Establishment and Simulating Verification for Hyperbolic Tangent Model of Magneto-rheological Damper

Gang Li1,2*, Hao Lin1, Na Ouyang3, Guoliang Hu1, Rongxia Xu1 and Ruiheng Gu1

1Key Laboratory of Conveyance and Equipment, Ministry of Education, East China Jiaotong University, Nanchang, Jiangxi, 330013, China
2Key Laboratory of Vehicle Intelligent Equipment and Control of Nanchang, East China Jiaotong University, Nanchang, Jiangxi, 330013, China
3Jiangxi Traffic Technical School, Nanchang, Jiangxi, 330105, China
*Corresponding author’s e-mail: ligang0794@163.com

Abstract. Firstly, the parameters of hyperbolic tangent model with magneto-rheological (MR) damper are identified via particle swarm optimization algorithm based on the mechanical properties test. Then, the functional relationship between the identified parameters and input current is fitted by curve fitting toolbox. Ultimately, Simulink toolbox is utilized to design and establish the hyperbolic tangent simulation model with MR damper, meanwhile, the different input currents and sinusoidal signals with other amplitudes and frequencies are selected for simulation and comparative analysis. The results show that parameter identification accuracy of particle swarm optimization algorithm is high. The simulation and experiment data under combination conditions with different input currents and other sinusoidal signals are in good agreement, which verifies the generality and accuracy of the parameter identification results.

1. Introduction
Magneto-rheological (MR) damper is a semi-active intelligent control device that has possessed the advantages such as simple structure, low power consumption, controllable force, quick response and unaffected by faults [1-2]. MR damper is filled with an intelligent material (MR fluid), applying the rheological characteristics with MR fluid, the magnetic field intensity of the environment where the MR fluid is located can be adjusted via controlling the input current flowing through the copper wire coil winded on the outer wall with MR damper, so that the output damping force of MR damper can be regulated continuously in a certain range. Consequently, MR damper has utilized extensively in many control fields such as mechanical vibration attenuation and bridge quake-proof.

The MR fluid will occur shear thinning phenomenon during the rheological process, it not only makes that the mechanical properties curve of MR damper has non-linear hysteretic characteristics, but also leads to establish the accurate, simple and practical model of MR damper difficultly [3]. Up to now, the common mechanical models mainly include bingham model, double viscous hysteretic model, bouc-wen model, modified bouc-wen model, hyperbolic tangent model, modified dahl model, neural network model, polynomial model and so on [4-5]. Experts and scholars have done a lot of researches on parameter identification of mechanical model. Liu et al proposed a method of combining genetic and pattern search algorithm to identify unknown parameters of bouc-wen model, which can describe the hysteretic characteristics of MR damper significantly, but the reliability and accuracy of identified parameters are poor when the excitation amplitude is large [6]. Xiao et al utilized unscented kalman
filter algorithm to identify unknown parameters of bouc-wen model, although this method can ensure the accuracy of parameter identification, the identification process is complicated, mathematical theory is too difficult to understand, and the factors are considered too much [7]. Hu et al used the least square method to identify unknown parameters of the modified hyperbolic tangent model, this method can reduce the complexity of identification process to a certain extent, but it also will decrease the accuracy of parameters identification [8]. Hu et al presented a method that combining genetic and nonlinear least square algorithm to identify unknown parameters of hyperbolic tangent model, which can further enhance the accuracy of parameter identification, but this algorithm optimization process possessed too many iterations, slow identification speed and low efficiency [9].

In this paper, we utilize particle swarm optimization algorithm to identify unknown parameters of hyperbolic tangent model with MR damper based on the data collected from the mechanical properties test, and make use of the curve fitting toolbox to fit the functional relationship between the identified six parameters and the input current. Meanwhile, the hyperbolic tangent simulation model is design and establish through the Simulink toolbox, and the different currents and the sinusoidal signals with other amplitude and frequency are selected to verify the universality and accuracy for the parameter identification results.

2. Hyperbolic Tangent Model
In 2006, Kwok et al proposed the hyperbolic tangent model using hyperbolic tangent function initially. This model mainly consists of viscous damping unit, spring unit and hysteretic unit in parallel, and its structure is shown in figure 1. The hyperbolic tangent model not only can better describe the hysteretic characteristics of MR damper, but also can be provided with the advantages such as less identification parameters and simple mathematical expressions. The specific mathematical expressions of hyperbolic tangent model are as follows [10]:

\[
F = \alpha \tanh(\beta \dot{x} + \delta \text{sign}(x)) + c \dot{x} + kx + f_0
\]

Where, \(F\) denotes the output damping force of MR damper; \(\alpha\) denotes the proportional factor of hysteresis loop; \(\beta\) denotes the slope of hysteresis loop; \(\dot{x}\) denotes the velocity of piston rod with MR damper; \(\delta\) denotes the hysteresis loop width coefficient; \(x\) denotes the displacement of piston rod with MR damper; \(c\) denotes the viscous damping coefficient; \(k\) denotes the stiffness coefficient; \(f_0\) denotes the offset damping force.

Thus, there are six unknown parameters, i.e., \(\alpha, \beta, \delta, c, k\) and \(f_0\) in the hyperbolic tangent model of MR damper, which need to be identified optimally.

3. Mechanical Properties Test
Figure 2 shows the specific physical picture of MR damper designed and manufactured through our research group, and its working mode belongs to shear-valve type. Figure 3 shows the mechanical properties test system with MR damper, which mainly composes of INSTRON tensile machine, WYK-301 DC regulated power supply, controller monitor and MR damper. During the experiment, the MR damper is fixed on the INSTRON tensile machine with fixture, and the excitation is utilized the sinusoidal signals with amplitudes of 5 mm, 7.5 mm and 10mm, and the frequency of 0.5 Hz, 1 Hz, 1.5 Hz and 2 Hz, respectively. The MR damper is supplied by WYK-301 DC regulated power supply,
the input current ranged from 0 to 1.5 A, and the current interval is 0.3 A. In addition, the controller monitor is used to collect the output damping force, displacement and velocity data under different excitations and input current conditions.

**Figure 2.** The physical picture of shear-valve MR damper.

**Figure 3.** The mechanical properties test system for MR damper.

The data collected by the controller monitor are processed to obtain the mechanical properties curves with MR damper. Figure 3 shows the $f-x$ and $f-v$ curves with the amplitude of 10 mm and the frequency of 1 Hz under different input current, respectively. As can be seen from the figure 3, the $f-x$ curve approximates rectangular, and the output damping force of the MR damper increases with the enlargement of the applied input current correspondingly under the same excitation signal. Besides, the $f-v$ curve approximates symmetric nonlinear hyperbola, and the output damping force with MR damper is not equal to zero when the operating velocity of the piston rod is zero, which represents that this curve can describe the strong double viscous loop characteristics of MR damper.

**Figure 4.** The experimental results for the damping force-displacement curve.

**Figure 5.** The experimental results for the damping force-velocity curve.

### 4. Parameter Identification

Particle swarm optimization is a random search algorithm that it is developed to simulate the foraging behaviour of birds based on the group assistance. This method has the advantages of fast convergence, high precision and easy implementation, and it is similar to the genetic algorithm. The system is initialized as a group of random solutions, simultaneously, the fitness function is used as the criterion to seek the optimal solution through iterating in turn.

The invocation format of the particle swarm optimization algorithm in MATLAB software is as follows:

\[
[x_m,f_v] = \text{POS(@fitness},N,c_1,c_2,w,M,D) \tag{2}
\]

Where, $x_m$ represents the independent variable value when the fitness function is the minimum; $f_v$ represents the minimum value of fitness function; $N$ represents the particle number, $N=40$; $c_1$ represents the local learning factor, $c_1=2$; $c_2$ represents the global learning factor, $c_2=2$; $w$ represents
the inertia weight, \( w = 0.5 \); \( M \) represents the maximum iteration number, \( M = 1000 \); \( D \) represents the independent variable number, \( D = 6 \); fitness denotes the fitness function, which is set as follows:

\[
fitness = \sum_{i=1}^{k} \left( F_{i}^{exp} - F_{i}^{sim} \right)^2
\]

Where, \( k \) denotes the number of test data points; \( F_{i}^{exp} \) denotes the damping force obtained via the experiment; \( F_{i}^{sim} \) denotes the damping force obtained via the simulation.

Based on the above analysis, the identification program of particle swarm optimization algorithm has written with the help of MATLAB software and real number coding, and the experiment data that the amplitude is 10 mm, the frequency is 1 Hz, and the current ranges from 0 to 1.5 A are collected by the controller monitor to identify the six unknown parameters in the hyperbolic tangent model with MR damper. The parameter identification results are shown in table 1.

| Current | Parameter | \( a \) | \( \beta \) | \( \delta \) | \( c \) | \( k \) | \( f_0 \) |
|---------|-----------|--------|--------|--------|------|------|------|
| 0A      |           | 217.826| 2.674  | 1.221  | 5.379| 15.026| -3.446|
| 0.3A    |           | 342.869| 2.433  | 1.089  | 15.089| 18.916| -2.708|
| 0.6A    |           | 464.626| 2.346  | 1.042  | 23.599| 23.362| -2.362|
| 0.9A    |           | 582.746| 2.316  | 1.026  | 30.978| 28.365| -2.408|
| 1.2A    |           | 697.136| 2.312  | 1.024  | 37.245| 33.926| -2.847|
| 1.5A    |           | 807.787| 2.324  | 1.031  | 42.399| 40.045| -3.678|

By utilizing the curve fitting toolbox, the specific mathematical function relationship between the six parameters and input current can be fitted.

\[
\begin{align*}
\alpha &= -20.12I^2 + 423.6I + 217.7 \\
\beta &= 0.3169I^2 - 0.6794I + 2.649 \\
\delta &= 0.1736I^2 - 0.371I + 1.207 \\
c &= -6.3I^2 + 34.1I + 5.395 \\
k &= 3.096I^2 + 12.03I + 15.03 \\
f_0 &= -2.18I^2 + 3.115I - 3.446
\end{align*}
\]  

![Hyperbolic tangent simulation model established in Simulink toolbox.](image)

Applying the Simulink simulation toolbox, the hyperbolic tangent simulation model is established and shown in figure 6. Meanwhile, the sinusoidal signal with amplitude of 10 mm and frequency of 1 Hz has chosen to simulate the excitation of the INSTRON tensile machine, so the simulation data such as the output damping force, displacement and velocity under different input current conditions can be calculated and obtained.
Figure 7 shows the comparison of test and simulation results for the damping force-displacement curve. Figure 8 shows the comparison of test and simulation results for the damping force-velocity curve. It can be seen that the simulation data obtained through utilizing hyperbolic tangent simulation model is in good agreement with the test data under different current, and it can describe the viscous characteristics of MR damper greatly. Hence, the feasibility and accuracy of parameter identification of hyperbolic tangent model by particle swarm optimization algorithm are verified.

5. The Verification of Simulation Model
Due to the unknown parameters in the hyperbolic tangent model of MR damper are only identified by the test data under sinusoidal signal with amplitude of 10 mm and frequency of 1 Hz.
In order to further verify whether the hyperbolic tangent simulation model identified through particle swarm optimization algorithm can absolutely describe the viscous characteristics of MR damper, it is vital to utilize the experiment and simulation data under different input current and other excitations for the comparative analysis, so as to demonstrate the generality and accuracy of hyperbolic tangent model. The test data of sinusoidal signal with amplitude of 5 mm and 7.5 mm, frequency of 0.5 Hz and 1 Hz are compared with the corresponding numerical simulation data. The comparison curves are shown in figure 9 to 12, respectively.

As can be seen from figure 9 to 12, the hyperbolic tangent model identified by particle swarm optimization algorithm can exactly describe the viscous characteristics of MR damper under different input current and sinusoidal signals with other amplitude and frequency, moreover, it is also verified the universality and accuracy of this model.

6. Conclusion
According to the test data collected by the mechanical properties test system, the unknown parameters of the hyperbolic tangent model with MR damper are identified through particle swarm optimization algorithm. The functional relationship between six parameters and input current can be fitted from the curve fitting toolbox, and the hyperbolic tangent simulation model for MR damper can be established and designed via utilizing the Simulink toolbox. Furthermore, the simulation data obtained through selecting sinusoidal signals with other amplitudes and frequencies and different input current are in good agreement with the corresponding test data, and this model can greatly represent the nonlinear hysteretic characteristics of MR damper, which lays a foundation for further investigate on the semi-active control for MR damper.

Acknowledgments
This work was supported by Key R & D Project of Jiangxi Province (No. 20192BBEL50012).

References
[1] Dutta S, Chakraborty G. (2014) Performance analysis of nonlinear vibration isolator with magneto-rheological damper. Journal of Sound and Vibration. 333(20): 5097–5114.
[2] Uz M E, Hadi N S. (2014) Optimization design of semi-active control of adjacent buildings connected by MR damper based on integrated fuzzy logic and multi-objective genetic algorithm. Engineering Structures. 69: 135–148.
[3] Peng G R, Li W H, Du H, et al. (2014) Modelling and identifying the parameters of a magneto-rheological damper with a force-lag phenomenon. Applied Mathematical Modelling. 38(15-16): 3736–3773.
[4] Li Z W, Li Z J. (2012) Status of researching on dynamical models of MR damper. Machine Building and Automation. 41(1): 142–145.
[5] Zhang J Q, Peng H, Sun Y Q, et al. (2016) Review on mechanical modelling of magneto-rheological damper. Journal of Academy of Armored Force Engineering. 30(6): 31–38.
[6] Liu Y Q, Yang S P, Liao Y Y. (2018) A new method of parameters identification for magneto-rheological damper model. Journal of Mechanical Engineering. 54(6): 62–68.
[7] Xiao Z R, Zhang Z W. (2019) Application of UKF algorithm in parameter identification of magneto-rheological damper. Bulletin of Science and Technology. 35(3): 70–74.
[8] Hu G L, Liu Q J, Ding R Q, et al. (2017) Vibration control of semi-active suspension system with magneto-rheological damper based on hyperbolic tangent model. Advances in Mechanical Engineering. 9(5): 1–15.
[9] Hu H G, Hu M, Chen Y H, et al. (2017) Parameter identification for hyperbolic tangent model of magneto-rheological damper. Ship Engineering. 39(5): 31–34.
[10] Kwok N, Ha Q, Nguyen T, et al. (2006) A novel hysteretic model for magneto-rheological fluid damper and parameter identification using particle swarm optimization. Sensors and Actuators A Physical. 132(2): 441–451.