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A Study of Bouc-Wen Model of Magnetorheological Fluid Damper for Vibration Control

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Abstract

Magnetorheological dampers more commonly called as MR dampers. MR damper is an intelligent damper, which is used as automobile suspension for vibration control. MR fluids represent a class of smart materials that respond to an applied electric or magnetic field with a dramatic change in rheological behavior. The main advantages of MR dampers are that they need very less control power, has simple construction, quick response to control signal and very few moving parts. MR damper have received a great deal of attention in the last two decades due to their being a potential technology to conduct semi-active control. It is therefore vitally important to understand the dynamic behavior of such devices whose nonlinear hysteresis is a rather complicated phenomenon. The behavior of MR dampers can be presented with different mathematical models. This paper illustrates the analysis of Bouc-Wen mode for MR damper.

1. Introduction

The properties of automobile suspension mostly influence the vehicle ride quality and safety. At present, the widely used hydraulic mount is incapable of real-time performance adjustment based on road situation and vehicle operation estate. Therefore, it is necessary to develop an intelligent automobile suspension which is capable of real-time performance adjustment. MR damper is becoming the most promising vibration controller in the intelligent suspension presently and it wins the favors of vehicle manufactures, because it takes the advantageous of high strength, good controllability, wide dynamic range, fast response rate, low energy consumption and simple structure [1].

Conventional damper has constant setting throughout their lifetime, and hence will not be able to operate satisfactorily in a wide range of road conditions. It is for these reasons that semi-active systems like MR dampers have attracted the attention of suspension designers and researchers [2]. Moreover, with the increasing requirement of vehicle ride comfortable and safety, intelligent suspension will be widely adopted in normal cars and engineering automobile, consequently, it will bring broad market of automobile suspension made of MR damper [1].

Models that can accurately represent the behaviour of MR dampers are essential in understanding the operation and working principles of the device. Such models can eliminate a great deal of uncertainties during the design process, which can subsequently enable control strategies for the damper to be developed efficiently and reliably. A mathematical model that is derived from their physical features like geometry and construction can provide insights into the way various parameters affect the performance of the device, and will allow design decisions to be made on the basis of engineering judgments [4].

The models can be classified into two main categories as parametric and non-parametric [5]. Parametric models are the most desirable ones as their parameters have some physical meaning. These models consist of some mechanical elements such as linear viscous, friction, springs, etc. Parameters associated with these mechanical elements are estimated by comparing the models with experimental results [6]. Parametric models are useful for direct dynamic modeling of MR dampers i.e. the prediction of the damper force for given inputs (voltage signal and the time-history of the relative displacement across the damper's ends) [5]. Nonparametric models establish a relationship between measured quantities, by purely mathematical means; the occurring parameters do not have a direct physical meaning [7]. A literature survey would indicate that, although non-parametric models can effectively represent MR damper behavior, they are highly complicated and demanding massive experimental datasets for model validation [6].

Although the MR damper is promising in control applications, its major drawback lies in the non-linear and hysteretic force–velocity response. Furthermore, the design of a controller generally requires a model of the actuator which may be challenging in the case of employing the MR damper. The modeling of the hysteresis had been studied including the Bingham visco-plastic model, the Bouc–Wen model, the modified Bouc–Wen model and many others. These models range from simple dry-friction to complicated differential equation representations [8].

The most extensively used model for modeling hysteretic systems is the Bouc–Wen model. The Bouc–Wen model was initially proposed by Bouc early in 1971 and generalized by Wen in 1976 and since then it has been called the Bouc–Wen model. The general Bouc–Wen model predicts the force displacement behavior of the damper well, and it possesses force–velocity [6].

2. MR fluid damper

Nowadays dampers based on MR fluids are receiving significant attention especially for control of structural vibration and automotive suspension systems. Multiple types of devices have been designed to implement this versatile fluid, including linear dampers, clutches, work-piece fixtures, and polishing machines. The devices have been used in automobiles, washing machines, bicycles, prosthetic limbs, and even smart structures [9].

2.1. Physical study

Typically, a MR damper consists of a hydraulic cylinder, magnetic coils and MR fluid offering design simplicity. In addition to field controllability and design simplicity, MR dampers have many other advantages such as they (i) require relatively very low power input, (ii) produce high yield stress up to 100 kPa, (iii) can be stably operated in a wide range of temperature (−40–150 ◦C) and (iv) MR fluids are not toxic and are insensitive to impurities [10].

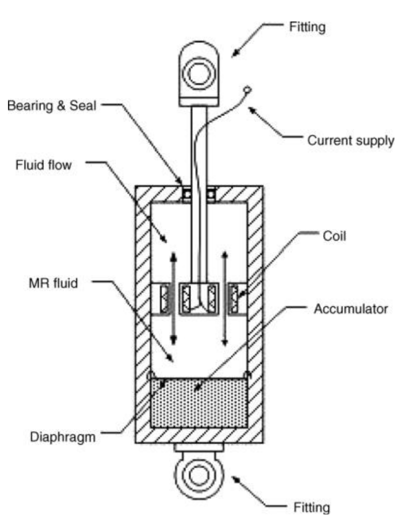


Figure 1. MR damper.

There are three main types of MR dampers. These are the mono tube, the twin tube, and the double-ended MR damper. The three design types reflect methods of adjusting the fluid volume to account for the volume of the damper shaft. Monotube designs are the most common damper design; they exhibit simplicity and compactness of design and with the ability to be mounted in any orientation [9].

2.2. MR fluid

MR fluids fall into a class of smart fluids whose rheological properties (elasticity, plasticity, or viscosity) change in the presence of a magnetic field. MR fluids are suspensions of soft particles, having a diameter of 1–5 mm, in a special carrier liquid such as water, mineral oil, synthetic oil, and glycol [12]. When an external magnetic field is applied to the fluid, the suspended particles in the fluid form chains and the suspension becomes like a semi-solid material due to the increase in the apparent viscosity. Under the magnetic field, an MR fluid behaves like a non-Newtonian fluid with controllable viscosity. However, if the magnetic field is removed, the suspension turns into a Newtonian fluid in a few milliseconds, and the transition between these two phases is highly reversible, which provides the unique feature of magnetic field controllability of the flow of MR fluids [6].The chains form causes about 50 kPa of yield stress depending on type of MR fluids in a few millisecond, the case creates a resistance against the fluid flow [9].

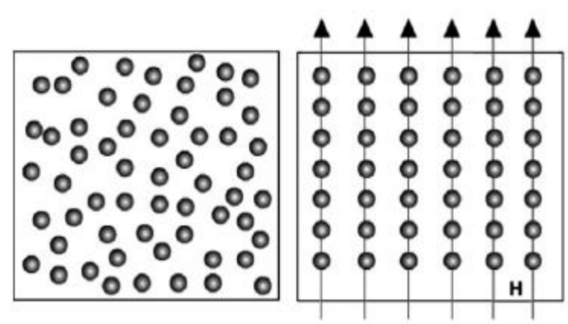


Figure 2. MR effect.

If a force is applied on the chains form, the shape of the form changes in terms of magnitudes of the force and magnetic field. The pressure reaction on MR fluid is called ‘MR effect’. In figure 2 as can be seen that the particles are scattered randomly in the liquid carrier, when magnetic field applied, the particle array in the direction of the magnetic flux lines to resist the flow [13]. MR Fluids can be used in three different modes Flow mode, Squeeze-flow mode, and shear mode [14].

3. MR damper model

The MR damper, however, is an intrinsically nonlinear device, which makes the modeling and design of suitable control algorithms an interesting and challenging task. To evaluate the potential of MR dampers in control applications and to take full advantages of its unique features, a mathematical model that accurately reproduces the dynamic behavior has to be developed through a suite of tests conducted using MR damper.

3.1 Bouc-Wen Model

The most extensively used model for modeling hysteretic systems is the Bouc–Wen model. The Bouc–Wen model was initially proposed by Bouc and generalized by Wen hence it has been called the Bouc–Wen model [6]. This model is extremely versatile and can exhibit a wide variety of hysteretic behavior. This model contains components viscous damper, spring and a hysteretic component. To evaluate the performance of MR dampers in vibration control applications Bouc–Wen model is adopted by many researchers [6,8,16]. Figure 3 shows a schematic of simple Bouc-Wen model.

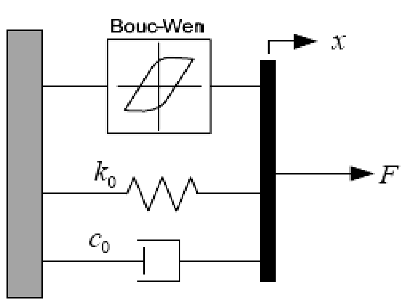


Figure 3. Schematic of simple Bouc-Wen model.

The force in nonlinear hysteresis system is divided into two parts.

$$F(x,\dot{x}) = g(x,\dot{x}) + \alpha z(x) \qquad (1)$$

where $g(x,\dot{x})$ is a non-hysteresis component that possesses a functional relationship with instantaneous displacement and velocity, α is scaling value for the Bouc-Wen model and *z(x)* represents the hysteresis component with respect to the time history of displacement. The evolutionary variable is governed by

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

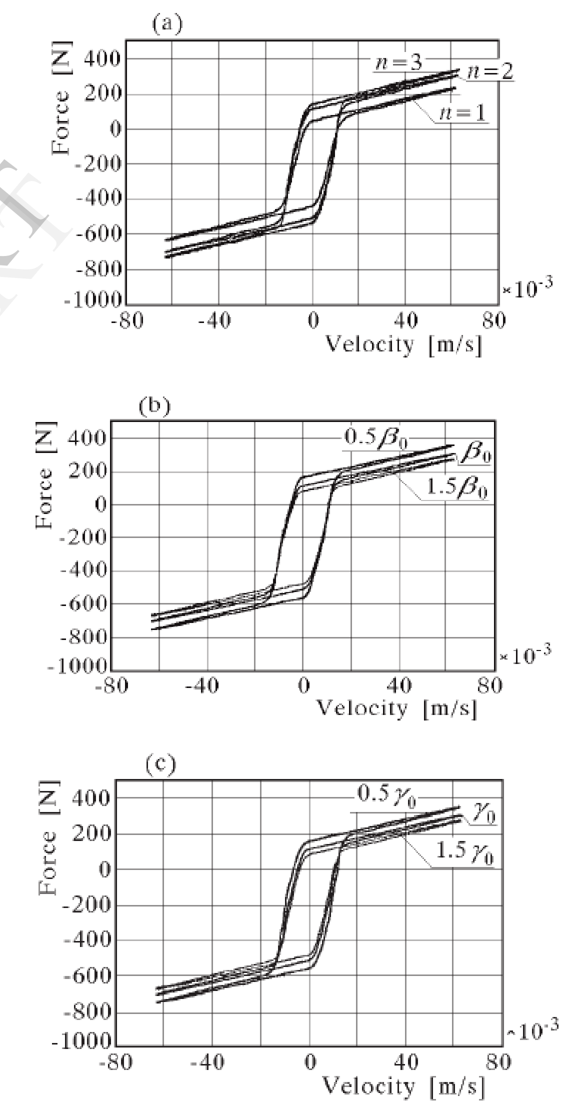
where x is the displacement at the damper location; z is the evolutionary variable; and β, γ, n, and A are parameters controlling the linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region. For an odd n, the equation is

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

However for an even number

$$\dot{z} = -\gamma|\dot{x}||z|^{n-1} - \beta\dot{x}|z|^{n} + A\dot{x} \qquad (4)$$

The influence of n on the dependence of the MR damper force on the velocity, through the chosen parameters of the Bouc-Wen model and for n = 1, n = 2, n = 3, is shown in figure 4(a). Using this method, the prediction accuracy of behavioral structures with hysteresis is satisfactory as compared with the experimental results gained for n = 2.



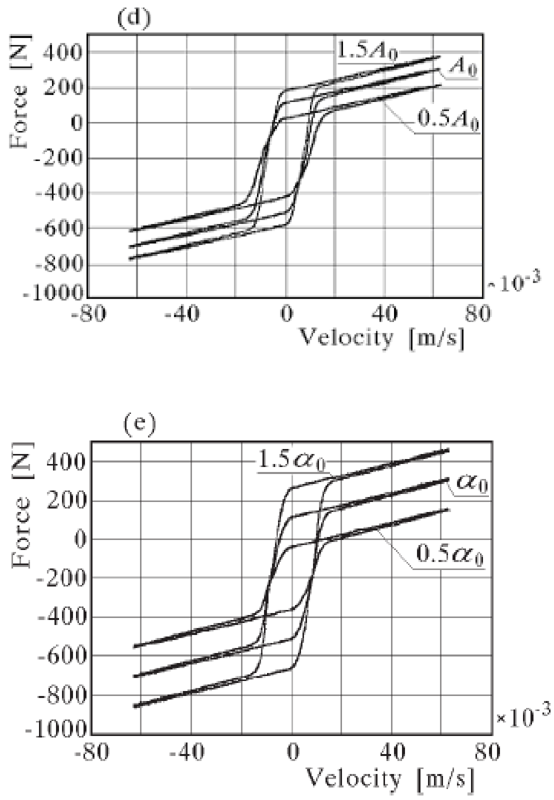


Figure 4. Influence of parameters: n, β, γ, A and α on force-velocity curves [18].

The damping force in the Bouc-Wen model can be written as

$$F = c_0\dot{x} + k_0(x - x_0) + \alpha z \qquad (5)$$

where c_0 and k_0 are the viscous and stiffness coefficient, respectively and the initial displacement x_0 of the spring was incorporated into the model to present an accumulator, z is an evolutionary variable defined in equation. By adjusting the parameter of n, β, γ and A the shape of the force-velocity characteristics can be controlled.

$$\dot{z} = -\gamma z|\dot{x}||z|^{n-1} - \beta\dot{x}|z|^n + A\dot{x} \qquad (6)$$

The influence of the parameters n, β, γ, A and α on the accuracy of hysteresis prediction in the damping force-velocity curve is shown for the Bouc-Wen model in figure 4 (a),(b),(c),(d) and (e).

The characteristics response of Bouc-Wen model is compared with experimental responses shown in figure 5. From the response curve is cleared that the property of the MR damper can be described with the Bouc–Wen model. Hence this model is most extensively used for modeling of MR damper [15].

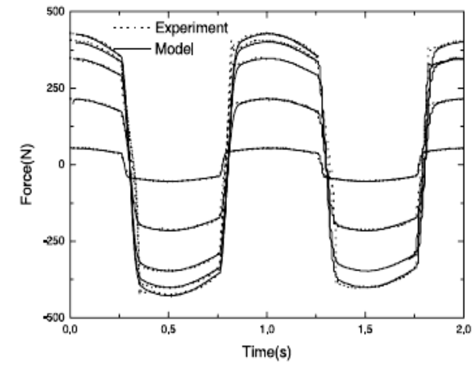


Figure 5 (a) Force vs. time.

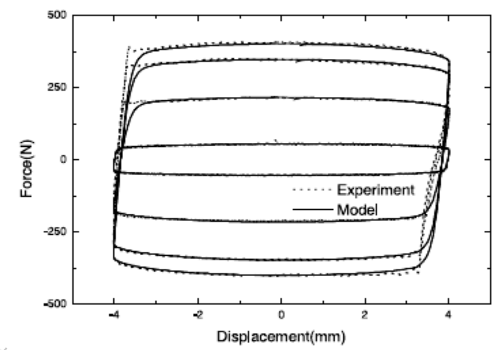


Figure 5 (b) Force vs. displacements.

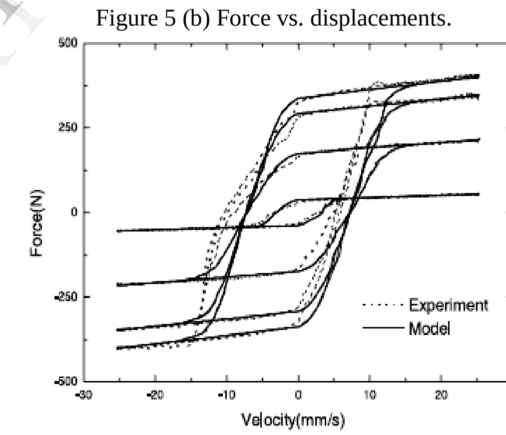


Figure 5 (c) Force vs. velocity.

Figure 5. Comparison of estimated responses with corresponding experimental responses [15].

3.2 Modified Bouc-Wen model

The extensions of the Bouc-Wen model proposed by Spencer with additional element dashpot c_1 and spring k_1 are introduced in order to obtain a more accurate model. The Bouc-Wen model is shown in figure 6.

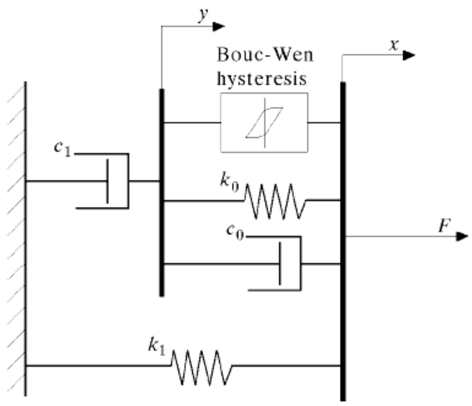


Figure 6. Modified Bouc—Wen model.

Since the nonlinear force–velocity response of the Bouc–Wen model does not roll-off in the region where the acceleration and velocity have opposite signs and the magnitudes of the velocities are small and in order to better asses the property of MR damper in vibration control application and make full use of the apparatus, a mechanical model was developed by Spencer [16].

Damping force in Spencer's model can be expressed as

$$F = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - y) \qquad (7)$$

or can also be written as

$$F = c_1\dot{y} + k_1(x - x_0) \qquad (8)$$

where z is evolutionary variable given by

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \qquad (9)$$

where

$$\dot{y} = \frac{1}{c_0 + c_1}[\alpha z + c_0\dot{x} + k_0(x - y)] \qquad (10)$$

In the modified model, the accumulator stiffness is represented by k_1 and the viscous damping observed at larger velocities is represented by c_0. A dashpot, represented by c_1, is included in the model to produce the roll-off that was observed in the experimental data at low velocities, k_0 is present to control the stiffness at large velocities and x_0 is the initial displacement of spring k_1 associated with the nominal damper force due to the accumulator.

The model complexity is unavoidably increased with an extended number of model parameters which may impose difficulties in their identification. Therefore, this model is only used in applications where an accurate model is required.

Comparing the modified phonological Bouc-Wen model with the simple Bouc-Wen model, we can find out that an internal displacement y is introduced to the model to better capture the behavior of the damper in cases when velocities with a small absolute value and there is an operational sign opposite to the acceleration. Equation related to this model presents the mechanical status when the damper is taking constant magnetic excitation. But to decide for a model that is also valid at magnetic fields, the parameter dependent on the applied voltage or current must be determined. Therefore following relation proposed.

$$\alpha = \alpha(u) = \alpha_a + \alpha_b u$$
$$c_1 = c_1(u) = c_{1a} + c_{1b}u \qquad (11)$$
$$c_0 = c_0(u) = c_{0a} + c_{0b}u$$

where the dynamics involved in the MR fluid reaching rheological equilibrium are accounted for through the first order filter:

$$\dot{u} = -\eta(u - v) \qquad (12)$$

where v is the applied voltage to the current driver. The total of 14 parameters (c_{0a}, c_{0b}, k_0, c_{1a}, c_{1b}, k_1, x_0, α_a, α_b, γ, n, β, η and A) have to be decided in Bouc-Wen model to accurately describe the hysteresis behaviour of MR damper [8].

Figure 7 shows the comparison of the predicted model with the experimental data for five constant voltages (0, 0.5, 1, 1.5 and 2 V). It can be seen that the model accurately predicts the behaviour of the damper [11].

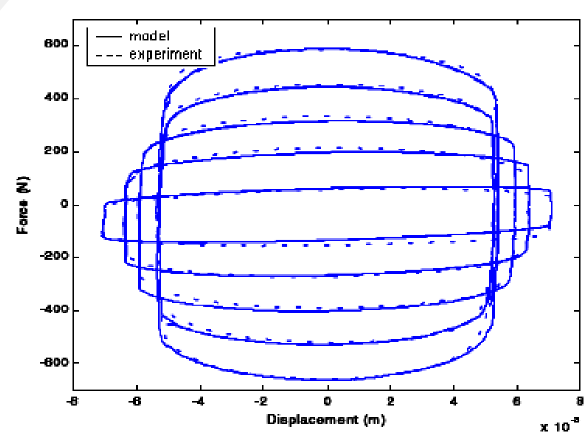


Figure 7(a). Force–displacement relationship.

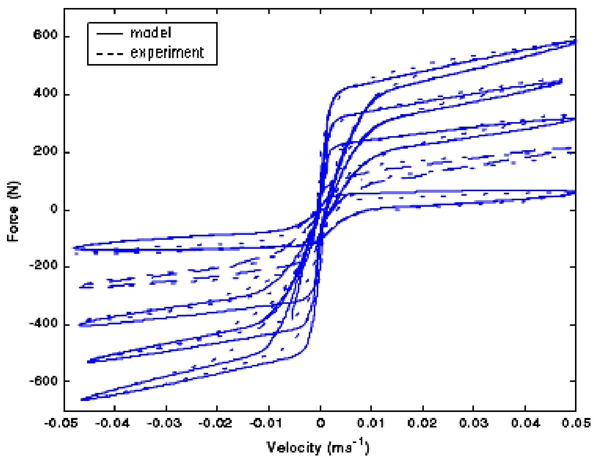


Figure 7(b). Force–velocity relationship.

Figure 7. Comparison of model and experimental results. (a) Force–displacement relationship (b) Force–velocity relationship.

4. Conclusion

This paper has presented a Bouc-Wen Model and Modified Bouc-Wen model for a magnetorheological damper to study the hysteretic relationship between the damping force and the velocity. To evaluate the performance of MR dampers in vibration control applications Bouc–Wen model is adopted by many researchers. The comparison of the model with the experimental data is presented for both the models. From the response curve it can be seen that the model accurately predicts the behaviour of the damper.

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