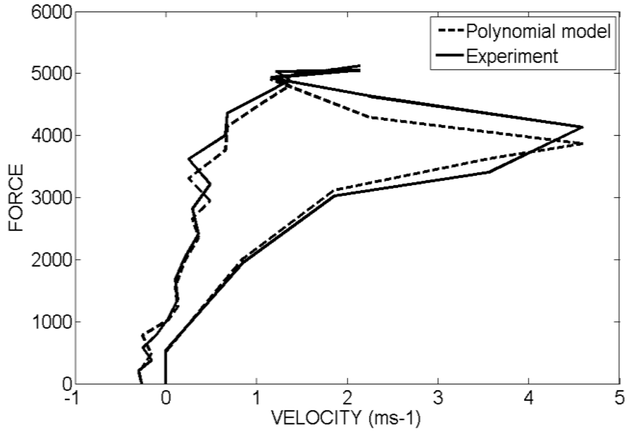
Negative Acceleration			
Parameter	**Value**	**Parameter**	**Value**
k_0	-453.9306	q_0	-302.6362
k_1	2.291×10^5	q_1	1.113×10^5
k_2	-1.838×10^7	q_2	-1.152×10^7
k_3	5.446×10^8	q_3	4.786×10^8
k_4	-5.375×10^9	q_4	-7.044×10^9

Table 6: Coefficients of the polynomial model for velocity damper in negative acceleration region

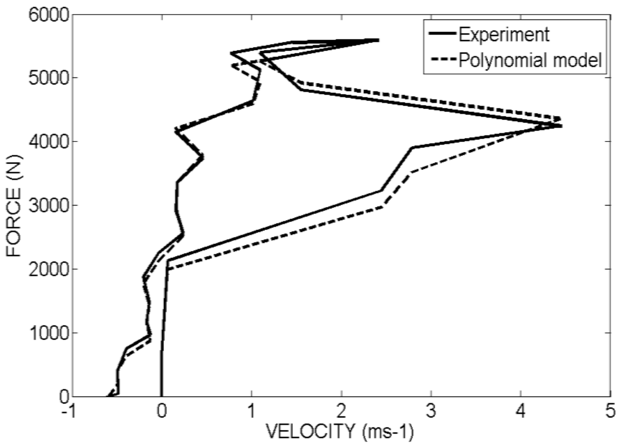
Negative Acceleration			
Parameter	**Value**	**Parameter**	**Value**
n_0	293.7498	r_0	69.44732
n_1	50.3556	r_1	-1.405×10^4
n_2	-2.877×10^5	r_2	7.564×10^5
n_3	1.41×10^7	r_3	-1.38×10^7

IV. EXPERIMENTAL RESULT AND MODEL VALIDATION

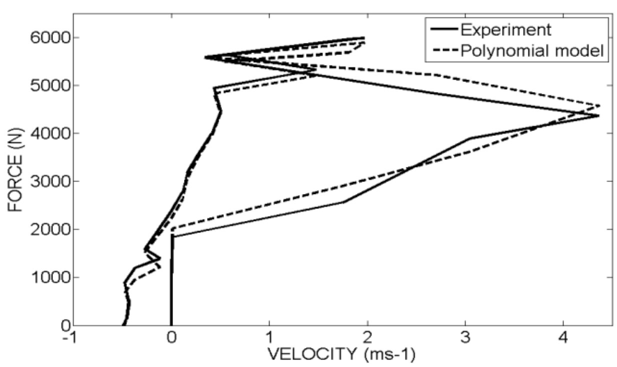
Simulation was performed to explore validity and accuracy of the proposed model in Matlab-Simulink environment. During simulation study, the mass of pendulum are chosen as 25 kg. The overall comparison of force versus velocity characteristics under various input currents between experimental data and polynomial model responses are shown in Fig. 12. On the other hands, it can be seen that the proposed polynomial model is able to follow the experimental data in fluid locking, positive acceleration and negative acceleration regions.



(a) 0.5 Ampere



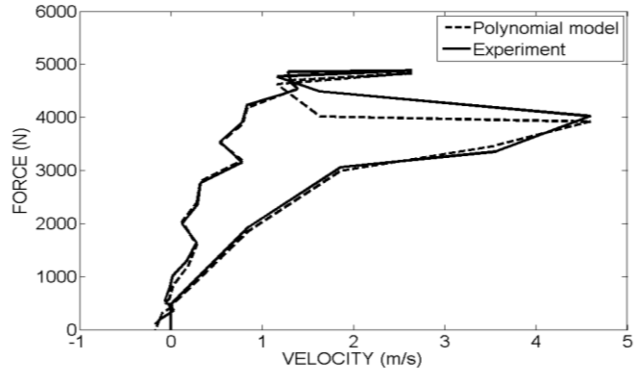
(b) 1.0 Ampere



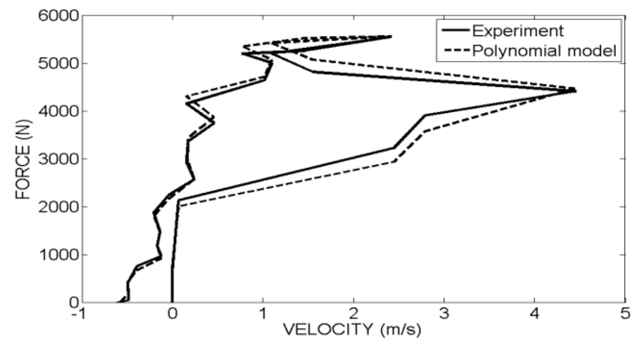
(c) 1.5 Ampere

Figure 12: Comparison of the measured and predicted forces versus velocity for several applied currents: (a) 0.5Amp. (b) 1Amp. and (c)1.5Amp

In order to validate the effectiveness of the proposed polynomial model, the input current will be changed. The measured damping force obtained from experimental work and the predicted force versus velocity from the proposed model are compared as shown in Fig. 13(a) and (b), where the pendulum mass and applied current are selected as 25 kg, 0.25 Amp and 1.25 Amp respectively. It is clearly observed that the polynomial model predicts well the force versus velocity behavior of MR damper at various input currents.



(a) 0.25 Ampere



(b) 1.25 Ampere

Figure 13: Damping force characteristics under various input currents: (a) 0.25Amp., (b) 1.25Amp.

V. CONCLUSION

The proposed polynomial model for field-dependent transmitted force of MR damper under impact loading has been investigated in this study. The measured experimental transmitted force was compared with the proposed model. It has been demonstrated that the proposed model has the ability to follow the curve in fluid locking, positive and negative acceleration regions of the MR damper in the form of force versus velocity characteristics. The advantages of the proposed model are in the use of a simple algorithm and do not need a length numerical optimization for parameter estimation. In future, the proposed model will be connected with the controller system such as inner loop and outer loop controller for semi active system.

REFERENCES

[1] Ahmadian, M., Appleton, R. and Norris, J.A. (2002) 'An analytical study of fire out of battery using magnetorheological'. *Journal of Shock and Vibration*, 9(3):pp.29–42.

[2] Ahmadian, M. and Song, X. (1999) 'A non-parametric model for magnetorheological dampers', *Proceedings of the 1999 ASME Design Engineering Technical Conference*, September 12-15. Las Vegas, Nevada.

[3] Ahmadian, M. and Norris, J.A. (2007) 'Experimental analysis of magnetorheological dampers when subjected to impact and shock loading' *Center for Vehicle Systems and Safety (CVeSS)*, Virginia Tech (MC-0901), Blacksburg, VA 24061, United States.

[4] Ang, W.L., Li, W.H. and Du, H. (2004) 'Experimental and modeling approach of a MR damper performance under harmonic loading', *Journal of The Institution of Engineers*, Singapore, 44(4): pp.1–14.

[5] Butz, T. and Stryk, O. (1999) 'Modelling and simulation of rheological devices', *Tehnische Universitat Munchen, Universitat Augsburg, Preprint,* SFB-438-9911.

[6] Chang, C. C. and Roschke, P. (1999) 'Neural network modeling of a magnetorheological damper', *Journal of Intelligent Material Systems and Structures*, 9(9): pp.755-764.

[7] Choi, S.B., Lee, S.K. and Park, Y.P. (2001) 'A hysteresis model for the field-dependent damping force of a magneto-rheological damper', *Journal of Sound and Vibration*, 245(2): pp.375–383.

[8] Giuclea, M., Sireteanu, T., Stancioiu, D. and Stammers, C.W. (2004) 'Modeling of magnetorheological damper dynamic behavior by genetic algorithms based inverse method', *Proc. Romanian Academy*, 5(1): pp.1–10.

[9] Lee, D.Y., Choi, Y.T. and Wereley, N.M. (2002)'Performance analysis of ER/MR impact damper systems using Herschel-Bulkley model', *Journal of Intelligent Material Systems and Structures*, 13(7–8):pp. 525–531.

[10] McManus, S.J., ST. Clair, K.A., Boileau, P.E., and Boutin, J. (2002) 'Evaluation of vibration and shock attenuation performance of a suspension seat with a semi-active magnetorheological fluid damper', *Journal of Sound and* V*ibration,* 253(1);pp. 313-327.

[11] Roschke, P.N. and Atray, V. (2002) *Neuro-Fuzzy Control of Vertical Vibrations in Railcar Using Magnetorheological Dampers*, Report No. 405450-00112, Association of American Railroads, Pueblo, CO.

[12] Song, H.J., Choi, S.B., Kim, J.H. and Kim, K.S. (2004) 'Performance evaluation of ER shock damper subjected to impulse excitation', *Journal of Intelligent Material Systems and Structures,* 13(10):pp. 625–628.

[13] Song, X. (1999) 'Design of adaptive vibration control systems with application of magnetorheological dampers', *PhD Dissertation,* Virginia Polytechnic Institute and State University.

[14] Wang, E. R., Ma, X. Q., Rakheja, S. and Su, C. Y. (2005) 'Force tracking control of vehicle vibration with MR-damper', *Symposium on Intelligent Control*, Limassol, Cyprus, June 27-29.