A novel MR device with variable stiffness and damping capability

Shiyu Zhao[1], Huaxia Deng[1]*, Jin Zhang[1], Shuaishuai Sun[1,2], Weihua Li[2]*, Laijun Zhou[1]

[1]School of Instrument Science and Opto-electronics Engineering, HeFei University of Technology, Hefei, China.
[2]School of Mechanical, Materials & Mechatronic Engineering, University of Wollongong, Wollongong, Australia

*Corresponding author: hxdeng@hfut.edu.cn and weihuali@uow.edu.au

Abstract

- This paper proposes a novel device based on the Magnetorheological (MR) fluid which has the capability to change stiffness and damping under control. MR fluid is a type of smart material whose properties could be controlled by the external magnetic field. Most of MR devices are MR dampers, which normally are used as variable damping devices. The presented device consists of two hydro-cylinder-spring structures and one MR valve linking these two structures. The rheological characteristics of MR fluid in the fluid flow channels of MR valve are controlled by the strength of magnetic fields, which directly affect the link conditions. The equivalent stiffness and damping coefficients of the device thus varies with the rheological characteristics of MR fluid simultaneously. A mathematical model is established to describe the properties of the proposed device based on the Bouc-wen model. The mathematical model the simulation results indicate that the proposed device can control both the stiffness and damping which has potential to be applied for restrain vibration mitigation efficiently.

Keywords: Variable stiffness and damping, MR damper, effective stiffness and damping coefficients

Introduction

In the engineering circle or daily life, there exists a great deal of vibration and most of them are harmful which may result in financial loss or endanger lives. Numerous researchers from various fields investigate the methods to reducing and controlling the vibration. The traditional passive vibration control method [1] is widely used, but the effect of controlling vibration is not well at certain working conditions especially in the changing conditions. Because of the fixed stiffness and damping, the passive control devices normally are designed for a certain stable working condition. This kind of vibration control methods can not adjust for the changing conditions, which may even induce the vibration worse at some conditions. The active vibration control methods are proposed for providing extra energy to mitigate the vibration. This method needs more power and the control strategies of the control system are complicated, the requirement of active vibration control methods limits their applications in practice. Semi-active vibration control method is a method which balance the advantages of the two methods mentioned above. By changing the parameters itself with less energy to adjust the changing conditions, the semi-active control method achieve improved performances over a wide operating range and has long been receiving people's attention.

The damper based on magnetorheological fluids (MRF) is a typical semi-active device. MR fluid is one kind of smart materials, which is similar to the electrorheological (ER) fluid. Because of many merits, such as quick response, easy control, low energy, changing reversely etc., the MR damper become one of the most potential vibration control device. The rheological properties of MRF is highly related to the external magnetic field induced by control current and the parameters of MR damper can be easier changed by controlling the current[2]. Researchers do a lot of study on the theory and application of the MR device. In order to analyze the ER damping mechanism, Stanway et al proposed a Bingham model [3]. Due to similar behavior [4], the Bingham model is also widely used to describe the MR damper. Spencer build a model containing a Bouc-Wen hysteretic operator and this model can describe the characteristics of MRF very well, especially for the hysteretic performance[5]. Xu proposed the temperature phenomenological model with mass element [6] and do some research on house anti-seismic capability by using MR damper. Laura M. Jansen studied various algorithms used to control multiple MR dampers and analyze the performance of the algorithms by making comparisons [7]. Lord Corporation did a lot of researches on development and application of MR damper and their products were used in the cable-stayed Dongting Lake Bridge to reducing the rain-wind induced vibration. Seung-Bok Choi applied the MR damper to a full-car model and derived the governing equations of motions based on the skyhook controller[8]. The result of the experiment indicated that MR damper can improve the security and comfort. Beside, MR damper is widely used in the aerospace, military machine, electrical appliances, etc. The simple MR device is MR damper and MR damper only can change the damping. Deng developed a series of adaptive tuned vibration absorbers[9-11] based on MR elastomer(MRE) which has changeable and controllable stiffness. It will be better for restraining vibration if the damping and stiffness are both variable. W.H. Li proposed a MR bladder can change the damping and stiffness simultaneously [12]. The model is composed by two air springs and the two springs were connected by a MR valve. The equivalent stiffness of the device is controlled by MR valve. However, the device is very large and requires extra equipment to provide air pressure. Liu propose a model which may have variable stiffness and damping capability [13-14]. The model is consisted of two elements in series and every element contain a variable damping and a spring in parallel [15].

The purpose of this paper is to present a novel vibration control device with controllable damping and stiffness. This device is based on the MRF and it is consisted of two MR dampers in series. A model is build to describe the device and simulated by Simulink. In the model, Bouc-Wen model is used to describe the characteristics of the MR damper. The force versus displacement figures and force versus velocity figures are got through simulation and used to discuss the parameters on the capability of changing equivalent damping and stiffness.

Model of the MR damper

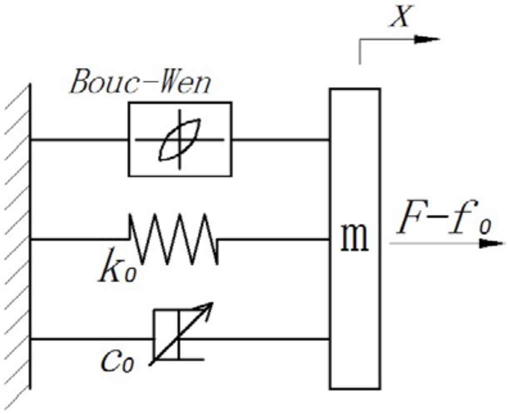


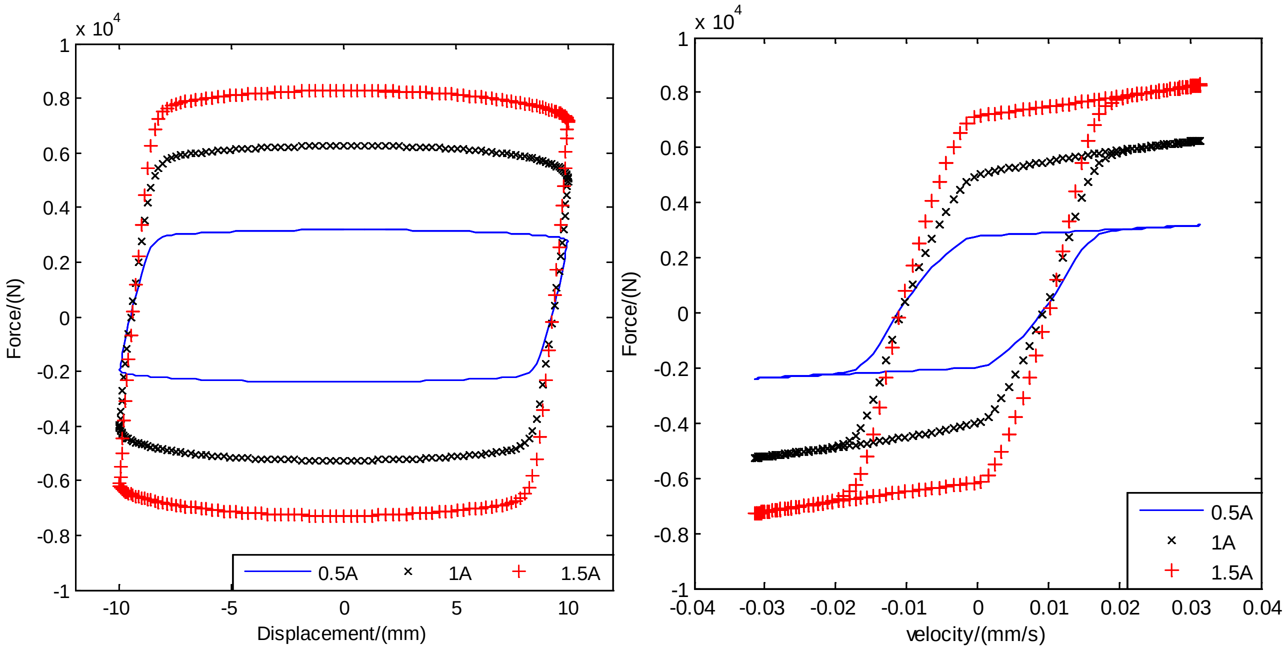
Fig.1 Bouc–Wen model

MR damper is based on the MRF and the characteristics of MR damper is complex. Bouc-Wen model is one of the most widely used models to describe the characteristics of MR damper. As shown in Fig.1, the Bouc-Wen model is consisted by three part: a spring with constant stiffness, a damper related to the magnetic field and a Bouc-Wen winding [2] which can represent the hysteresis. The equation of Bouc-Wen are as follows：

$$F - f_0 = \alpha z + k_0 x + c_0\,\dot{x} + m\,\ddot{x} \tag{1}$$

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

The characteristic curve of the MR damper is obtained through the Eq.(1) to Eq.(2) shown in Fig.2.



(a) (b)

Fig.2 Simulinked damping forces of the MR damper under a 1.00 Hz sinusoidal excitation with amplitude of 10.00 mm for three current levels: (a)the force versus displacement, (c) the force versus velocity

Fig.2.(a) shows the relation between force and displacement and x-axis and y-axis are the force and displacement respectively. The area of the loop showed in Fig.2.(a) represents work of the damper force which indicate the damping and the ratio of the curve reflect the stiffness. Fig.2.(b) shows the relation between force and displacement and x-axis and y-axis are the force and velocity respectively. The ratio of the curve reflects the damping. Through these two figures, the damping is increased with the increasing current and the stiffness neatly has no change.

Model of the novel variable stiffness and damping device

A model of the novel vibration control device is shown in Fig.3.(a) and the equivalent model is shown in Fig.3.(b). The model is composed of two MR dampers in series. The damping and hysteretic loop is changed with the variable current and the stiffness is fixed. The initial values of all the parameters is fixed when the MR damper is designed. The model of the device is equivalent to the model shown in Fig.3.(b). and Eq.(1) is expressed as Eq.(3):

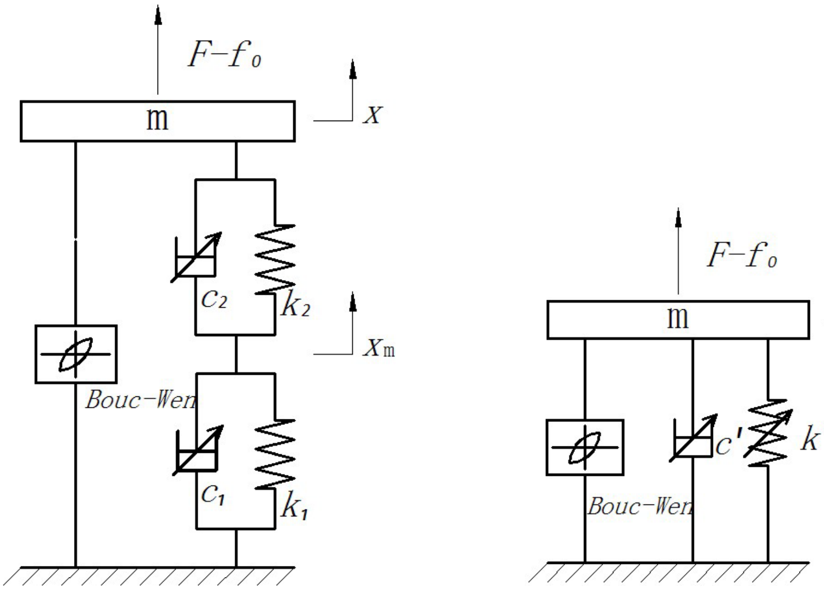
$$F - f_0 = \alpha z + k' x + c'\,\dot{x} + m\,\ddot{x} \tag{3}$$

The equivalent damping c' and the equivalent stiffness k' are as followings [11]

$$k^{'}=\frac{(k_1k_2-c_1c_2\omega^2)(k_1+k_2)+(k_1c_2+k_2c_1)(c_1+c_2)\omega^2}{(k_1+k_2)^2-(c_1-c_2)^2\omega^2}, \tag{4}$$

$$c^{'}=\frac{(k_1c_2+k_2c_1)(k_1+k_2)-(k_1k_2-c_1c_2\omega^2)(c_1+c_2)}{(k_1+k_2)^2-(c_1-c_2)^2\omega^2}, \tag{5}$$

Eq.(1) and Eq.(2) show that k' is related with the parameters k_1, k_2, c_1, c_2, ω. k_1, k_2 are determined by the design of MR damper. c_1, c_2 are determined by the magnetic induction intensity generated by controllable current. ω is determined by the input excitation. The stiffness and damping of the device can be controlled by controlling these parameters.



(a) **(b)**

Fig.3 The structure of the vibration control system
(a)Original model and (b) Equivalent model

Discussion of the characteristics of the device

As shown in the above analysis, the equivalent damping and stiffness of the proposed structure has the relationship with the parameters. In order to analyze the influence induced by the changing parameters on the equivalent stiffness and damping of system. The force versus displacement diagrams are showed in the Fig.4 and Fig.6. The force versus velocity diagrams are showed in the Fig.5 and Fig.7. In each figure, there are six subplots and the stiffness ratio of two springs is different. In each subplot, there are three curves corresponding three different control currents: 0.5A, 1A, 1.5A. Comparing the same curve in different subplots of one figure can be used to analysis influence of the stiffness ratio between two springs. Comparing the different subplots in one figure can be used to analysis influence of the changing of the ratio between two different springs to the change of the damping. Comparing the two figures can be used to analysis the influence of the different MR damper in the control current. In figures, the unit of k is $N\cdot m^{-1}$ and the unit of c is $N\cdot s\cdot m^{-1}$.

Fig.4 shows the relation between force and displacement in six different stiffness ratios. In each subplot, the control currents of MR damper 1 are varied and the currents of MR damper 2 are fixed.

In each subplot of Fig.4, the area of loop under the curve is varied with the change of current, but the changes of slope of the curves are inconspicuously. When the current achieved at 1.5 A, a strong nonlinearity behavior is encountered for $\boldsymbol{k}_1$ at 40000 N/m and 6000 N/m. It can be conclude that the damping of system is varied with the increasing current and the stiffness of system neatly has no change.

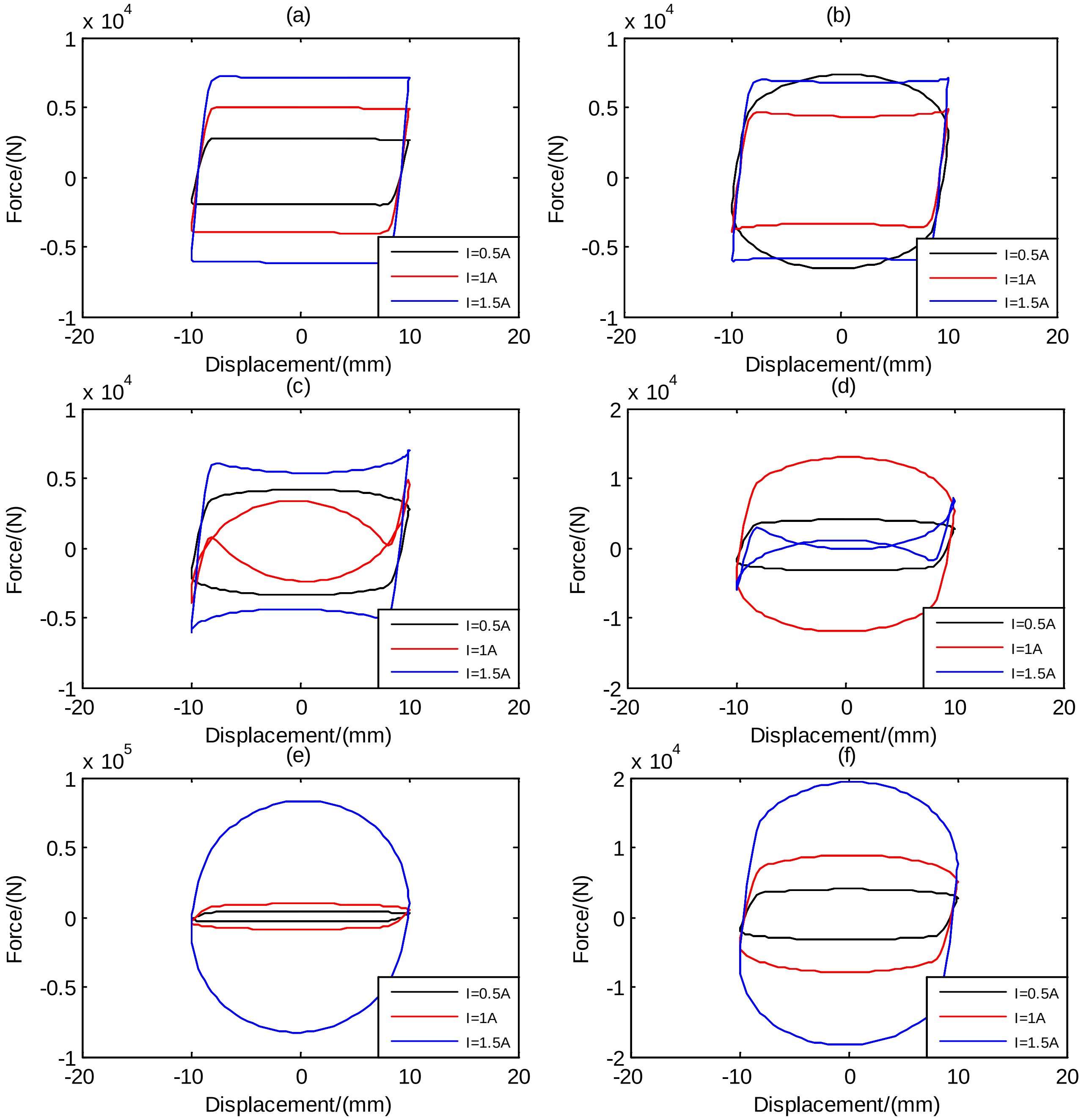


Fig.4 damping forces versus displacement with varying current on MR damper 1 in different parameter: (a) k_1=2500N/m, k_2=2500N/m, (b) k_1=20000N/m, k_2=2500N/m, (c) k_1=40000N/m, k_2=2500N/m, (d) k_1=60000N/m, k_2=2500N/m, (e) k_1=80000N/m, k_2=2500N/m, (f) k_1=100000N/m, k_2=2500N/m

Fig.5 shows the relation between force and velocity in six different stiffness ratios and the parameters are in the same with Fig.4. In each subplot, the slope of curves are varied which also indicate that the damping is varied with the increasing current.

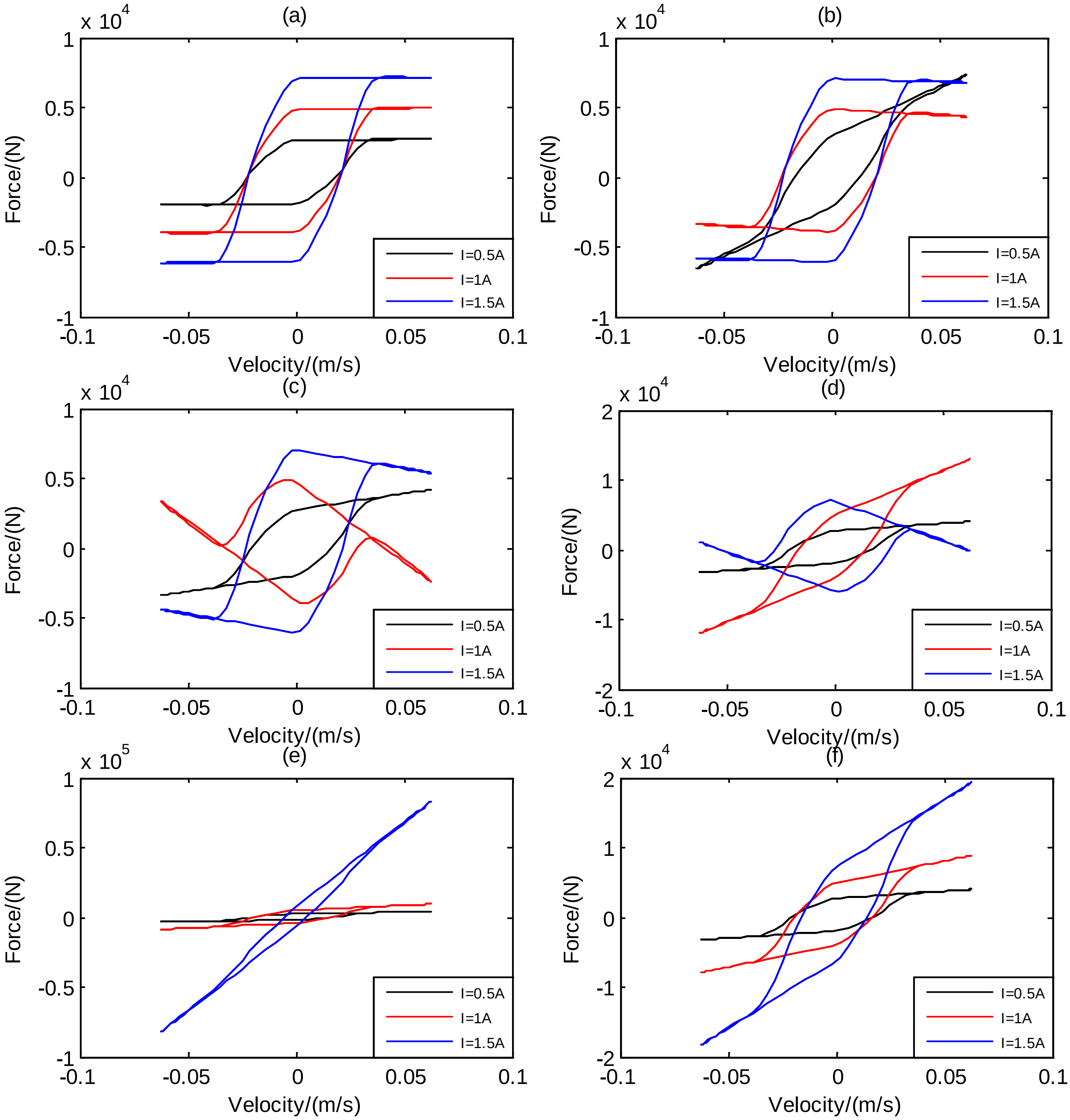


Fig.5 Simulinked damping forces versus velocity with varying current on MR damper1 in different parameter: (a) k_1=2500N/m, k_2=2500N/m, (b) k_1=20000N/m, k_2=2500N/m, (c) k_1=40000N/m, k_2=2500N/m, (d) k_1=60000N/m, k_2=2500N/m, (e) k_1=80000N/m, k_2=2500N/m, (d) k_1=100000N/m, k_2=2500N/m

Fig.6 shows in the same with Fig.4, the difference is that the control currents of MR damper1 is fixed and the current of MR damper2 is varied. The area of loop under the curve is varied with the increasing current which indicate that the damping is varied and the change of slope of the curves is inconspicuously which indicated that the stiffness neatly have no change. The area of loop under the curve and the slope of the curves both are varied which indicated that the stiffness and damping both change dramatically with the increasing current. The stiffness changing capability is largely influenced by the parameters especially for the ratio of two spring elements. At last, the stiffness will maintain a constant with increasing current when the current is larger than a limited value.

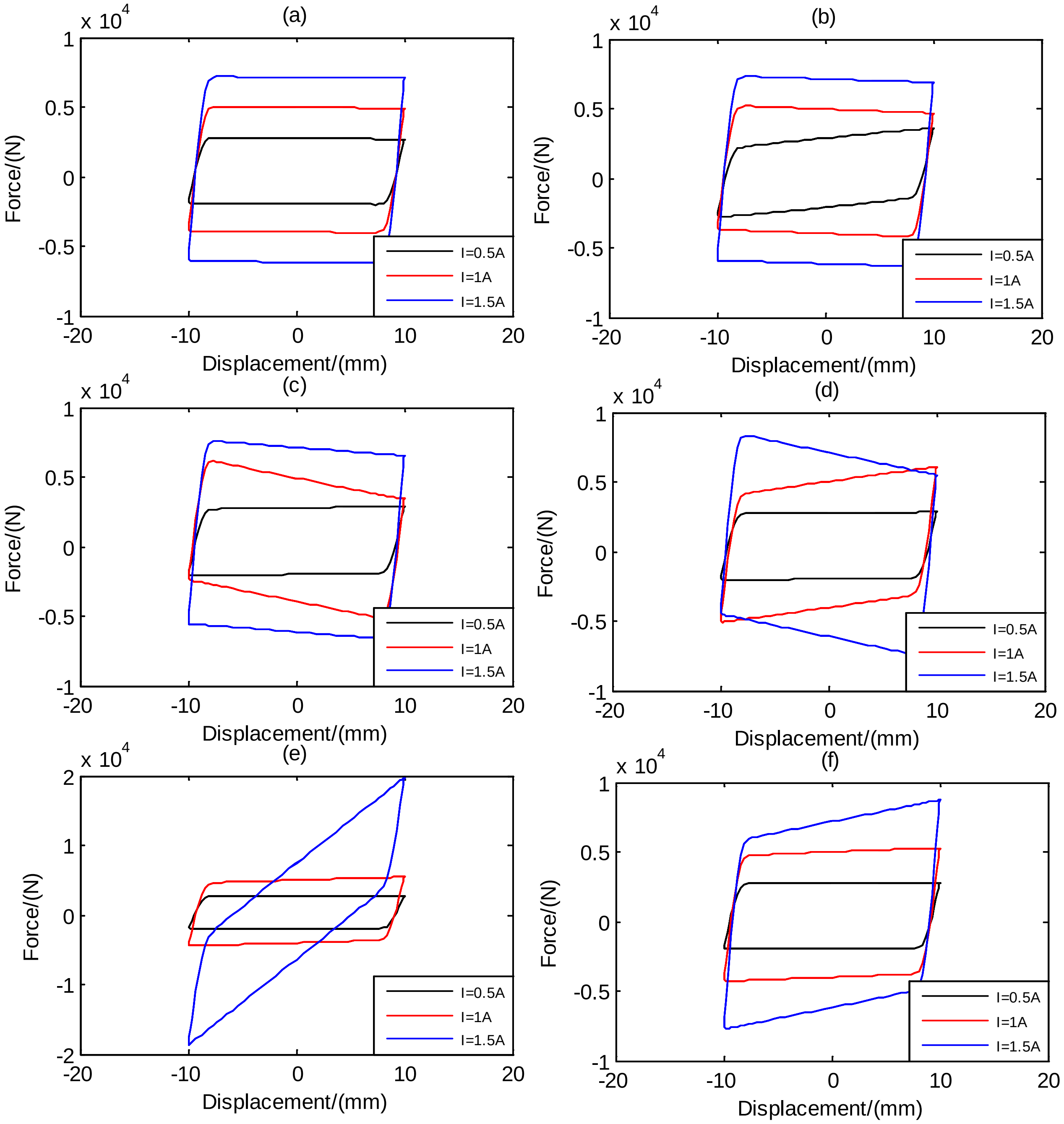


Fig.6 damping forces versus displacement with varying current on MR damper2 in different parameter: (a) k_1=2500N/m, k_2=2500N/m, (b) k_1=20000N/m, k_2=2500N/m, (c) k_1=40000N/m, k_2=2500N/m, (d) k_1=60000N/m, k_2=2500N/m, (e) k_1=80000N/m, k_2=2500N/m, (f) k_1=100000N/m, k_2=2500N/m

Fig.7 shows in the same with Fig.5, the difference is that the control currents of MR damper1 is fixed and the current of MR damper2 is varied. Comparing among the subplots of Fig.5, it clearly shows that the area of loop changed with the increasing current which indicate that the damping is varied. Comparing the four figures, the MR damper2 has more influence on the change of the stiffness and damping of the system and these two equivalent damping and stiffness will be increased with the increase of the stiffness ratio of two spring elements.

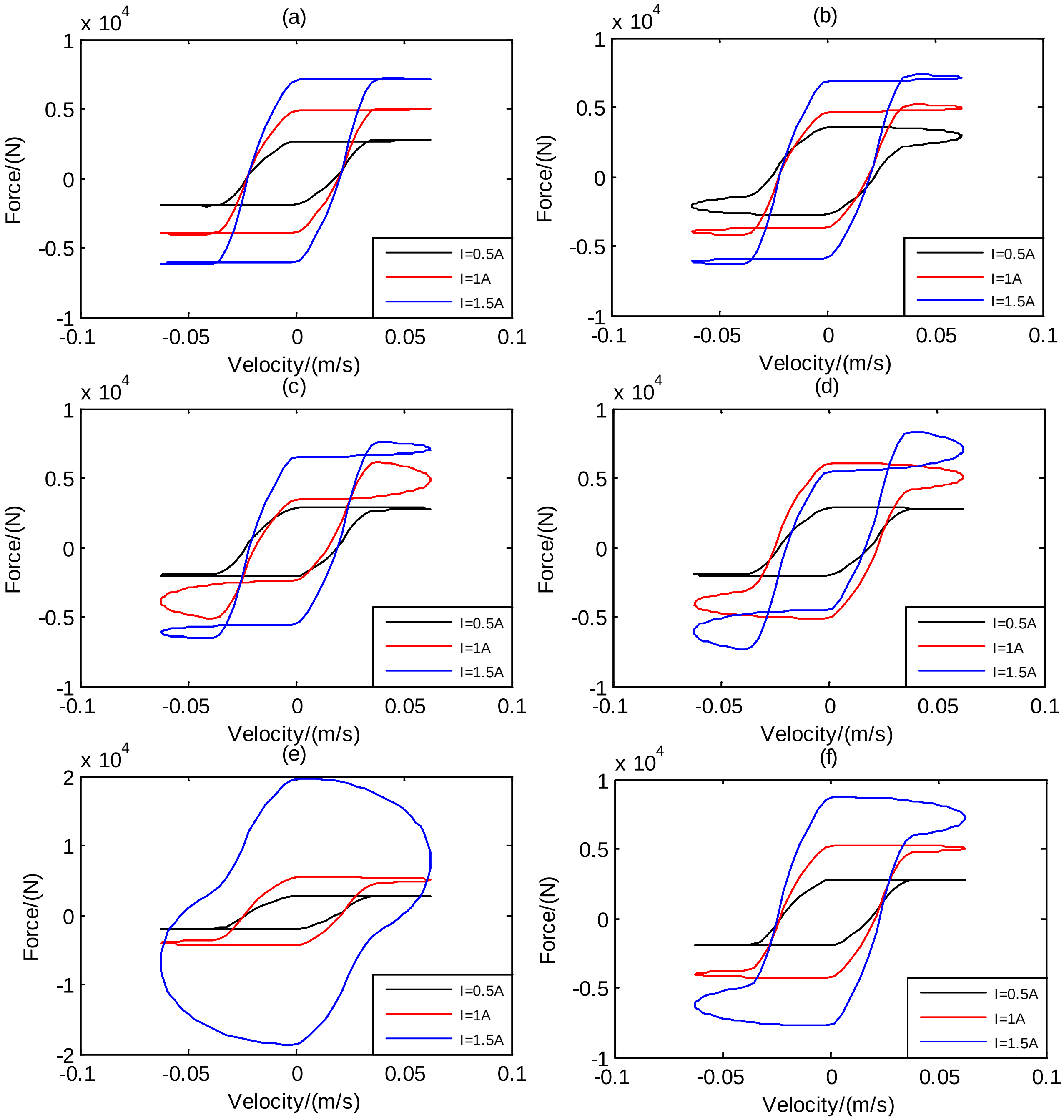


Fig.7 damping forces versus velocity with varying current on MR damper2 in different parameter: (a) k_1=2500N/m, k_2=2500N/m, (b) k_1=20000N/m, k_2=2500N/m, (c) k_1=40000N/m, k_2=2500N/m, (d) k_1=60000N/m, k_2=2500N/m, (e) k_1=80000N/m, k_2=2500N/m, (f) k_1=100000N/m, k_2=2500N/m

Conclusion

In this paper, a novel vibration device with variable stiffness and damping is proposed on the basis of MR fluids. A Bouc-Wen model is used to describe the characteristics of MR device. An equivalent model is built to analyze the equivalent damping and stiffness of the system. Through analyzing the characteristics of MR damper, it is clear that simply MR damper has no capability of changing stiffness. Comparing the original model with the equivalent model, it will be found that the stiffness and damping of the system is related with stiffness and damping of MR damper constituting the device. The results of simulation show that the stiffness and damping of the device both are varied with the variable current simultaneously at certain parameters.

Acknowledgement

The authors would like to appreciate for the supports of 111 project (No. B12019), National Natural Science Foundation of China (No.51305121, No. 51205100, No. 51328502), Higher Specialized Research Fund for the Doctoral Program (No. 20120111120020) and the Fundamental Research Funds for the Central Universities.

References

[1] G.Yang, B.F. Spencer Jr., J.D. Carlson, M.K. Sain. (2002), Large-scale MR fluid dampers: modeling and dynamic performance considerations. Engineering Structures, 24, 309–323.

[2] D H Wang and W H Liao. (2011), Magnetorheological fluid dampers: a review of parametric modelling. Smart Mater. Struct, 20, 1-34.

[3] R Stanway, J L Sproston and N G.Stevens (1987), Non-linear modelling of an electro-rheological vibration damper. J. Electrostat, 20, 167–84.

[4] N D Sims, D J Peel, R Stanway, A R Jonhson, and W A Bullough, (2000) The ER long-stroke damper: a new modelling technique with experimental validation. J Sound Vib.,229(2), 207–227

[5] B F Spencer, S J Dyke, M K Sain and J D Carlson (1997), Phenomenological model for magnetorheological dampers. J. Eng. Mech. ASCE, 123, 230–8.

[6] Z D Xu, A Q Li, W R Cheng, J H Ye (2005), A temperature phenomenological model with mass element of MR damper. Engineering Mechanics, 22(2), 144-145.

[7] M J Laura and J D Shirley (2000), Semiactive control strategies for MR dampers: comparative study. J. Eng. Mech, 126, 795-803.

[8] S B Choi, H S Lee and R H Sung, et al. (2000), Control and Response Characteristics of a Magneto-Rheological Fluid Damper for Passenger Vehicles. SPIE, 11, 80-87,

[9] H X Deng , X L Gong. (2007), Adaptive Tuned Vibration Absorber based on Magnetorheological Elastomer. Journal of Intelligent Material Systems and Structures, 18, 1205-1210.

[10] H X Deng , X L Gong. (2008), Application of magnetorheological elastomer to vibration absorber. Communications in Nonlinear Science and Numerical Simulation, 13, 1938 – 1947.

[11] H X Deng , X L Gong and L H Wang. (2006), Development of an adaptive tuned vibration absorber with magnetorheological elastomer. Smart Mater. Struct. 15, 111–116

[12] W H Li, X Y Wang, X Z Zhang and Y Zhou. (2009), Development and analysis of a variable stiffness damper using an MR bladder. Smart Mater. Struct. 18, 1–8..

[13] Y Q Liu, Hiroshi Matsuhisa, Hideo Utsuno, Jeong Gyu Park. (2005), Vibration isolation by a variable stiffness and damping system. JSME International Journal, 48(2), 1036-1041.

[14] Y Q Liu, Hiroshi Matsuhisa, Hideo Utsuno, (2008), Semi-active vibration isolation system with variable stiffness and damping control. Journal of sound and vibration, 313, 16-28..

[15] M Ismail, F Ikhouane, J Rodellar. (2009), The Hysteresis Bouc-Wen Model, a Survey. Arch Comput Methods Eng, 16: 161–188.