System Identification of Magnetorheological Damper for Various Configurations

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Abstract. A symmetrical Bouc Wen hysteretic model has been proposed for different configuration of MR damper in this paper. The various configurations of the MR damper include varying the annular gap between the cylinder and the piston, the amount of carbonyl iron particles present in the carrier fluid and varying the current. The symmetrical Bouc Wen model is simulated using the MATLAB software and the experimental and simulated force, displacement values are compared, and the maximum damping force is found among the various parameters considered. It is found that the maximum damping force was obtained for 1mm annular gap and a fluid configuration of 80% carbonyl iron particles when excited at a frequency of 0.5Hz with 2.5A power supply.

1. Introduction

In recent years, many seismic control devices are being investigated for vibration control for prevention of complete building collapse during earthquakes. Magnetorheological (MR) damper is one such device which has attracted the researchers around the globe to explore the various application and enhancement of this control device. It is a semi-active control device. Ordinary viscous fluid damper has viscous fluid inside the cylinder, however viscous fluid inside the cylinder of the MR damper has small polarizable particles. MR damper considered for study in this experiment has a coil wound inside the hollow cylinder. When external current is applied to the coil, a magnetic field is generated. By increasing magnitude of the magnetic field, fluid inside the MR damper changes its state to semi-solid and vice versa. Magnetorheological fluid (MRF) technology has been already successfully applied in automotive semi active suspension and structural vibration reduction. MR dampers finds major application in safeguarding the civil engineering structures due to the advantageous features such as damage reduction, low power consumption, force control and rapid response. But the major drawback of this system is its nonlinearity and its hysteretic behaviour.

The Bouc–Wen model, is more prevalent in structural and mechanical engineering. In case of Bouc-Wen symmetrical model, analytical description of the system yields a smooth hysteretic behaviour. A single nonlinear differential equation is used to analyse the hysteretic behaviour of materials or structural elements or vibration isolators in a unified manner. Bouc Wen model is the inverse problem approach. A set of experimental input–output data is taken. The Bouc–Wen model parameters are applied and altered so that the output of the model matches the experimental data. The resulting model is considered as a "good" approximation of the true hysteresis, after above parameters are tuned by using a suitable identification method. The error between the experimental data and final outcome of the model should be very minimal from practical point of view.

Upon different, researches the basic MR damper model is found to be Bouc wen model and so Li Wang, Zhong-Rong Lu (2017) have taken this model to identify the parameters. Hence using a
general inverse approach, in which the parameter identification is taken as an optimization problem. The objective function is nonlinear least squares function. A Bouc Wen model parameter identification was used by N.M.Kowk (2006) for a MR damper. The parameter identification was done by computationally efficient Genetic Algorithm and its efficiency has been improved. The parameter identification is done for a squeeze mode MR damper by using Genetic Algorithm by Lin (2013). Since it is a squeeze mode damper the use of Bouc Wen model is restricted and Biviscosity model is used for modelling. Aristotelis E (2010) the parameters of Bouc-Wen hysteretic model are examined in detail. An on-line identification algorithm and modified Bouc-Wen model are used by Pei-Yang Lin (2005) to identify a mathematical model of the MR damper performance according to experimental results. Their effect on the overall response is clarified and discussed. A large-scale MR damper used in a benchmark building is being identified Bahar (2010) using normalized Bouc Wen model and the validation is carried out using a black box model. MR damper manufactured by LORDS corporation is tested using INSTRON testing machine to investigate the mechanical behaviour of the MR damper by Li (2000). It is seen that, a viscoelastic-plastic model has been proposed.

Xian (2013) studied the design, fabrication and testing of the MR damper by utilizing the inner flow gap. The inner flow gap (i.e.) the annular gap influences the stroking load of the damper. It is analysed using Bingham plastic nonlinear fluid mechanics model and the advantages over the conventional MR damper are investigated. The influence of annular gap size on the viscous stress of MR fluid is investigated by Fathima (2014). The simulation is done using the finite element analysis. The experimental results are compared with the simulated results. It is inferred that the annular gap size influences the dynamic range of the MR fluids. Young-Thai Choi (2014) analysed the flow mode of MR damper for eccentric annular gap size. It is observed analytically that the damper forces in eccentric annular gap size decreases when compared to that of the concentric annular gap size. A finite element model of MR damper is built by Sadak (2012) for six different piston configurations. Variations in current and piston velocity are done and experimental results are obtained. The simulation of these configurations show that the performance of the single coil with filleted piston ends are more superior to other piston configurations comparatively for same current and piston velocity.

A self-constructed MR damper is tested by Peng (2014) for its hysteretic behaviour and mechanical performance by using instron testing machine. A modified Bouc Wen Baber Noori model was proposed due to the force lag phenomenon exhibited by the damper. The identification of the parameter was done in MATLAB SIMULINK design and optimization toolbox. The parametric identification of extended Bouc Wen differential model has been investigated by Ma (2004). Monte carlo simulation methods are used to identify the insensitive parameters in the model and to simplify the model. Parametric identification of MR damper is done by Giuclea (2004) the experiments are performed and various time history and force, velocity and displacement values for different constant and variable current values are obtained and the parameters are identified using Genetic Algorithm Ahmadian (2007) has experimentally investigated the characteristics of two types of MR dampers under impulse loading. MR damper with single stage, double ended piston and MR damper with mono tube, two ended piston are tested. It is seen that the force and displacement values showed variations in both the cases. The maximum peak force was attained by single stage MR damper. An Enriched Imperialist Competitive Algorithm was proposed by Talatahari (2015) for the system identification of MR damper. Two types of experimental data are used and the optimization problem is carried out for two types of hysteretic Bouc Wen model and the parameters are identified. An extended Bouc Wen model was proposed by Giuclea (2010) based on the experimental results and the optimization of parameters are done using Genetic Algorithm. Numerical simulation is done for the validation of the model for the given experimental outputs. A new model for the prototype of the LORDS MR damper was proposed by (Dyke S.J. 1996). Bingham model is modified, and the parameters are identified using constrained nonlinear optimization using the quadratic programming algorithm available in MATLAB. Therefore, in the present work a comparison on the annular gap
with various MR fluids was studied experimentally and analytically.

2. Proposed MR Damper

![Section view of proposed Magnetorheological Damper](image1)

**Figure 1.** Section view of proposed Magnetorheological Damper

In recent times, MR dampers have turned out to be an object of intense research because of their physical behaviour and their capability to control damping in structures. Damping force of MR damper which is a semi active device is controlled by the MR fluid. when exposed to a magnetic field, MR fluid changes from liquid to semi-solid that possess good yield strength that to in milliseconds [16]. Due to this behaviour, there is a proper link between electrical and mechanical systems. The fabricated shear mode MR damper’s performance were studied with various annular gap which decides the damping as depicted in figure 2. They also require less electric current. Different magnitude of vibration can be achieved by differing the annular gap. The section view of MR Damper is shown in figure 1.

![Fabricated MR Damper](image2)

**Figure 2.** Fabricated MR Damper
3. Shear Mode

The MR Damper used for the research purpose is a shear mode type MR damper. The shear mode MR damper consists of a paramagnetic sliding or rotating surfaces which has magnetic fluid present in between the surfaces as shown in figure 3. The magnetic field is perpendicular to the motion of the moving surfaces. The coils are wound inside the hollow cylinder and the wires are connected to the power supply.

![Shear Mode](image)

**Figure 3. Shear Mode**

4. MR Fluid

The magnetorheological fluid is made of a carrier oil called magnetec oil which has carbonyl iron particles added to it in different proportions. In this investigation various proportions of iron particles are added to the magnetec oil [17]. The various liquid configurations include 32% iron particles and 68% magnetec oil (MRF 32), 50% iron particles and 50% magnetec oil (MRF 50), 80% iron particles and 20% magnetic oil (MRF 80) as shown in figure 4. These fluids at varying currents are used for experimental investigation and the liquid for which maximum damping force occurs is found.

![Preparation of MR Fluid](image)

**Figure 4. Schematic representation for preparation of MR Fluid**

5. Annular Gap

The annular gap is the small gap between the cylinder and piston. This annular gap variations are also a parameter which affects the effective damping. The annular gap is also varied as 1mm, 1.5mm and 2mm and the effect of damping force is investigated.

6. Experimental Test Setup

The MR Damper is tested using Computer controlled hydraulic Universal Testing Machine- MTS. The lower head was fixed, and the upper head is attached to the hydraulic actuator that moves up and down as shown in figure 5. The Universal Testing Machine is activated by a actuator and hence it cannot carry out high frequency tests except for small displacements as depicted. The maximum capacity of MTS is 1000KN.
7. Test Procedure
The testing is to be carried out for varying fluid configuration and annular gaps by giving different amount of power supplies. The cyclic load is given for the MR Damper. The excitation frequency is around 0.5Hz for all the required testing. The maximum displacement or amplitude of the MR Damper is fixed as ±5mm. The coil wires are connected to the power supply. The current supply is varied from 0A to 2.5A for each fluid configuration and annular gaps. The set of tests include,

The numerous tests are performed, and the force and displacement values are collected directly as output. The force vs displacement graph is plotted, and the maximum damping force values are identified from the experimental results. These values are compared with the model values obtained from the Bouc Wen model.

8. Bouc Wen Model
The Bouc Wen hysteretic model is used for the investigation. Bouc Wen model is a set of differential equations which is used to describe the hysteretic behaviour of damper. The hysteretic behaviour is seen in the force-displacement and force velocity responses. This leads to nonlinearity behaviour of MR damper as shown in figure 6.

There are numerous efficient models of MR dampers. The identification procedure starts with the basic model. Thus, Bouc Wen model is considered for modelling.

The basic symmetrical Bouc Wen model has been considered in this investigation for primary comparison of the results. Consider a Single Degree of Freedom System (SDOF) with Bouc Wen hysteretic model.
The general differential equation of the Bouc Wen hysteretic model is given by,

\[
f(t) = mx + cx + kx + r
\]

\[
r = \frac{1}{\eta} [A\dot{x} - \upsilon \beta r r^{-1} x + \gamma r^n x]
\]

where \(m\) is the mass of the damper, \(c\) is the damping coefficient, \(k\) is the stiffness coefficient and \(r\) are the restoring force. \(x\) is the displacement, \(\dot{x}\) is the velocity and \(\ddot{x}\) is the acceleration for the given system. \(\eta, A, \upsilon, \beta\) and \(\gamma\) are the hysteretic parameters which influences the hysteretic behaviour of the damper.

\section{9. Parameter Identification}

In order to simplify the parameter identification process, the parameters \(\eta\) and \(\upsilon\) which are used to control the degrading and pinching behaviour of the hysteresis curve is considered to be unity. The parameter \(n\) is an exponential parameter and denotes the thermodynamic admissibility which takes a value greater than 1 (i.e) \(n \geq 1\). Another constraint \(|\gamma| \leq \beta\) is also considered.

Both the linear system parameters and Bouc Wen hysteretic parameters are to be identified in order to compare the results with experimental values. The linear system parameters include \(m, c\) and \(k\). The hysteretic parameters include \(A, \beta, \gamma\) and \(n\).

The value of ‘\(m\)’ is fixed based on the mass of the damper and the values \(c\) and \(k\) are to be identified. These values are obtained from the experimental values. The maximum values of \(c\) and \(k\) are obtained from the experimental graph.

Assuming that the hysteresis is symmetric about the zero-displacement axis, the maximum values (i.e.) the upper bound values are obtained by,

\[
c_{\text{max}} = \frac{f_{\text{max}} - f_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}
\]

\[
k_{\text{max}} = \frac{f_{\text{max}} - f_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}
\]

these maximum values of the linear parameters are used in the simulation of bouc wen model.
The values of $A$ and $\beta$ are obtained from the above Bouc Wen hysteretic model graph based on the shape of the hysteresis curve as shown in figure 7.

The nonlinear parameters are non-dimensional in nature and highly influence the hysteresis curve. The upper bound values of these parameters are taken as, $A = 0.9$, $\beta = 0.9$ and $\gamma = 0.5$. The parameter $n$ is an exponential parameter and its value is taken as 2.

10. **ODE45 Solver**

The differential equations of the Bouc Wen model are linearized as follows,

$$
X_1 = x_2
$$

$$
X_2 = \frac{1}{m} f t - x_3 - \frac{c}{m} x_2 - \frac{k}{m} x_1
$$

$$
x_3 = Ax_2 - (\beta x_3 x_3^{-1} x_2 + \gamma x_3^n x_2)
$$

This linearized equation is solved in MATLAB coding by using the ODE 45 solver. The identified parameters are given as inputs and the coding is run and the output plots can be obtained. A set of force displacement and velocity values are obtained. These results are analysed, and the maximum damping force is found and the Bouc Wen model fitness to the given MR damper is found.

11. **Algorithm for Bouc Wen Model**

The set of simulated force displacement values are obtained for each experimental data set. The graphs are plotted, and the results are compared. The Root Mean Square Error is found for each experimental result. The algorithm for model is shown in figure 8.
Figure 8. Bouc Wen Model Algorithm

\[ f(t) = m\ddot{x} + c\dot{x} + kx + r \]
\[ \dot{r} = \frac{1}{\eta} \left[ A\dot{x} - v(\beta r|r|^{n-1}|\dot{x}| + \gamma r|\dot{x}|^n) \right] \]

Defining the parameters (c, k, A, β, γ and n)

Call the function using ODE45 solver

Force vs displacement plot

12. Results and Discussions

12.1 Comparison of Experimental and Simulation Results

The experimental and Bouc Wen model simulation data are plotted and compared for each MR fluid with various annular gap configuration.

12.2 Annular Gap 2mm - 32% Iron Particles

Figure 9. Force vs Displacement for Annular Gap 2mm (MRF 32)

a) 0 A, b) 0.5 A, c) 1, d) 1.5, e) 2, d) 2.5
When 32% iron particles are added to the carrier oil and tested for an annular gap of 2mm, it is seen that the simulation test results achieve maximum damping force than experimental damping force as shown in figure 9.

12.3 Annular Gap 2mm - 50% IRON PARTICLES

![Figure 10. Force vs Displacement for Annular Gap 2mm (MRF 50)](image)
a) 0 A, b) 0.5 A, c) 1, d) 1.5, e) 2, d) 2.5

When 50% iron particles are added to the carrier oil and tested for an annular gap of 2mm, the simulation results are higher for minimum current values and as the power supplied increases, the experimental results show higher values than simulation results as shown in figure 10.

12.4 Annular Gap 2mm - 80% Iron Particles

![Figure 11. Force vs Displacement for Annular Gap 2mm (MRF 80)](image)
a) 0 A, b) 0.5 A, c) 1, d) 1.5, e) 2, d) 2.5

When 80% iron particles are added to the carrier oil and tested for an annular gap of 2mm, it is seen that when the current is applied to the system, the experiment values are far more than the simulation values as shown in figure 11.
When 32% iron particles are added to the carrier oil and tested for an annular gap of 1.5mm, it is seen that the simulation results are higher than the experimental results as shown in figure 12.

When 50% iron particles are added to the carrier oil and tested for an annular gap of 1.5mm, it is seen that the simulation and experimental results have minimum variations as shown in figure 13.
When 80% iron particles are added to the carrier oil and tested for an annular gap of 1.5mm, it is seen that the simulation and experimental results have much variations as shown in figure 14.

**12.8 Annular Gap 1mm - 32% iron particles**

When 32% iron particles are added to the carrier oil and tested for an annular gap of 1mm, it is seen that the simulation and experimental results have much variations but for 2A and 2.5A current had little variations as shown in figure 15.
When 50% iron particles are added to the carrier oil and tested for an annular gap of 1mm, it is seen that the simulation and experimental results have more variations as depicted in figure 16.

When 80% iron particles are added to the carrier oil and tested for an annular gap of 1mm, it is seen that the simulation and experimental results have maximum variations as shown in figure 17.

Based on the experimental results it is very clear that the annular gap of the MR damper plays a major role in achieving maximum damping force. The minimum annular gap increases the area of contact of the piston with the carrier oil and produces greater damping force. The increase in the ratio of iron particles also has significant effect on the damping. It is seen that the experimental damping force has
an increase when the percentage of iron particles increases. The increase in the input current will definitely have an increasing effect on the damping force. Hence from the experimental datasets it is clear that the maximum damping force is obtained in case of minimum annular gap and for maximum percentage of iron particles and maximum current input. In this investigation it is seen that the maximum damping force was achieved for an annular gap of 1mm having 80% iron particles at an input current of 2.5A.

The simulation is done using the ODE45 solver in MATLAB. The simulation of the Bouc Wen model is carried out by taking the maximum values for the various Bouc Wen model parameters. The parameter values are obtained as discussed earlier. Certain parameters are taken as constants for the purpose of simplification of the equation. From the simulation results it is clear that the upper bound values of the parameters need not give maximum damping force for all the configurations. The results show variations in damping force in random manner. In this case it is seen that the simulated damping force is maximum for an annular gap of 1.5mm having 32% iron particles at an input current of 0A.

From the experiment and simulation results the Root Mean Square Error (RMSE) values are calculated by using the formula,

\[ e = \frac{(f_{\text{sim}} - f_{\text{exp}})^2}{n} \]  

(3)

The error values are calculated and plotted, and the results are analysed, and the results are discussed.

| Annular Gap | MR Fluid Composition | 0A  | 0.5A | 1A  | 1.5A | 2A  | 2.5A |
|-------------|----------------------|-----|------|-----|------|-----|------|
| 2mm         | 32% IP               | 4.24%| 15%  | 5.30%| 5.21%| 0.91%| 1.81%|
|             | 50% IP               | 7.38%| 4.96%| 3.11%| 1.23%| 0.56%| 0.96%|
|             | 80% IP               | 2.46%| 0.69%| 0.89%| 1.74%| 3.21%| 4.98%|
|             | 32% IP               | 16.10%| 8.10%| 7.82%| 6.80%| 7.20%| 2.90%|
| 1.5mm       | 50% IP               | 3.94%| 0.95%| 0.04%| 1.29%| 1.60%| 2.26%|
|             | 80% IP               | 0.30%| 3.56%| 4.82%| 5.35%| 6.55%| 7.53%|
|             | 32% IP               | 7.69%| 4.88%| 4% | 1.93%| 1.14%| 0.17%|
| 1mm         | 50% IP               | 3.12%| 0.85%| 3.02%| 3.56%| 4.12%| 4.87%|
|             | 80% IP               | 0.06%| 6.16%| 6.46%| 7.73%| 7.98%| 8.62%|

**Figure 18.** Error distribution for 2mm annular gap
For 2mm annular gap damper the error value is maximum in case of 32% iron particles and for a power supply of 0.5A and minimum for 50% iron particles and 2.5A power supply, as shown in figure 18.

Figure 19. Error distribution for 1.5mm annular gap

As depicted in figure 19, 1.5mm annular gap damper the error value is maximum in case of 32% iron particles and for a power supply of 0A and minimum for 80% iron particles and 0A power supply.

Figure 20. Error distribution for 1mm annular gap

For 1mm annular gap damper the error value is maximum in case of 80% iron particles and for a power supply of 2.5A and minimum for 80% iron particles and 0A power supply as shown in figure 20.

The main objective of the investigation is to find the percentage fitness of the Bouc wen model to our MR Damper tested. The parameters of the Bouc wen model are assigned the maximum values in this case. The RMSE values for all the configurations are calculated and analysed. The error value should be minimum for the Bouc wen model to fit the given MR dampers for the parameters considered. The minimum error is found to be 0.04% for an annular gap of 1.5mm having 50% iron particles at an input current of 1A and the second minimum error is found to be 0.06% for an annular gap of 1mm having 80% iron particles at 0A input current. Maximum deviation is found to be 16.10% for an annular gap of 1.5mm having 32% iron particles at 0A current and second maximum deviation is 15% for an annular gap of 2mm having 32% iron particles at an input current of 0.5A.
Hence, it is clear that the fitness of Bouc Wen model for certain configurations is maximum when upper bound values of the parameters are considered. At the same time large amount of deviations are found in certain configuration. So, it is very much needed to optimize the parameters of the Bouc wen model to obtain high level of accuracy in the fitness for all configurations for the given MR Damper. The optimization of these parameters can be done by any of the several optimization methods available. After optimization again, the simulation is done for all the configurations and the experimental and analytical values are compared for maximum fitness of the Bouc wen model to our MR Damper system.

13. Conclusion
This paper has presented the comparison and error distribution for experimental and simulated values. The symmetrical Bouc Wen model has been identified for the given MR Damper configurations. It is seen that certain error values are minimum and certain values are very high. The error should be minimised for each experimental dataset. The parameters are to be optimized for each set of values and hence the error can be minimised.

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