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Parameter Identification of Long Stroke and Short Stroke MR Damper for its Use in Semi-Active Vibration Control

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Abstract Magnetorheological (MR) dampers are devices that can be used for structural vibration reduction under seismic excitation. These devices are used in semi-active control which require less power compared to active devices and offer high reliability compared to passive devices. Despite the advantages of MR damper, use of these dampers in an effective way in a structure is highly challenging and a precise modelling is required as these dampers are highly non-linear. Among the parametric models available, Bouc–Wen model is widely used because of its effective modelling of the hysteretic force–velocity curve of MR damper. The parameters of Bouc–Wen model are damper dependent and hence need to be identified before utilising the damper for further simulation studies. In this work, the parametric identification of Bouc–Wen model for commercially available long stroke and short stroke MR damper (RD 8040-1 and RD 8041-1) is done. For this, experimental characterization of the dampers are carried out using hydraulic actuators mounted on a self-restraining frame. The damper is driven harmonically in the testing setup at various combinations of frequency, amplitude, current and displacement. Using the experimental characterization, parameters of Bouc–Wen model are identified by Levenberg–Marquardt optimization Algorithm (LMA). The identified parameters are validated by comparing with the experimental results. The identified parameters are believed to be worthwhile for the use of these MR dampers in further studies of real-time semi-active vibration control of structures.

Keywords MR damper · Bouc–Wen model · Parameter identification · Experimental characterization

Introduction

Modern day structures are built such that they are taller, longer and more flexible towards vibrations. Because of their increased flexibility, higher safety levels and sustainable construction practices, it is vital to design them as seismic resistant structures to avoid major losses to lives and economy. The concept of structural control is applied as a design method in the field of seismic vibration control of structures, to dissipate energy from the earthquakes and reduce structural vibrations. Major method involves efficiently adding stiffness, damping or both to the structure. Among the various control devices, semi-active control devices are proved to be more energy efficient than active devices and more effective in reducing seismic structural vibrations than passive devices in the literature. Among the various control devices, magneto- rheological fluid dampers have gained greater attention due to their spectrum of advantages like cost effectiveness, easy maintenance, very fast response time and low power requirements over other commonly used seismic control devices [1–3]. MR damper has a hydraulic cylinder arrangement containing a linear viscous fluid called MR fluid. The MR fluid contains micron-sized magnetically polarizable particles suspended in a liquid such as water, glycol, mineral or synthetic oil. When an external magnetic field is applied to the damper, the micro-sized particles align themselves in the direction of the applied field (Fig. 1). This causes the MR fluid to change from a free-flowing viscous state to a semisolid state. The yield

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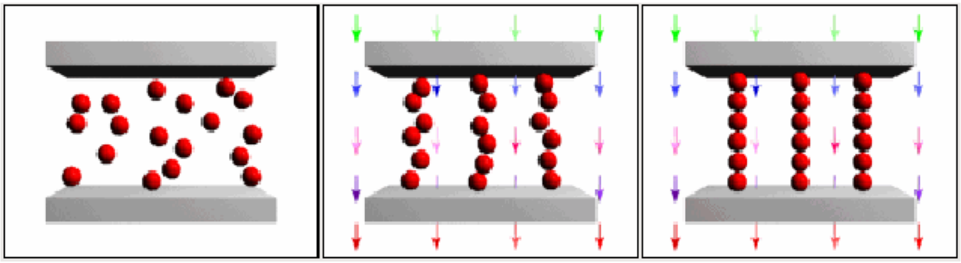


Fig. 1 MR fluid behaviour (LORD Corporation 1997–2005). **a** No Magnetic field **b** and **c** Increase in Magnetic field

strength of this change can be controlled by carefully controlling the externally applied magnetic field.

Characteristics of MR Dampers

MR dampers are highly nonlinear devices. It is very vital to understand and model the non-linearity of the damper for its application with a structure in vibration mitigation. Structural vibration control application of MR damper has two steps: first being the identification of suitable mathematical model of the damper and then establishing the hysteretic property of the damper. The force–velocity relationship exhibits a hysteretic behaviour which is challenging to mathematically model. Hysteresis can cause serious problems in controlled systems such as instability and loss of robustness. Identifying suitable model and its parameters to capture the non-linearity and hysteresis for each application plays a key first step in the structural control design. Modelling of MR dampers can be done using non-parametric and parametric models. Parametric models usually consists of a spring and dashpot system using which the dynamics of the device is described. Some of the extensively used parametric models are the Bingham, Bouc-Wen, modified Bouc-wen, Hyperbolic tangent, Dahl and other models. Nonparametric models are based on the input–output data of the device. These input–output data are mapped using either fuzzy logic, neural networks based on AI or any other biologically inspired training methods.

Bouc–Wen Model

The most widely used model for hysteretic system has been the Bouc–Wen model developed by Wen based on Bouc hysteretic model [4]. Figure 4 shows the schematic diagram of Bouc–Wen model. The model contains in series, a spring, a dash-pot and the Bouc–Wen hysteretic element. A mechanical analogue of the Bouc–Wen model is shown in Fig. 2 [5]. The force generated by the device is given by,

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

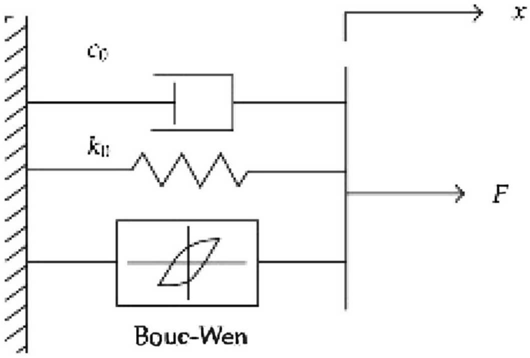


Fig. 2 Bouc–Wen model of MR Damper [5]

where c_0 is the damping coefficient, k_0 is the linear spring parameter, x_0 is the initial displacement of spring, α is the coefficient of the Bouc–Wen parameter associated with evolutionary variable z where the hysteretic component z satisfies,

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

The parameters α, β, γ, A and n are adjusted such that the force- velocity characteristics of MR damper can be best captured. The input current dependency of the damper affects the parameters α, c_0 and k_0. These parameters can be written as,

$$\begin{aligned} &\alpha(u) = \alpha_a + \alpha_b u; \quad c_0(u) = c_{0a} + c_{0b}u; \\ &k_0 \quad (u) = k_{0a} + k_{0b}u \end{aligned} \tag{3}$$

where u is obtained from the input voltage v as $\dot{u} = -\eta(u - v)$.

12 parameters (c_{0a}, c_{0b}, k_{0a}, k_{0b}, x_0, α_a, α_b, β, γ, A, η and n) of the Bouc–Wen hysteretic model has to be identified before using any MR damper for structural control application. The researchers have [6] estimated the parameters of Bingham and Bouc–Wen model from the experimental results using standard visual compatibility criterion for a RD-1005 MR damper. Some of the investigators have [7] utilised a new method adapting the CSS algorithm inspired by the governing Coulomb and Gauss laws from electrostatics and the governing motion from Newtonian mechanics for the parameter identification of Bouc Wen model. The Particle Swarm Optimisation algorithm [PSO] [8] has been utilized earlier for the parameter identification and found that extensive scrutinizing is required to achieve a closer match to the experimental results. The field-

Fig. 3 Test setup for MR damper characterization **a** Loading frame **b** Close up view of the damper **c** Wonderbox used to supply current

dependent hysteretic behavior of the shear stress in a commercially available MR fluid has been investigated and identified using a Preisach model for shock control applications [9]. In the current study, first the experimental characterization of two commercially available MR dampers are carried out using various input frequencies and amplitudes. The experimental results are then grouped into datasets and utilised for identification of Bouc–Wen model parameters. The parameters are identified using non-linear least squares method employing Levenberg–Marquardt Algorithm (LMA). The identified parameters are then validated using the validation data set from the experimental results.

Experimental Characterization

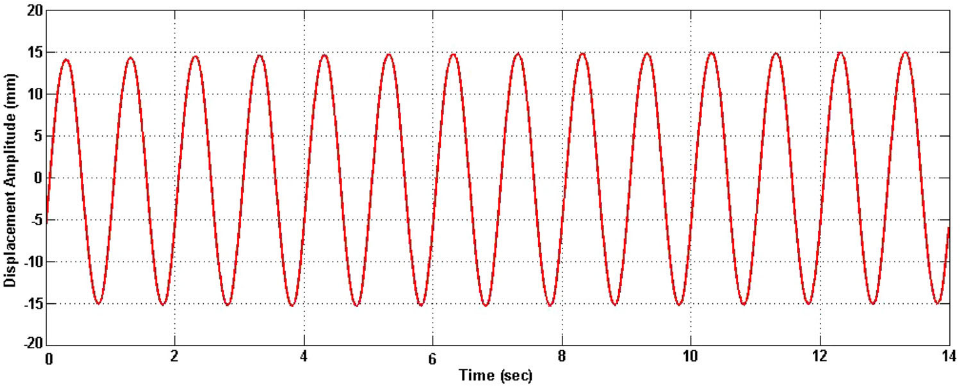
Experimental investigations are carried out on commercially available long stroke and short stroke (RD 8040-1 and RD 8041-1) MR dampers manufactured by Lord Corporation. Testing is done using a loading frame designed and built for the purpose of obtaining the MR damper response data necessary for identification under a wide range of magnitudes of control current and excitation conditions to characterize the hysteretic force property. The test setup is shown in Fig. 3. The setup consists of hydraulic actuator mounted on a self-restraining frame. The damper is fixed to the actuator and subjected to displacement controlled sinusoidal input excitation. Two dampers of each stroke are tested to ensure repeatability of the results.

Based on the operating ranges of the damper provided by the manufacturer, the damper is excited with a sinusoidal frequency ranging from 0.5 to 3 Hz with an amplitude range of 5–15 mm for short stroke RD-8040-1 damper and 5–20 mm for long stroke RD-8041-1 damper. In each case, considering some time for actuator stabilization, the damper is driven until a miminum of 10 stable cycles are recorded. This is ensured by assuming the middle 10 cycles are stable ones while the initial and last cycles are discarded from further processing. The loading curve for sinusoidal displacement of 1 Hz and 15 mm amplitude is shown in Fig. 4. An input current in the range of 0–1 A is supplied to the damper using the Wonderbox provided along with MR damper by the manufacturer. All the experiments are carried out at room temperature of 26–35 °C. The experimental data recorded are typically grouped according to the variability of the different parameters sets as current input tests, frequency-dependent tests and amplitude-dependent tests to obtain the characteristic curves of MR damper.

Results and Discussion

Figures 5 and 6 show the characteristic curves of short stroke damper and long stroke damper respectively which are sinusoidally excited at 1 Hz frequency and 15 mm amplitude with varying currents. Taking into account of the stabilisation time of the actuator for data recording, from the 10 cycles of data recorded, the 5 and 6th cycle in each case are taken as most stable and used for further studies. From the

Fig. 4 Loading profile for sinusoidal displacement input of 1 Hz frequency and 15 mm amplitude



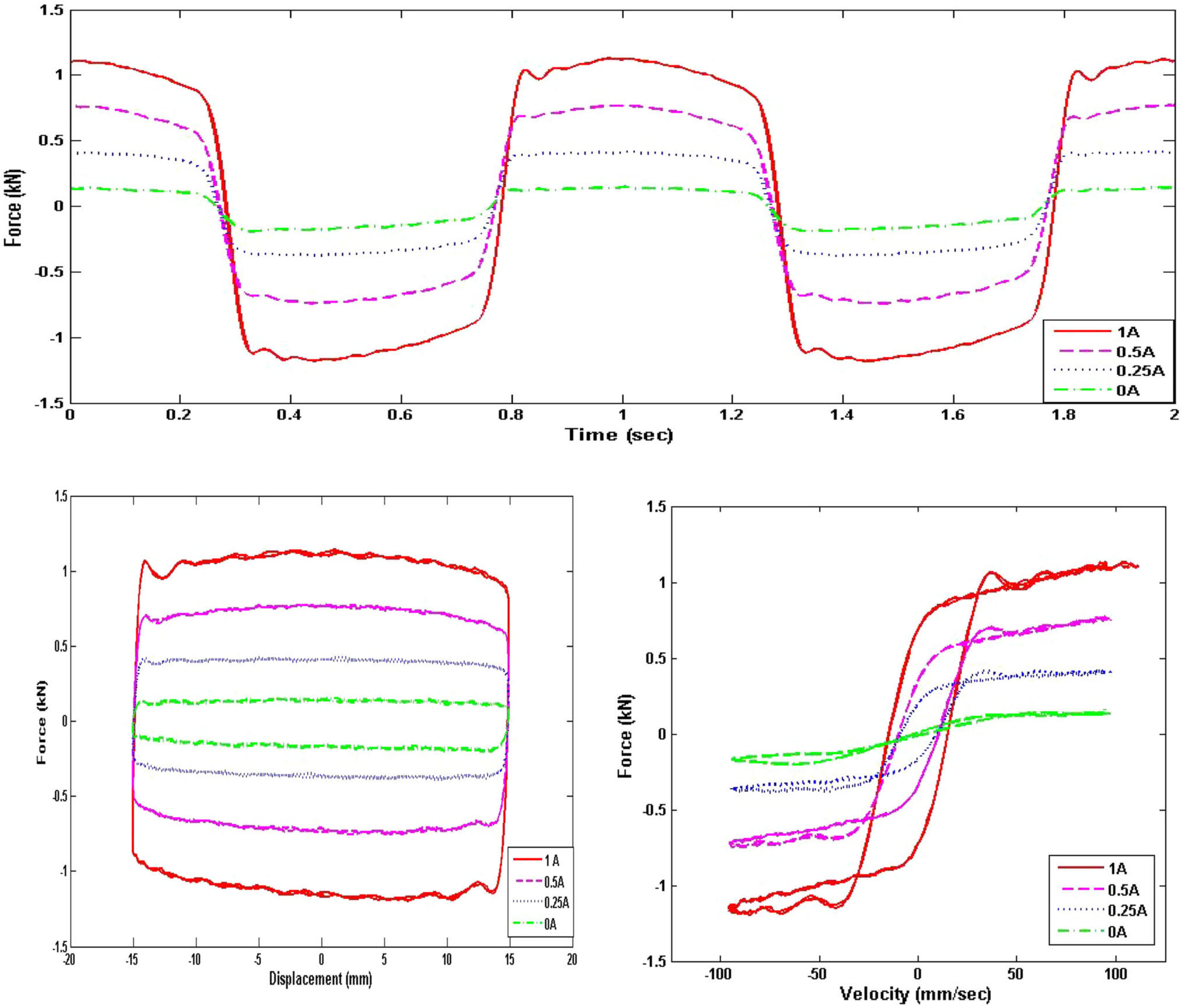


Fig. 5 Characteristics curves of RD 8040-1 short stroke MR damper with sinusoidal excitation of 15 mm amplitude 1 Hz frequency with varying input currents

figures, it can be observed that both long stroke and short stroke dampers behave similarly for lower input currents. Figure 6 show that the maximum force is slightly higher for the long stroke damper at 1 A current than the short stroke damper. Also, the post yield velocity of long stroke damper tend to increase at 1 A current that that of the short stroke damper. This increase can be clearly observed from the force velocity hysteresis of the long stroke damper. This change in post-yield behaviour results in the change in shape parameters of Bouc–Wen model. This warrants in independent identification of parameters for each of the dampers for their use in structural control applications.

Parameter Identification

12 parameters of the Bouc–Wen hysteretic model in Eqs. (1–3) are identified using the experimental results obtained. In the given equations, it should be noted that each variable corresponds to a specific characteristics for the shape and form of the curves. The variable ‘z’ is the internal state variable, v- input voltage, k_0 corresponds to linear spring stiffness, c_{0a} and c_{0b} are viscous damping coefficient, α_a and α_b are Stiffness of z(t). A, γ and β are the parameters which control the shape and the size of the hysteresis loop, while n is a scalar that governs the smoothness of the transition from elastic to plastic response. Keeping these in mind, the initial values of each parameter is assumed for parameter identification.

Optimization Problem

For the current study, the statement of the optimization problem is formed by using the method of nonlinear least

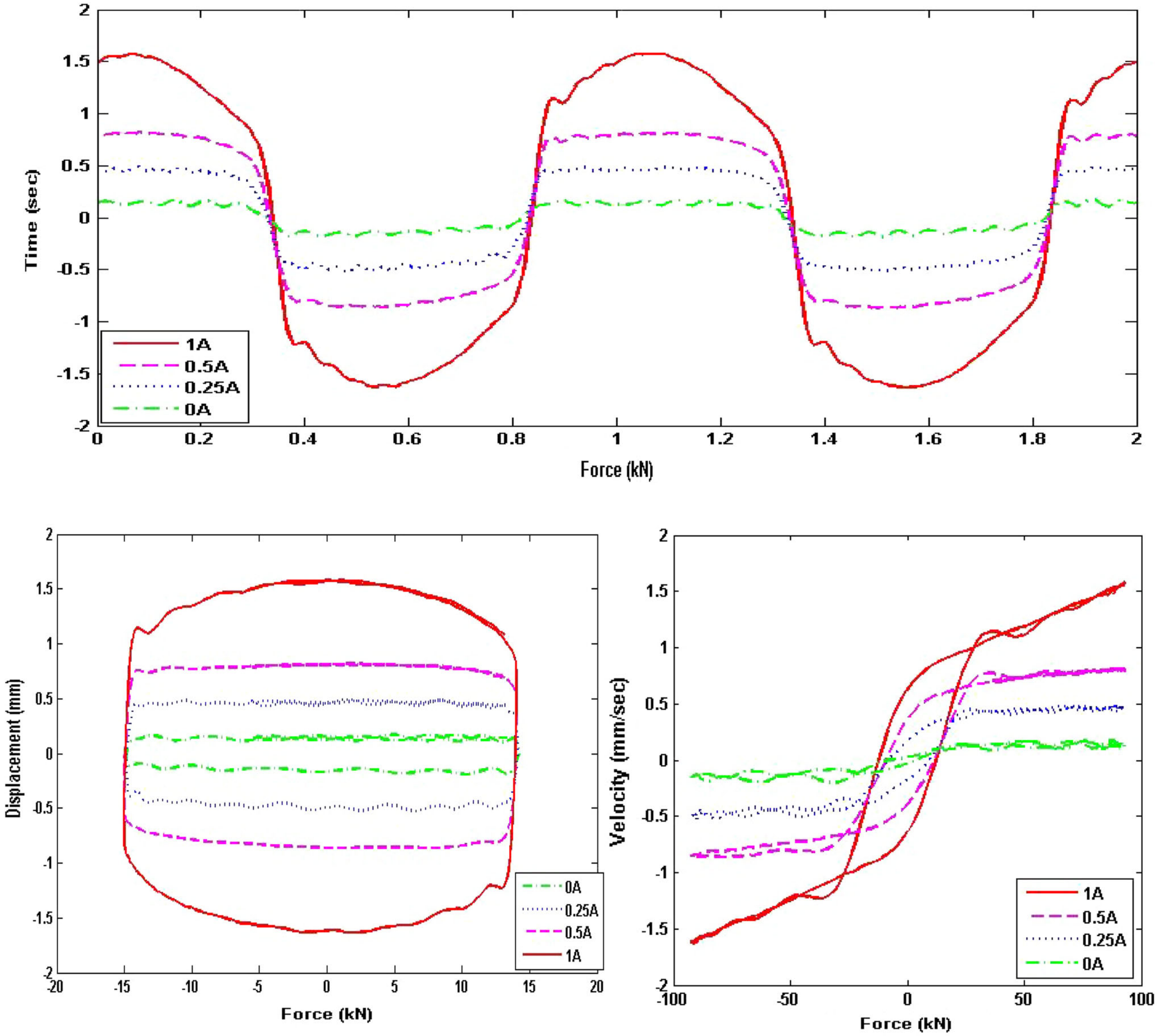


Fig. 6 Characteristics curves of RD 8041-1 long stroke MR damper with sinusoidal excitation of 15 mm amplitude 1 Hz frequency with varying input currents

squares. If x = [c_{0a}, c_{0b}, k_{0a}, k_{0b}, x_0, α_a, α_b, β, γ, A, η and n]^T, the objective function to be minimized for the identification of parameters is defined as,

$$\min Q(x) = \min \frac{1}{2} F(x)^T F(x) \tag{4}$$

where F(x) is a residual vector defined as,

$$F_i(x) = F_{ipred} - F_{iexp} \quad \text{for } i = 1, 2 \text{ to N, N being no of samples.} \tag{5}$$

The Levenberg–Marquardt (LM) Method

The optimality condition associated with the objective function given in Eq. (4) is given by,

$$\frac{\partial Q(x)}{\partial x} = J^T F(x) = 0 \tag{6}$$

where, J is the Jacobian matrix, whose elements are defined as,

$$J_{i,j} = \frac{\partial F_i(x)}{\partial x_j}, \quad i = 1, 2, \ldots N;\ j = 1, 2 \ldots 12 \tag{7}$$

Using a Taylor's expansion for F(x) about x^k and keeping only the terms up to the first order,

$$F\left(x^{k=1}\right) = F\left(x^k\right) + J^k \Delta x^k \tag{8}$$

where $J^k = J|_{x=x^k}$ and $\Delta x^k = x^{k=1} - x^k$ Using the above equations, the iterative procedure of LMA is given by,

$$x^{k+1} = x^k - \left[\left[\left(J^k\right)^T J^k\right] + \lambda^k I\right]^{-1} \left(J^k\right)^T F\left(x^k\right) \tag{9}$$

where k is the iteration counter, I is the identity matrix, and λ is a damping parameter, which is added with the aim of improving the stability of the iterative procedure [10]. When λ is large, the method takes a small step in the gradient direction. As the method nears a solution, λ is chosen to be small and the method converges quickly via the Gauss–Newton method. The algorithm [11] is given below,

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Input: f : $\mathbb{R}^n \rightarrow \mathbb{R}$, a function such that $f(X) = \sum_{i=1}^{m} \min \frac{1}{2} (f_i(x))^2$ where all the fi are differentiable functions.
x$^{(0)}$ an initial solution.
Output: x*, a local minimum of the cost function.

begin
  k ← 0;
  λ ← max diag($J^T J$) ;
  x ← x$^{(0)}$
  while STOP-CRIT and (k < $k_{max}$) do
    Find δ such that ($J^T J$ + λ diag($J^T J$)) δ=$J^T f$;
    x' ← x + δ;
    if f (x') < f (x) then
      x ← x' ;
      λ ← λ/υ ;
    else
      λ ← υ λ;
    k ← k+1;
  return x
end
```

The Bouc–Wen model is modelled in MATLAB/SIMULINK as shown in Fig. 7. Experimental data is clustered randomly into estimation and validation data. The estimation data is used for initial identification of parameters and later, the identified parameters are checked using the validation data. Identification is done using LM algorithm discussed above using parameter estimation toolbox available in Simulink. Each parameter is specified of its initial values to start with and also given lower and upper bound values for faster convergence. Maximum number of iteration is fixed as 1000 and a value of 1e-5 is used as parameter and function tolerances. With these, the 12 parameters for Bouc–Wen model are identified for both long stroke and short stroke damper and are listed in Table 1.

As seen from the identified parameters, the variation of hysteresis observed in long stroke and short stroke damper is reflected in the values of the shape parameters (A, γ and β). The variation of post yield velocity and post yield damping for long stroke damper at higher currents resulted in the change in values of c_{0a} and α_a. The linear spring stiffness constant k_{0b} is found to very small and hence the value is taken as zero.

Validation

The listed parameters are used in simulation studies of MR damper subjected to sinusoidal excitation of different amplitudes and frequencies. The force generated from the

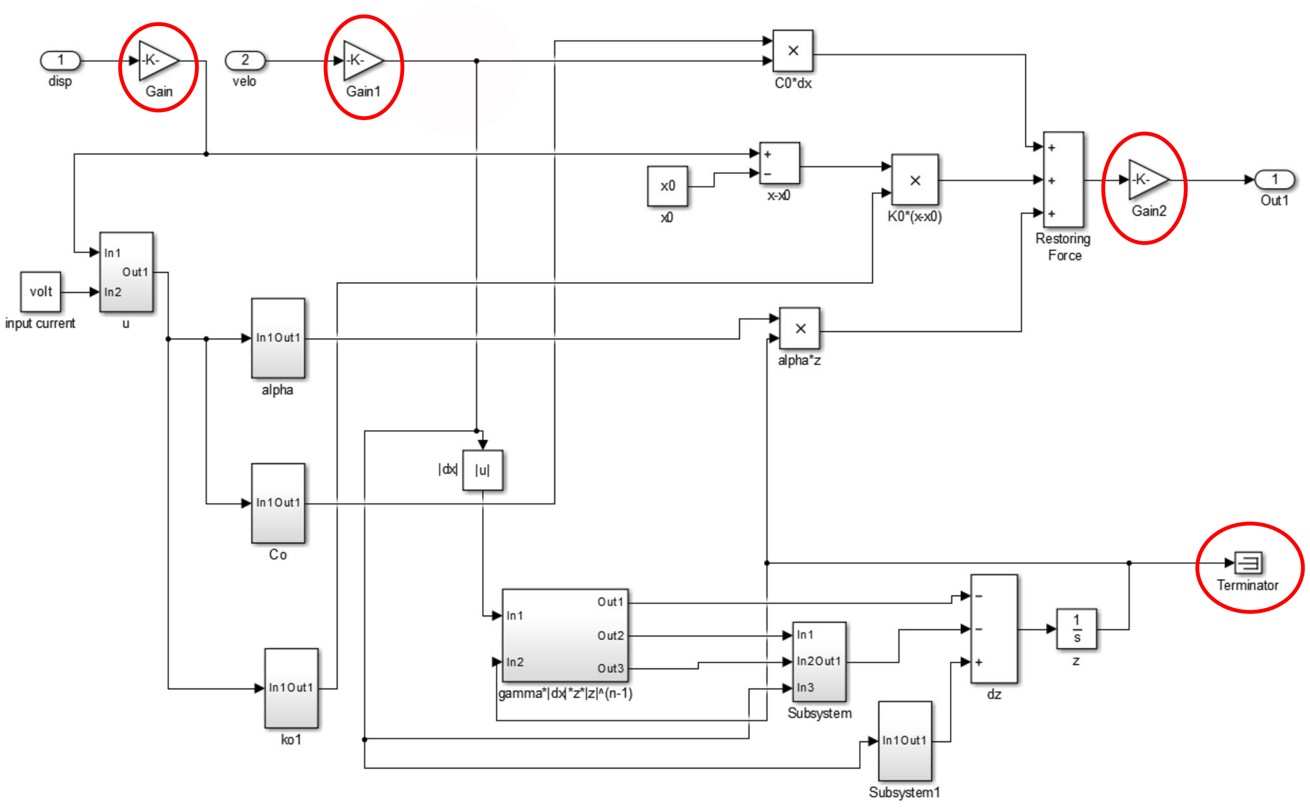

Fig. 7 Bouc–Wen model of MR damper in Simulink

Table 1 Identified Parameters of Bouc–Wen model for MR damper

Parameter	Short stroke	Long stroke	Unit
c_{0a}	3146.5	8186.5	kN.s/m
c_{0b}	0.6145	0.9945	kN.s/m/V
k_{0a}	0.2795	0.2795	kN/m
k_{0b}	0	0	kN/m
x_0	0.05	0.05	m
α_a	4404.5	5114.5	kN/m
α_b	0.0645	0.0645	kN/m/V
β	22,148	34,848	m^{-2}
γ	22,148	34,848	m^{-2}
A	1092.5	1091	–
η	157	157	s^{-1}
n	2.2	2.2	–

simulation are validated using the validation data set of the experimental results. From these validation studies, it is found that the listed parameters model the characteristics of the damper fairly close to the experimental results for all varying input conditions.

Comparison between the experimental and predicted force for a sinusoidal excitation of 15 mm amplitude, 1 Hz frequency of the short stroke RD 8040-1 damper with 1 A current input is presented in Fig. 8 and for the long stroke damper is presented in Fig. 9. The figure shows that the predicted force from the model is in good agreement with the experimental results. A variation is observed in the force velocity curve which can be attributed to the well documented limitations of Bouc–Wen equations in modelling the force velocity hysteresis. In order to better capture the force velocity hysteresis, the modified Bouc–Wen model with 14 parameters for both dampers will be identified as future part of the work.

Conclusion

In this study, experimental characterization of commercially available long stroke and short stroke MR damper (RD 8040-1 and RD 8041-1) is done using hydraulic actuators mounted on a self-restraining frame. The damper is sinusoidally excited at various combinations

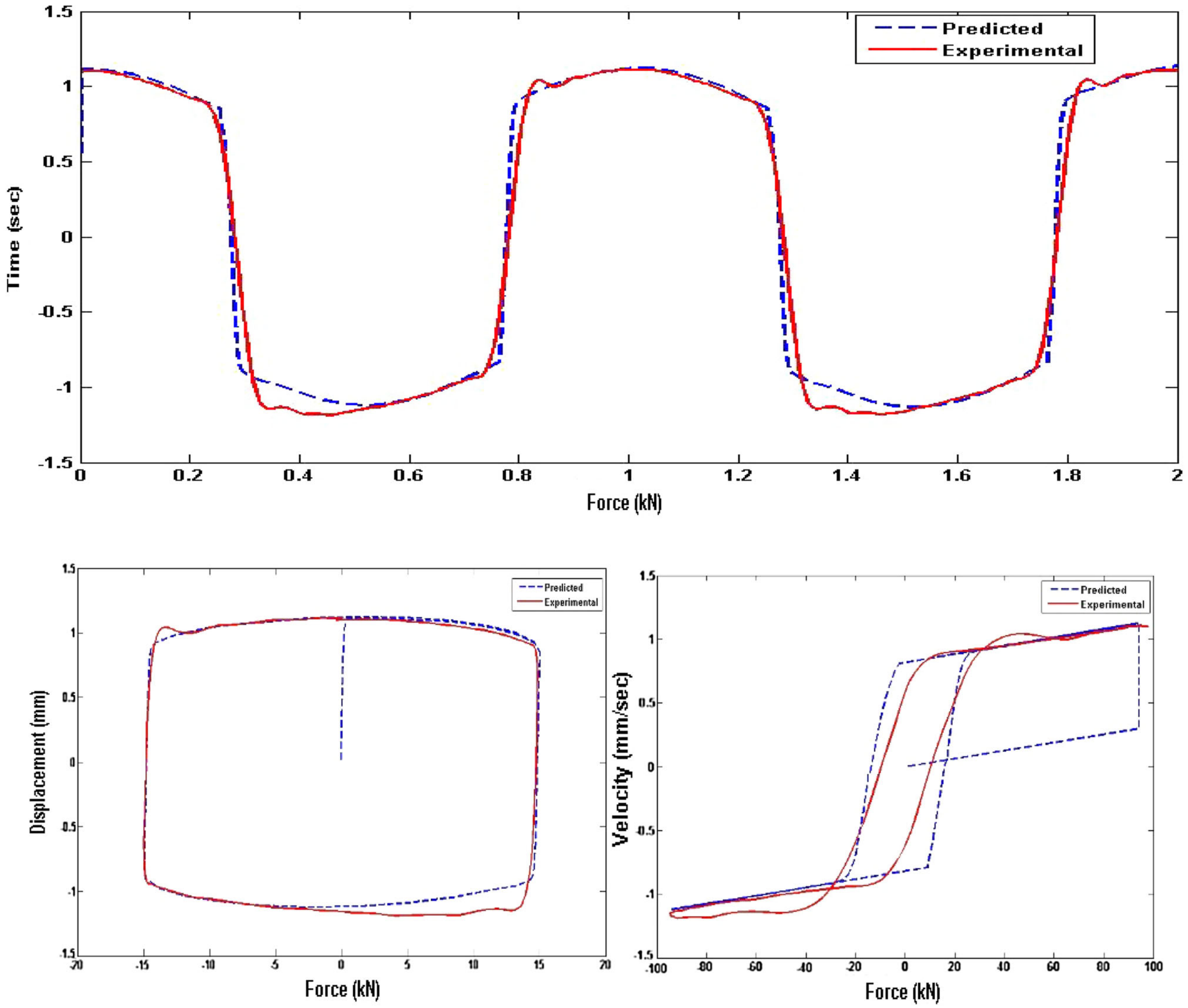

Fig. 8 Comparison of predicted and experimental results of RD 8040-1 short stroke MR damper with sinusoidal excitation of 15 mm amplitude 1 Hz frequency 1 A input current

of frequency, amplitude, current and displacement and characteristic curves are obtained. Using the experimental characterization, the parameters of Bouc–Wen model are identified using MATLAB/SIMULINK design and optimization toolbox. A simple and robust non-linear least squares method employing Levenberg–Marquardt Algorithm (LMA) is adopted for parameter identification. From the characterization studies, the post yield characteristics of long stroke damper is found to vary at higher currents and this is reflected in the change in parameter values during identification process. The identified parameters are then validated by comparing the predicted force with the validation data set of the experimental results. The parameters of Bouc–Wen

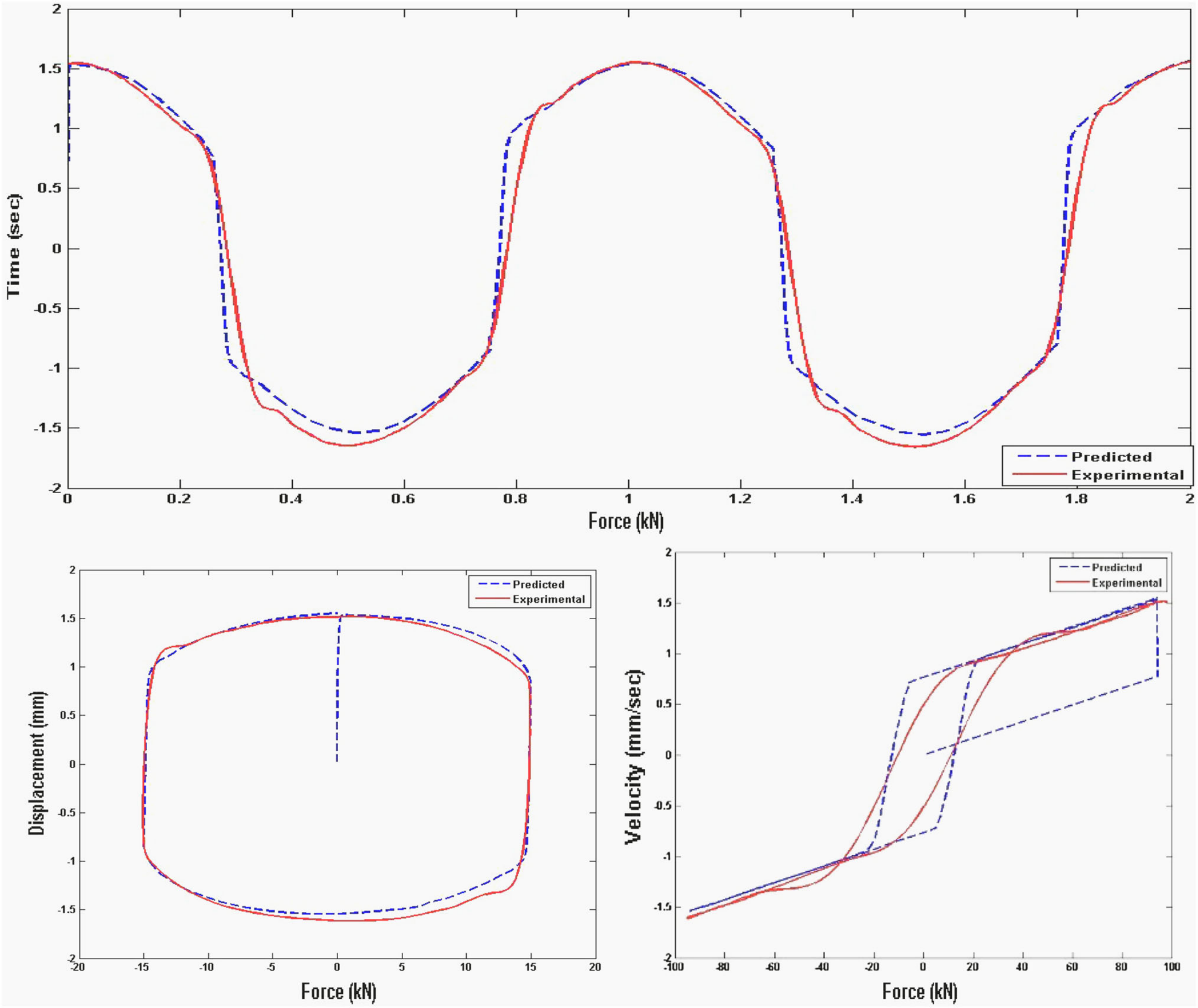

Fig. 9 Comparison of predicted and experimental results of RD 8041-1 long stroke MR damper with sinusoidal excitation of 15 mm amplitude 1 Hz frequency 1 A input current

model identified are believed to be worthwhile for the use of these MR dampers in further studies of real-time semi-active vibration control of structures.

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