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Effect of modified bouc-wen model parameters on the dynamic hysteresis of magnetorheological dampers

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Effect of modified bouc-wen model parameters on the dynamic hysteresis of magnetorheological dampers

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Abstract. Magnetorheological (MR) dampers are a semi active control device that becoming a promising actuators in vibration mitigation. The unique properties of MR fluids are used to control the damping force without consuming large power source. Despite MR dampers are fail-safe, efficient, and robustness devices, they poses significant nonlinear characteristics. A well-known Bouc-Wen models and their extension modified Bouc-Wen are the most accurate models that predict the hysteresis of the MR dampers. However, these models suffer from some complexity and limitations and they miss a good fitting to the measured data. In this paper, the existing modified Bouc-Wen (MBW) models are introduced and their dynamic characteristics are simulated using MATLAB Simulink environment. The robustness of the model is judged by a comparison between the experimental tests of the MR damper (on and off state) on the MTS damper test machine in MTC and the simulated characteristics. To better understand the damper nonlinearity, an investigation into the effect of the model parameters on the dynamic characteristics of the damper is studied. A parametric study is proposed to identify the optimal model parameters that best fits the experimental data. The response of the model with the obtained parameters is validated across the measured MR damper characteristics under different sinusoidal excitations and command current. The results show a good agreement between the simulated and measured responses of the MR damper.

1. Introduction
Recently, the magnetorheological (MR) damper has regarded as the most promising actuators in vibration control and structure isolations. Suspension system differs according to their construction to passive, active and semi active suspension. Passive suspension has linear and constant characteristics that limit the suspension performance. However, in the active suspension the system generates damping force based on the terrain excitations. This ability to change the damping force provides the opportunity to increase the rid comfort and vehicle handling at the expense of high power demand and cost [1] On the other hand, semi-active suspension overcomes the drawbacks of passive and active suspension systems.MR fluid consists of polarized particles affected by magnetic field in micron size suspended in a carrying medium like water or mineral oil. This type of fluid is not sensitive for impurities. Moreover, the yield strength of this fluid could be altered by changing the magnetic flux intensity in millisecond[2]. The magnitude of damping force changed with respect to electric power applied on damper terminals. When damper is not energized it acts as passive dampers (a fail-safe) actuators[3].

MR dampers possess high nonlinear characteristics which make the dynamic modelling of such dampers a challenge issue [4]. Despite the nonlinearity, MR fluid dampers have a lot of advantage as a mechanical simplicity, high dynamic range, low power requirement, large force capacity and robustness. Moreover, MR fluid could be changed from Newtonian fluid to semi solid(non-Newtonian) in millisecond[5].Several models such as Bingham, Bouc-wen and modified Bouc-Wen models have been developed to characterize the intrinsic dynamic of the MR damper[6]. These models classified as parametric models that have many parameters. These parameters are identified by comparing the simulated data with the experimental responses[7]. The difference between the parametric models and nonparametric models also introduced. The parametric models employ analytical expression based on testing data result and device principle for working[8].The nonparametric models can predict damper behaviour with no need to system physical characteristics[9]

In this article, a comparison between the experimental results obtained from testing of MR damper (RD-8040-1)of Lord Corporation and simulated results obtained from modified Bouc-Wen models. A parametric study held also to the modified Bouc-Wen model with 14 parameters to recognize the effect of each parameter on the damper hysteresis. A Simulink model constructed in Matlab/Simulink for the governing equations of the modified Bouc-Wen model. The model parameters varied to study their influence on the hysteresis performance. Finally, a parametric study proposed to identify the optimal parameters values that best fit the simulated data with the experimental responses.

2. Magnetorheological damper model

The MR damper is a smart device that has intrinsically nonlinear characteristics. These nonlinear dynamics make the modelling and design of control techniques of such device a challenging issue. To obtain the full advantages of the MR damper nonlinearity, an accurate and precise model has tobe identified. The ModifiedBouc-Wen model shown in Figure 1 is an extension of the Bouc-Wen model proposed by Spencer[8, 10]and it is considered as an accurate model that best tracks the MR damper dynamics. The damping force of the model expressed as follows:

$$F = c_1(\dot{y}) + k_1(x - x_0) \tag{1}$$

where the evolutionary variables given by:

$$\dot{z} = A(\dot{x} - \dot{y}) - \beta(\dot{x} - \dot{y})|z|^n - \gamma z|\dot{x} - \dot{y}||z|^{n-1} \tag{2}$$

$$\dot{y} = (c_0 - c_1)^{-1}(c_0\dot{x} + k_0(x - y) + \alpha z) \tag{3}$$

The following equations introduced for the model tobe taken into account for the applied voltage and/ or current dependent parameters.

$$\alpha = \alpha(u) = \alpha_a + \alpha_b u \tag{4}$$

$$c_1 = c_1(u) = c_{1a} + c_{1b}u \tag{5}$$

$$c_0 = c_0(u) = c_{oa} + c_{ob}u \tag{6}$$

$$\dot{u} = -\eta(u - v) \tag{7}$$

In the proposed model the gas stiffness is represented by a spring with constant, k1, the damping at high velocities is denoted by, co. A dashpot of damping c1, is presented in the model to be taken into account for the hysteresis characteristics at low frequencies. However, a spring, with constant, ko is introduced into the model for controlling stiffness at large velocities. It is supposed that the initial displacement due to the accumulator stiffness is, xo. A Simulink model that represents the modified Bouc-Wen model equation developed in Matlab environment as illustrated in Figure 2.

In the simulation, the damping force of the MR damper considered as the output of the model while the displacement, velocity and command voltage are the excitation inputs.

In modified Bouc-Wen model, there are 14 parameters describing the MR damper hysteresis these parameters have been determined in [10, 12] and are shown in Table 1. These two references denoted as MBW1 and MBW2 respectively. In order to judge these published parameters and their degree of fit to the experimental data, various experiments have been conducted on the pre-denoted short stroke MR damper.
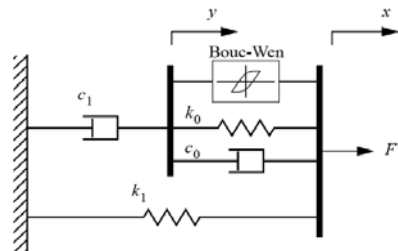
Figure 1. Modified Bouc-wen model [11].
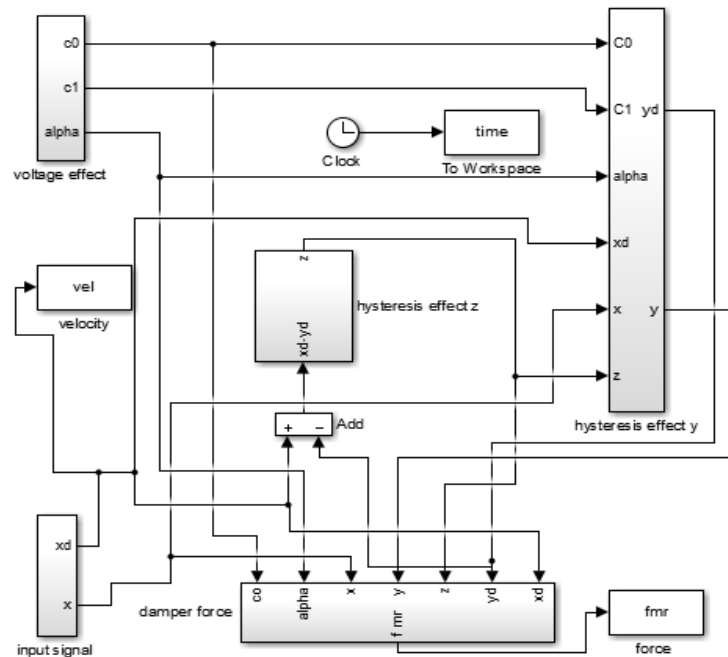
Figure 2. Simulink block diagram for modified Bouc-Wen model.

Determining the values of system parameter is necessary to minimize the deviation of the data obtained from the parametric model from the experimental results. A number of optimization methods used to select the 14- parameter values of modified Bouc-Wen model. [10, 12] have used two sets of parameter values that are supposed to represent the damper hysteresis accurately.

Table 1. Modified Bouc-Wen parameters

| Parameters	MBW1, Ref [10]	MBW2,Ref [12]	Unit
A	301	58	-
β	3630000	2059020	m^{-2}
n	2	2	m^{-2}
η	190	196	-
γ	3630000	136320	s^{-1}
c_{oa}	2100	784	N.s/m
c_{ob}	350	1803	N.s/m.V
c_{1a}	28300	14649	N.s/m
c_{1b}	295	34622	N.s/m.V
α_a	14000	12441	N/m
α_b	69500	38430	N/m.V
k_0	4690	3610	N/m
k_1	500	840	N/m
x_0	0.134	0.0245	m

3. Experimental testing of MR damper

The magneto-rheological damper used for obtaining the experimental result is a fixed orifice damper filled with MR fluid developed by Lord Corporation. The damper installed on the MTS Damper Test Machine as shown in Figure 3. The MTS machine consists of an upper crosshead frame with (5)KN force transducer and the actuator with linear variable differential transducer (LVDT) for measuring displacement. A 12V DC power supply used to provide the necessary command voltage and current for MR damper. The MR damper is excited with frequencies from 1 to 2.5 Hz with increment of 0.5 Hz and a dynamic amplitude of 5 mm at 0 and 0.5 A. The measured force and velocity filtered and smoothed in Matlab environment to avoid unwanted frequencies. The force-displacement and force-velocity histories presented for the measured and simulated data for comparison.

Figure 4 and Figure 5 show a comparison between the data obtained from two models denoted as MBW1, MBW2 and experimental results obtained at different frequencies with amplitude of 5 mm and an input current of zero and 0.5 A, respectively.

Finally, the comparison carried out between the model results and experimental results prove that modified Bouc-Wen parameter not valid for all MR dampers. Consequently, a parametric study has to be done in order to investigate the effect of each parameter on the dynamic hysteresis of the damper.

4. Influence of model parameters on MR hysteresis

A comprehensive analysis of the effect of modified Bouc-Wen [10] parameters on the dynamic behavior of the damper is addressed. To better understand the influence of variation of the model parameters on the damper output and identification of the optimal parameters, the parametric study is introduced. The method based on changing one parameter out of 14 parameters in a certain range and keeping the other parameters unchanged. The parameters are changed from the reference value (MBW1[10]) to ± 50% with interval 10%. Then, the simulation of the MBW1 model executed in Matlab for all values of the first parameter and keeping the rest of parameters unchanged. After that the simulations is repeated for all values of the second one parameter and further till the last parameter. The root mean square (rms) of the output damping force calculated each time for each run as shown in Table 2. For the sake of brevity, the force-velocity and force-displacement graphs from simulations are presented for only the reference and extreme values (-50% and +50%).
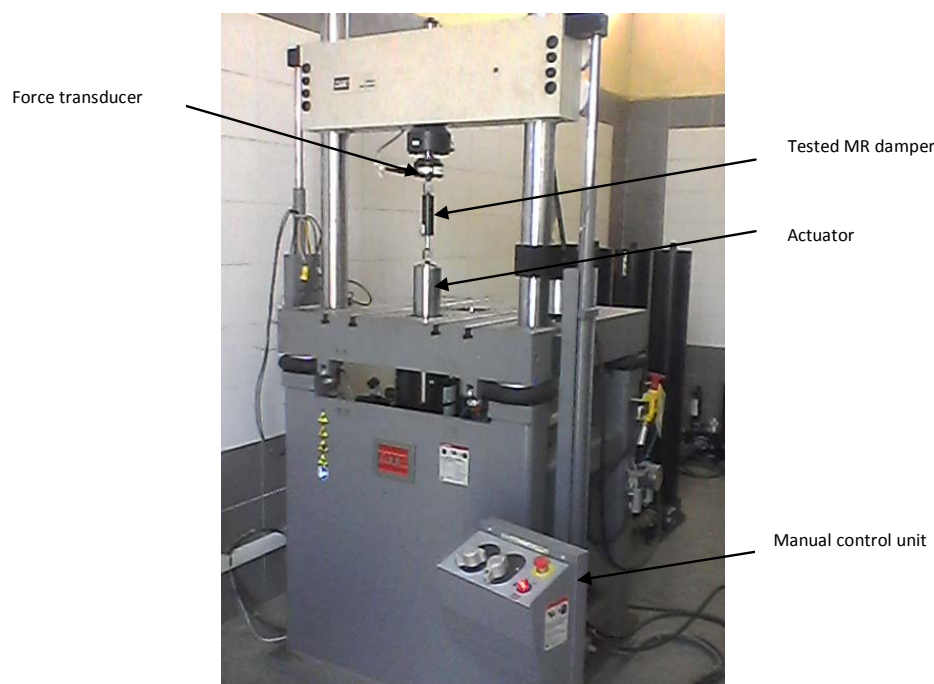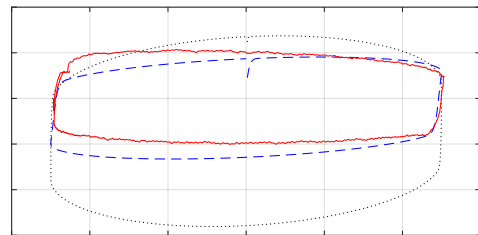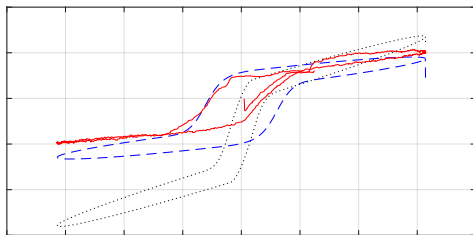

Figure 3. Damper test system used to identify MR damper characteristics.
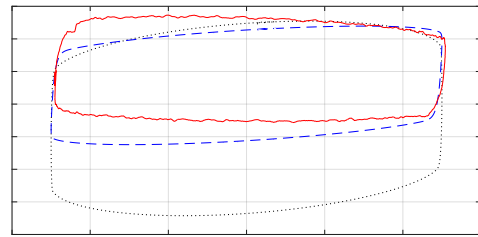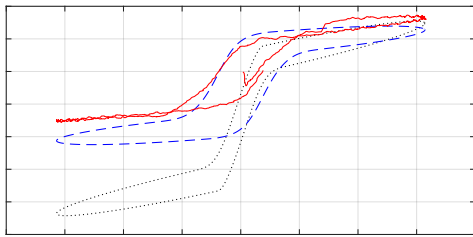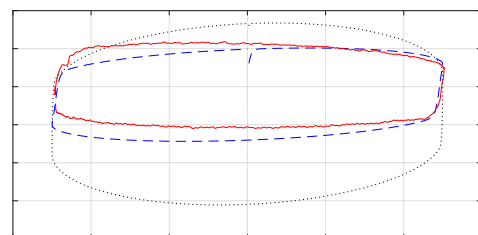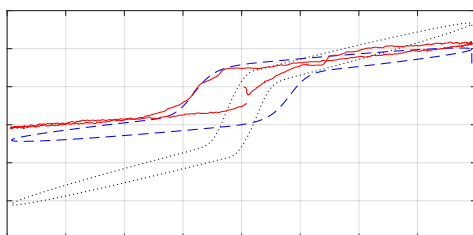
(a) At 1 Hz
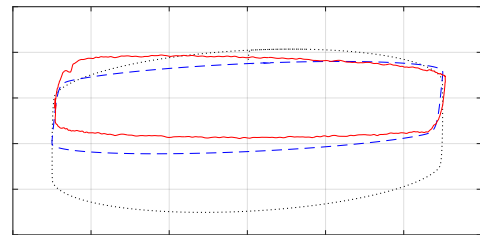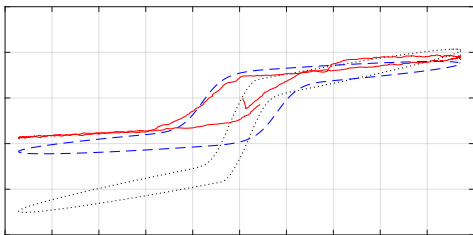
(b) At 1.5 Hz

(c)At 2 Hz

(d) At 2.5 Hz

Figure 4. Comparison between simulated and experimental data at zero current, amplitude of 5 mm and different frequencies; (solid, experimental; dot, MBW1; dash, MBW2)
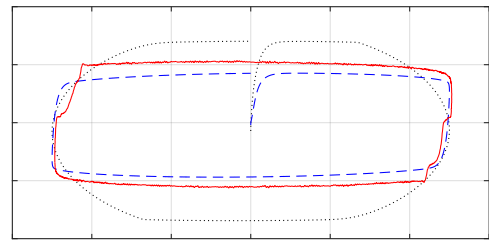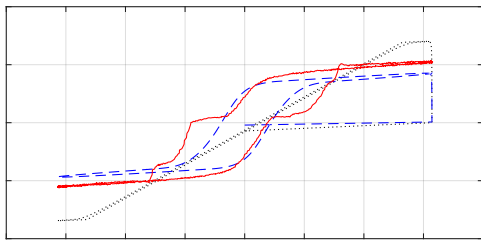
(a)At 1 Hz

(b) At 1.5 Hz

(c)At 2 Hz
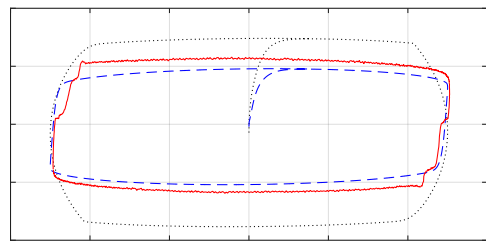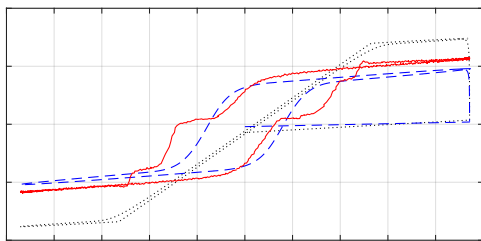

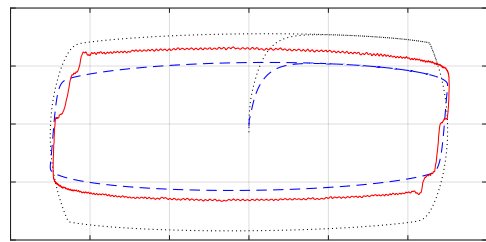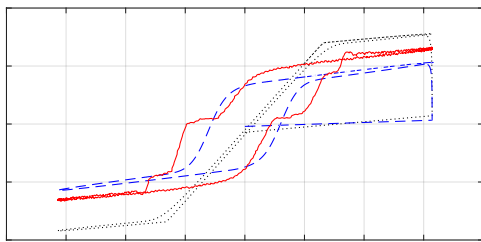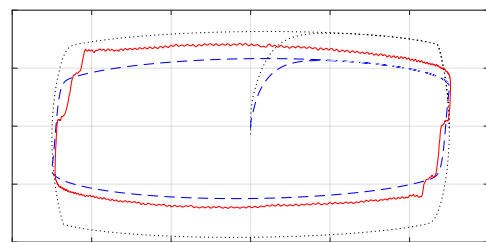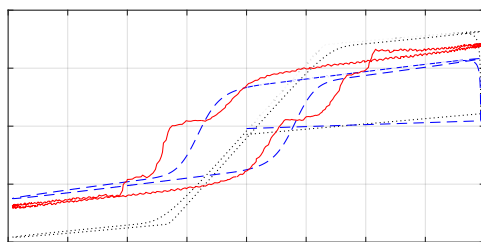(d) At 2.5 Hz

Figure 5. Comparison between simulated and experimental data at current of 0.5 A, amplitude of 5 mm and different frequencies; (solid, experimental; dot, MBW1; dash, MBW2)

Table 2. Rms values of damping force for MBW1 parameters (15 mm, 2.5Hz,1.5 volt)

Parameters	-50%	-40%	-30%	-20%	-10%	Ref	10%	20%	30%	40%	50%
A	870	914	955	993	1029	1063	1095	1125	1155	1183	1210
α_a	1024	1032	1093	1047	1055	1063	1071	1078	1086	1094	1102
α_b	772	830	888	947	1005	1063	1121	1178	1236	1293	1350
β	1164	1140	1118	1098	1080	1063	1047	1032	1018	1006	993
c_{1a}	972	1000	1022	1039	1052	1063	1072	1080	1086	1092	1097
c_{1b}	1062	1062	1062	1062	1062	1062	1062	1063	1063	1063	1063
c_{oa}	940	965	990	1015	1939	1063	1087	1110	1133	1156	1179
c_{ob}	1033	1039	1045	1051	1057	1063	1069	1075	1081	1086	1092
γ	1164	1140	1118	1998	1080	1063	1047	1032	1018	1005	993
k_1	1061	1061	1061	1062	1062	1063	1063	1063	1064	1064	1064
k_o	1062	1062	1062	1063	1063	1063	1063	1063	1063	1064	1064
n	439	666	972	1332	1696	1063	1915	1915	1916	1916	1917
η	1062	1062	1063	1063	1064	1063	1064	1064	1064	1064	1064
x_o	1061	1061	1061	1062	1062	1063	1063	1063	1064	1065	1066

Figure 6 depicts the force-displacement and force-velocity responses with respect to three values; a maximum level (+50%), a minimum level (-50%) and a reference value for the parametersβ, A, αa and αb. It is clearly seen that the force range decreases by increasing the value of β. But when increasing the parameters A, αa andαb, the force is increased. In addition, the ascending of parameter,a contributes to the narrowing of the enclosed area of the force-velocity loop.
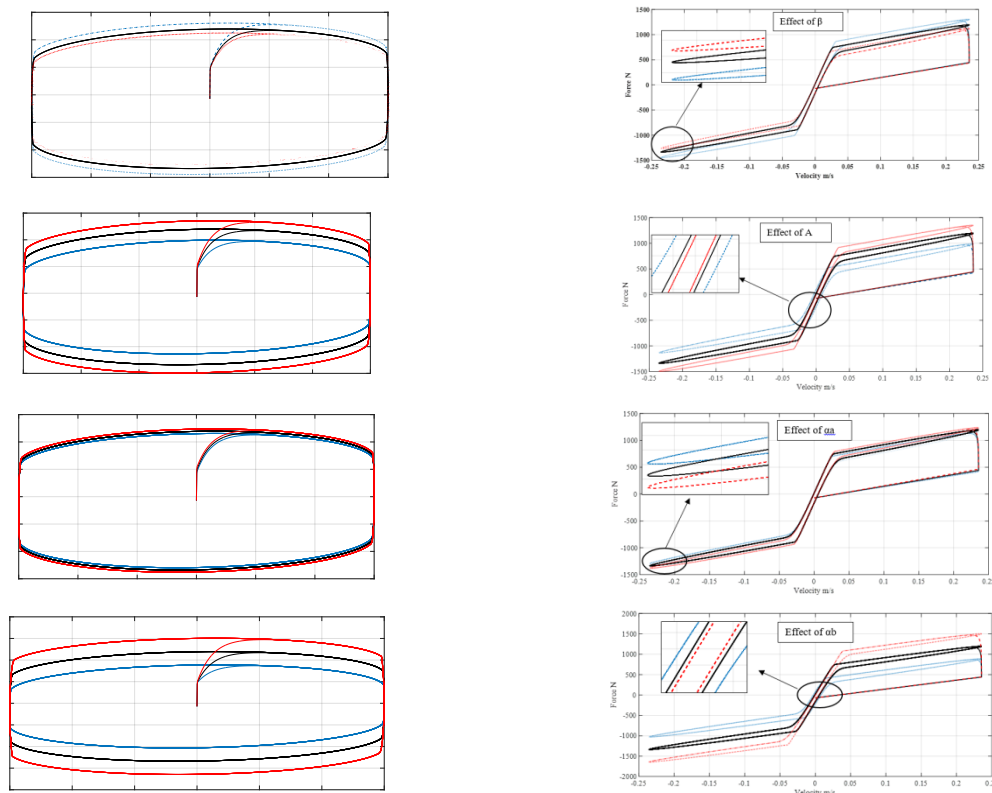
Figure 6. Force-displacement and force-velocity simulated responses with different values of parameters β, A, αa and αb

Figure 7 shows the consequent hysteretic responses of the model by varying parameters; C1a, C1b, Coa, Cob, andγ. It is obvious that parameter C1b, has very little influence on the slop of the loop (effective stiffness). However, the increase of the parameters C1a, Coa and Cob result in the increase of the dynamic force of the model. Moreover, the ascending of parameter, γ, results in descending of the effective stiffness.
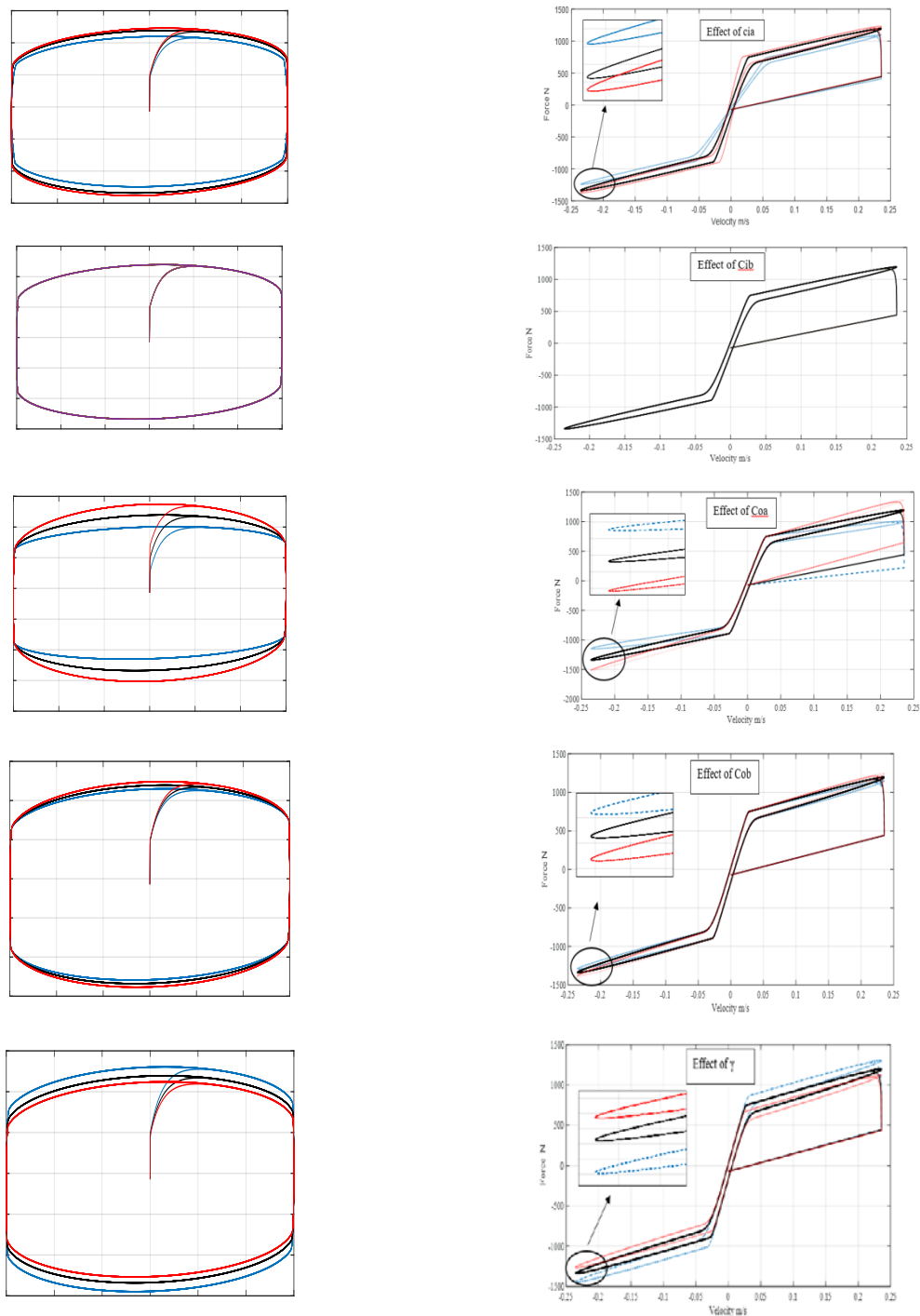
Figure 7. Force-displacement and force-velocity simulated responses with different values of parameters c1a, c1b, coa, cob and γ

Figure 8 describes the damper hysteresis with the variation corresponding to the parameters, k1, ko, xo, n and η. Different from the aforementioned parameters, there is no remarkable effect noticed for the parameters ko and η. It is noticed that the dynamic range increases by the increase in value of parameter k1. The variation of parameter xo results in shifting the hysteres is profile up and down from the equilibrium position. Exponent n is remarked as the crucial factor that controls the shape of the hysteresis loop. It is shown from the figure that the degree of nonlinearity becomes more obvious when the exponent, n is decreased. On the other hand, the hysteresis tends to be almost linear when the exponent, n is increased.
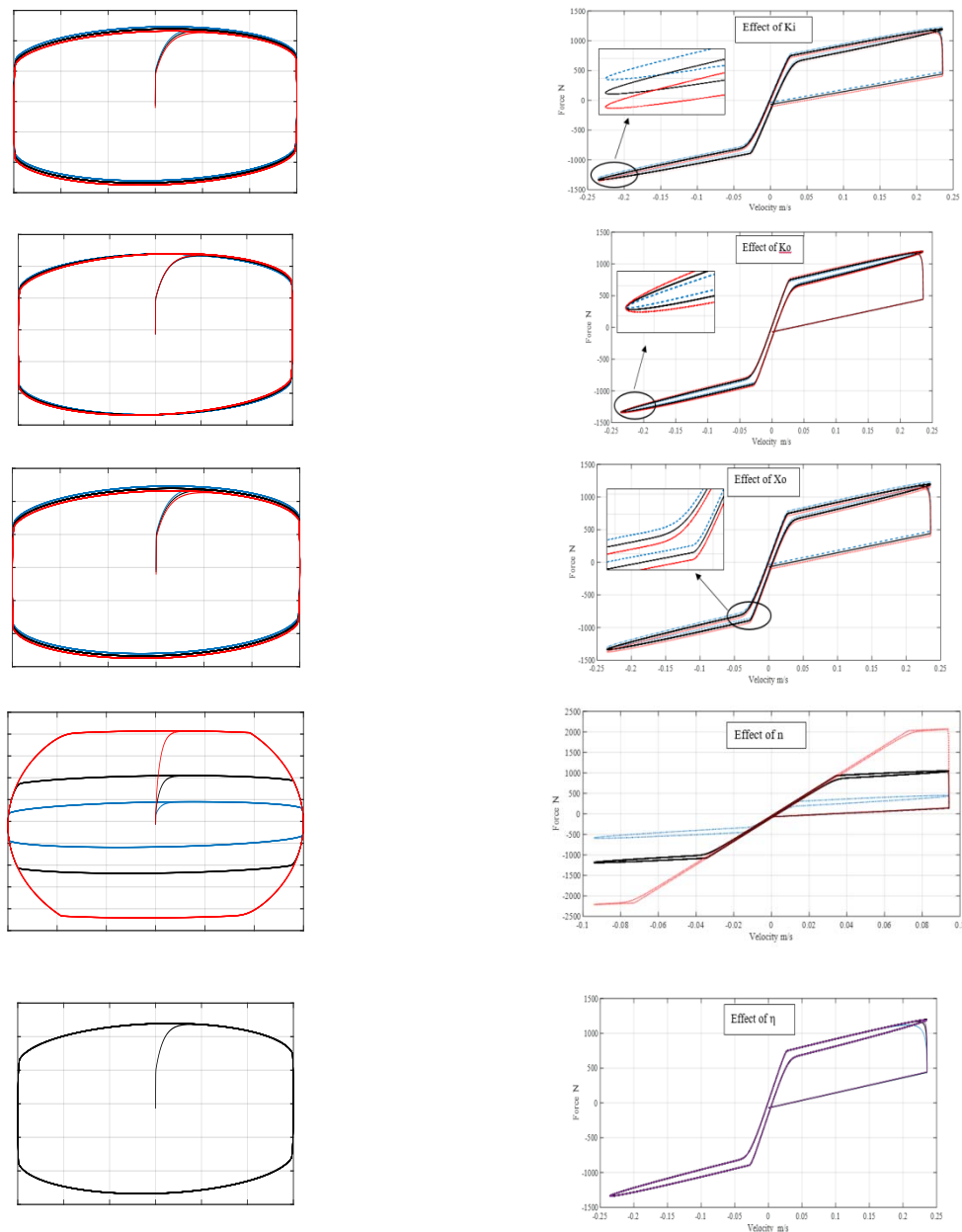
Figure 8. Force-displacement and force-velocity simulated responses with different values of parameters k1, ko,xo,n and η

5. Identification of optimal model parameters

The accuracy of the MR damper model is determined by the difference between the measured and simulated characteristics. When the simulated response of the model agrees closely with the measured data, the model can be used in simulation to represent the MR damper dynamics. Consequently, it is of rather importance to identify accurately the MR damper parameters that fit the experimental results. The accurate identification of the parameter values can be done using systematic search procedures with the objective to make the simulated characteristics similar to the measured response.

In order to demonstrate the influence of the identified parameters on the model response, and there, to obtain better estimates of the damper parameters of the modified Bouc-Wen model, a systematic method is employed. By this manner, all values of the reference parameters are varied systematically in order to predict characteristics that are similar to the measured data. The rms values of the damping force between the varied and reference parameters are used to identify the optimal parameters that best fit the damper output. The parameters A, β, γ, n. ko, k1, xo control the shape of the damper hysteresis with zero applied voltage. In addition, the parameters Coa,Cob,C1a,C1b, αa,αb control the dynamic force range.

Figure 9 and Figure 10 show the comparison between the force-displacement and force-velocity dependence of the simulated characteristics using the optimized parameters shown in Table 3and the measured response of the MR damper under sinusoidal excitation of 1 and 2 Hz and 5 mm amplitude at zero and 0.5 Amp respectively. It can be seen from the figures that the simulated response shows good agreement with the measured data.Also, the rms values and error percentage of the simulated and experiment responses have been calculated in order to judge the accuracy of the optimized parameters as shown in Table 4. The results show the rms values of the simulated damping force is closely match the rms values from experiment which prove the good match between the model and the experimental tests.

Table 3. Optimal parameters for fitting Modified Bouc-Wen model to experimental data

Parameter	Modified parameters	Unit
A	63	-
β	1963086	m^{-2}
n	2	m^{-2}
γ	206320	-
η	194	s^{-1}
c_{oa}	783	N.s/m
c_{ob}	2603	N.s/m.V
c_{1a}	15649	N.s/m
c_{1b}	45072	N.s/m.V
α_a	10441	N/m
α_b	45430	N/m.V
k_o	1750	N/m
k_1	317	N/m
x_o	0.0032	m

Table 4. Rms values and percentage of error

Parameters	Model (optimized parameters)	Practical	Percentage of error
1Hz, 0 A, 5mm	68.27	67.72	-0.8[1]%
1Hz, 0.5 A, 5mm	475.82	463.36	-2.68%
2Hz, 0 A, 5mm	84.31	83.55	-0.9%
2Hz, 0.5 A, 5mm	572.14	561.67	-1.86%

The negative sign in error percentage means the model force is larger than practical force.
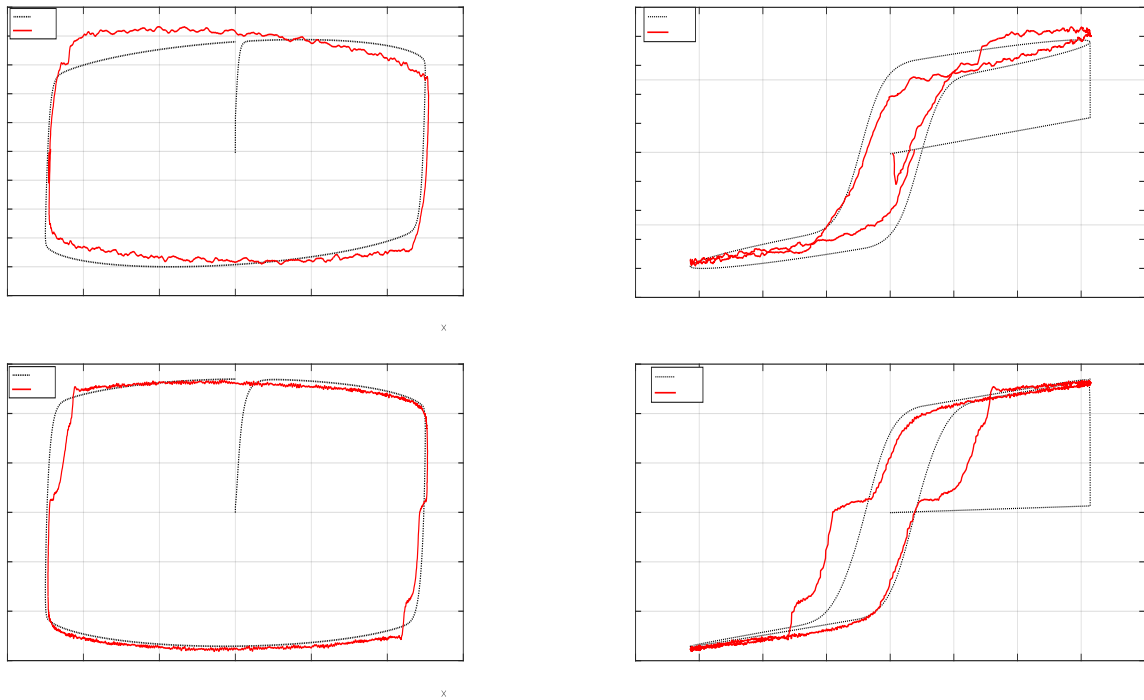
Figure 9. Comparison between force-displacement and force-velocity responses predicted by modified Bouc-Wen using optimal parameters and the measured data under excitation of 1Hz and 5 mm amplitude at zero and 0.5 Amp
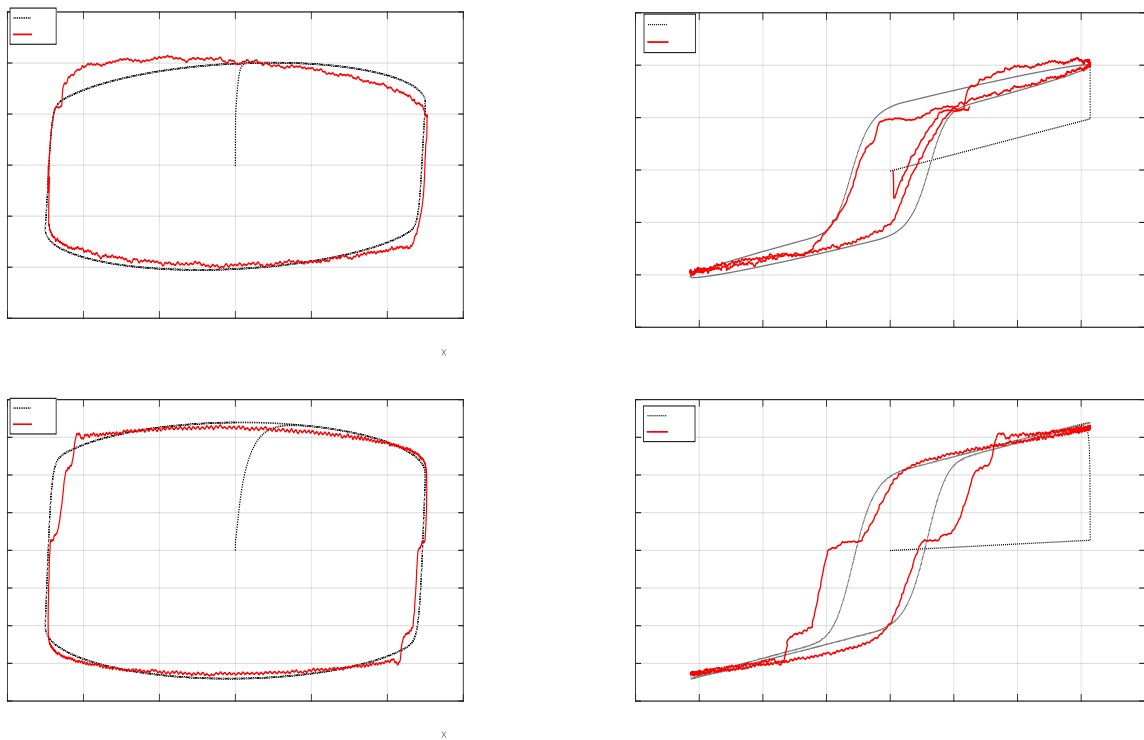
Figure 10. Comparison between force-displacement and force-velocity responses predicted by modified Bouc-Wen using optimal parameters and the measured data under excitation of 2Hz and 5 mm amplitude at zero and 0.5 Amp.

6. Conclusion

This paper presents an investigation on the effect of the modified Bouc-Wen on the dynamic characteristics parameters of a short stroke MR damper. The Experimental tests on the existing MR damper show the lack of the existing Bouc-Wen models (MBW1 and MBW2) to closely fit the measured damper characteristics. To improve the model accuracy, a parametric study was held to investigate the effect of each parameter on the hysteresis shape of the MR damper. The results show that the MR damper model characteristics are highly nonlinear and its parameters have a significant effect on the damper hysteresis. A parametric study is introduced to find the optimal parameters values that increase the degree of fitting between the simulated and measured data. Finally, the optimized parameters are introduced in the model and validated with the experimental responses which show good agreement between the simulated and measured results.

References

[1]   Bai X-X, Chen P and Qian L-J2015 Principle and validation of modified hysteretic models for magnetorheological dampers*Smart Materials and Structures* **24** (8)

[2]   Domínguez-González A, Stiharu I, and Sedaghati R2014 Practical hysteresis model for magnetorheological dampers*Journal of Intelligent Material Systems and Structures* **25** (8) pp 967-79

[3]   Balamurugan L, Jancirani J and Eltantawie M 2014 Generalized magnetorheological (MR) damper model and its application in semi-active control of vehicle suspension system I*nternational Journal of Automotive Technology* **15**(3) p p419-27

[4]   Zhao X, Qin W, Wu S and Pan H 2018 A dynamic hysteresis model for MR dampers based on particle swarm optimization*8th Annual International Conference on CYBER Technology in Automation, Control, and Intelligent Systems*

[5]   Yu J, Dong X and Zhang Z 2017 A novel model of magnetorheological damper with hysteresis division*Smart Materials and Structures* **26** (10)

[6]   Rossi A, Orsini F, Scorza A, Botta F, Belfiore N and Sciuto S 2018 A review on parametric dynamic models of magnetorheological dampers and their characterization methods*Actuators* **7** (2)

[7]   Peng Y and Yang J, Li J2018 Parameter identification of modified Bouc–Wen model and analysis of size effect of magnetorheological dampers*Journal of Intelligent Material Systems and Structures* **29**(7) pp 1464-80

[8]   Zamani A-A, Tavakoli S, Etedali S and Sadeghi J2019 Modeling of a magneto-rheological damper: An improved multi-state-dependent parameter estimation approach*Journal of Intelligent Material Systems and Structures* **30** (8) pp 1178-88

[9]   Metered H2012 Application of nonparametric magnetorheological damper model in vehicle semi-active suspension system*SAE International Journal of Passenger Cars-Mechanical Systems* **5**715-26

[10]   Spencer Jr B, Dyke S, Sain M and Carlson J 1997 Phenomenological model for magnetorheological dampers*Journal of engineering mechanics* **123**(3) pp 230-38

[11]   Şahin İ, Engin T, and Çeşmeci Ş2010 Comparison of some existing parametric models for magnetorheological fluid dampers*Smart materials and structures* **19** (3)

[12]   Lai C and Liao W2002 Vibration control of a suspension system via a magnetorheological fluid damper. *Modal Analysis* **8**(4) pp 527-47

Nomenclature

symbol	Meaning	Symbol	Meaning
v	Voltage applied to the current driver	α	Represent rheological effect
f	The resulting force from MR damper	z	Hysteresis variable
y	Internal dynamic variable	$\beta, A, \gamma, n, \eta$	Characterization parameter for MR damper nonlinearity
k_1	Accumulator stiffness	k_o	Control stiffness at large velocities
c_1	Represent the dashpot at low velocities	c_0	Viscous damping at large velocities
x_o	The initial displacement of spring k_1		