An Experimental Design of Bypass Magneto-Rheological (MR) damper

MM Rashid, Mohammad Abdul Aziz*, Md. Raisuddin Khan
International Islamic University Malaysia, Jalan Gombak, 53100 Kuala Lumpur, Selangor, Malaysia

E-mail*: abdul.aziz07me@gmail.com

Abstract. The magnetorheological (MR) fluid bypass damper fluid flow through a bypass by utilizing an external channel which allows the controllability of MR fluid in the channel. The Bypass MR damper (BMRD) contains a rectangular bypass flow channel, current controlled movable piston shaft arrangement and MR fluid. The static piston coil case is winding by a coil which is used inside the piston head arrangement. The current controlled coil case provides a magnetic flux through the BMRD cylinder for controllability. The high strength of alloy steel materials are used for making piston shaft which allows magnetic flux propagation throughout the BMRD cylinder. Using the above design materials, a Bypass MR damper is designed and tested. An excitation of current is applied during the experiment which characterizes the BMRD controllability. It is shown that the BMRD with external flow channel allows a high controllable damping force using an excitation current. The experimental result of damping force-displacement characteristics with current excitation and without current excitation are compared in this research. The BMRD model is validated by the experimental result at various frequencies and applied excitation current.

1. Introduction

Magnetorheological (MR) dampers is a smart device for controlling vibration using electro-magnetic field. MR damper contains smart fluids (MR fluid) that has a controllability for semi active passive system and required less power supply. The properties of MR damper can be changed by changing applied current[1]. MR damper have been chosen over a decade for vehicle suspension system[2-4], helicopters seat[5], civil structure base isolation [6-8], and railway transport[9, 10]. Semi-active MR damper is especially applicable for unpredictable motion conditions and capable large payload condition. In the MR damper, MR fluid has an ability to create controllable damping force and this controllable force can be creating by applying electromagnetic flux distribution through the whole MR damper body[11]. The modern design method of MR damper valve is familiar at all and bypass valve design requires an exact design configuration. During the experimental operation, the bypass valve is configured with accurate flow mode operation. Jin-Hyeong Yoo has proposed meso-scale valve of MR damper which produces higher ground relying yield stress of MR fluid. Whereas, MR valves are
controlled by analyzing axial flow rate and pressure drop in the valve[12, 13]. Xian-Xu Bai developed a series of inner, annular, bidirectional and radial bypass system. In the inner dispersion system offers maximum dynamic range to the minimum off stroke damping force range[14]. In the twin tube inner dispersion system added MR damper hydro-mechanical higher damping range and lower stroking load [15].

Other study analyzes an annular inner bypass with higher dampening force and lower field off-state stroking load. Bingham-plastic materials models removing minor losses of MR damper velocity profile[14]. The basic advantages of his works to optimize the MR damper performance and two concentric tubes, bobbin piston arrangement are used for MR fluid flow as well as shock and vibration control[16]. An annular radial duct process for series flow of MR fluid in the gap which increases velocity under controllable condition [17]. However, Mao et al. evaluated single ended MR Bifold valve for higher dynamic capacity which includes larger piston speed for damping operation. His proposed model demonstrates two MR damper valve model and firstly, piston head inside valve and secondly, bifold MR valve at MR damper both end[18]. Ryan m. robinson et al. and eugene cook et al. proposed porous media (variation of porosity and tortuosity) dispersion system of MR damper. In porous media ( compacted spheres and cylinder beds ) valve tests includes maximum force, damping coefficient, hydraulic piston cylinder cross-sectional area and yield stress production by varying magnetic field efficiency [19, 20].

In this research an experimental evaluation of Bypass MR damper with different stroke modes are analysed and it also illustrates the design technique of BMRD shear mode operation.

2. Experimental setup of Bypass MR damper

Bypass MR damper test components consists of bypass MR damper, universal testing machine (UTM) called Shimadzu. UTM staircase steps excitation analyze the bypass MR damper. However, for different types of test experiments compressor, grippers and upper and lower pulley are attach during the experiments. In the top and bottom of bypass MR damper, two rectangular aluminum plate have attach during the experiments. This is done due to higher pressure and tensile strength. Hydraulic actuator moves due to movable head in which TRAPEZIUM software is used to generate signal. In the lower head, a load cell is connected for measuring applied force to the bypass damper. A linear variable differential transformer (LVDT) sensor is used to measure the displacement of the BMRD piston. A DC voltage source is used to supply for controlling current in the damper inner coil and piston coils. Moreover, force-displacement, force-time, and stress-strain, time displacement graphs are produced during the experiment. In addition to that Stroke rate, stroke length and input currents is varied due to characterization of MR damper and performance. The total length of stroke from 10mm to 20mm were done during the experiment, which is shown in Figure 1. In figure 1 flow chart presents the experimental setup.
3. Bypass MR Damper Damping Constant Calculation for Shear Mode Operation

In figure 2 presents the MR damper piston cylinder arrangement in shear mode operation.

![Diagram of MR damper piston cylinder arrangement in shear mode](image)

**Figure 2.** MR damper piston cylinder arrangement in shear mode[29].

The viscous force for this annular damper [29]
\[ F = \pi D l \tau = \pi D l \frac{dx}{dy} dy \]  

(1)

The expression of shear stress
\[ \tau = -\mu \frac{dv}{dy} \]  

(2)

The negative sign is expressed for decreasing velocity gradient
\[ F = \pi D l \mu \frac{d^2v}{dy^2} \]  

(3)

The pressure difference causes due to force applied on the piston and calculated by the following equation
\[ p = \frac{p}{\pi D^2} = \frac{4p}{\pi D^2} \]  

(4)

Or
\[ \frac{d^2v}{dy^2} = \frac{4p}{\pi D^2} \]  

(5)

After two times integration using boundary condition \( v = -v_0 \) at \( y = 0 \) and \( v = 0 \) at \( y = d \), the equation becomes
\[ v = \frac{2p}{\pi D^2 l} (yd - y^2) - v_0(1 - \frac{y}{d}) \]  

(6)

The flow rate through the element after integration the equation becomes and the limits are \( y = 0, y = d \)
\[ Q = \int_0^d v \pi D dy = \pi D \left[ \frac{2pd^3}{6\pi D^2 l \mu} - \frac{1}{2} v_0d \right] \]  

(7)

The velocity of the piston will be equal to the rate of flow divided by the piston area
\[ v_0 = \frac{Q}{\pi/4 D^2} \]  

(8)

\[ Q\pi D \left[ \frac{2pd^3}{6\pi D^2 l \mu} - \frac{1}{2} v_0d \right] = \pi/4 D^2 \]  

(9)

From equation 1 & 2
\[ p = \left[ \frac{3\pi D^3 l \left( 1 + \frac{2d}{D} \right)}{4d^3} \right] \mu v_0 \]  

(10)

If the \( p = cv_0 \), then the damping constant
\[ c = \mu \left[ \frac{3\pi D^3 l \left( 1 + \frac{2d}{D} \right)}{4d^3} \right] \]  

(11)

Finally, the equation of motion can be rewrite as
\[
m\ddot{x}(t) + \mu \left[ \frac{3\pi D^3 l \left(1 + \frac{2d}{D}\right)}{4d^3} \right] \dot{x}(t) + kx(t) = f(t)
\] 

(12)

4. Damper configuration and testing setup

A bypass channel is developed and damping performance i.e. controllability is experimentally assessed using BMRD verification techniques. The bypass channel was constructed using a high strength alloy steel with an inner diameter of 10mm and length of 99 mm. The diameter of this piston rod is 10mm and the piston is 38mm and the applied current for sinusoidal displacement excitations ranging from 0 to 1.5 A. In figure 3 presents the BMRD structure and in table 5, the BMRD components are shown.

| Item no | Part Number            | Quantity |
|---------|------------------------|----------|
| 1       | Mono Tube Cylinder     | 1        |
| 2       | Pipe                   | 1        |
| 3       | Piston Cover           | 1        |
| 4       | Piston Cover Cap       | 2        |
| 5       | Piston Cap             | 1        |
| 6       | Piston Coil Cylinder   | 1        |
| 7       | Plastic Coil Case      | 1        |
| 8       | Copper                 | 1        |
| 9       | Top Rod                | 2        |
| 10      | Bypass pipe            | 10       |

Table 1: BMRD parts

Figure 3. Bypass MR damper structure

5. Bypass MR damper characterization

In figure 4 & 5 it is seen that the damping force rapidly increases during the beginning stroke for all the stroke rates applied during the experiment. After 4mm of stroke length, the damping force show steady behavior. In this curves least trend force is seen at 100mm where highest is seen 200 mm rate. The other rates are as 300, 400 & 500 mm shows force values between the 100 & 200 mm rates. Due to the applied load forces increases sharply and reached its peak. However, for the following 1 mm displacement, forces decrease slowly and stable at 10mm stroke. However, in figure 5 after 5mm of stroke length, the damping force show steady behavior. In this curves least trend force is seen at 500 mm where highest is seen 100 mm rate. The other rates are as 200, 300, 400 & 500 mm shows force values between the 100 & 500 mm rates. In addition, the steady force under different stroke rate do not maintain any trend for both 10 mm and 20 mm strokes.
Figure 4. Force vs Stroke curve for 10mm down stroke at zero current for different stroke rate.

Figure 5. Force vs Stroke curve for 20mm down stroke at zero different stroke rate.

Figure 6. Force vs Stroke curve for 10mm down stroke at different current supply for a stroke rate of 100mm/sec.
Figure 7. Force vs Stroke curve for 20mm down stroke at different current supply for a stroke rate of 100mm/sec.

Like the down stroke, the upstroke forces have been observed for different stroke length and stroke rate, and current was varied from 0.1A to 1.5 A. The applied force for this experiment from 100mm/sec to 500mm/sec. In figure 6 it is seen that the damping force rapidly increases during the beginning stroke for all the stroke rates applied during the experiment. After 4mm of stroke length, the damping force show steady behavior. However, the steady force under different stroke rate do not maintain any trend. In this curves least trend force is seen at 0.4A where highest is seen 1A current. The other currents are as 0.1A,0.2A,0.3A,0.4A,0.5A,0.6A,0.7A,0.8A,0.9A,1.1A,1.2A,1.3A,1.5A shows force values between the 0.2 & 0.4 A currents.

In figure 7 it is seen that the damping force rapidly increases during the beginning stroke for all the stroke rates applied during the experiment. After 4mm of stroke length, the damping force show steady behavior. However, the steady force under different stroke rate do not maintain any trend. In this curves least trend force is seen at 0.4A where highest is seen 0.2A current. The other currents are as 0.1A,0.3A,0.5A,0.6A,0.7A,0.8A,0.9A,1.1A,1.2A,1.3A,1.5A shows force values between the 0.2 & 0.4 A currents.

6. Conclusion
Magnetorheological damper with a bypass channel was developed to produce higher damping force. This external bypass method provides extra passage for flowing MR fluid and the flow of MR fluid controlled by current flow. The BMRD was tested for 10-20mm peak to peak amplitude and currents of 0 to 1.5 amps were applied to the coil. The damper was found to show sharp increase of damping force at the beginning of stroke for different stroke rates and then maintain steady force onwards. The lowest and highest forces found from shear mode experiments are 85.51 N and 1525.67 N respectively. It is also seen that the damping force increases with the increase of excitation current from the range of 0.2 ampere to 1.4 ampere. The design method was validated using experimental results.
7. Reference

[1] H. Fujitani, H. Sodeyama, K. Hata, Y. Komatsu, N. Iwata, K. Sunakoda, et al., "Dynamic Performance Evaluation of 200kN Magneto-rheological Damper," Technical Note of National Institute for Land and Infrastructure Management, vol. 41, pp. 349-356, 2002.

[2] S.-B. Choi, M.-H. Nam, and B.-K. Lee, "Vibration control of a MR seat damper for commercial vehicles," Journal of Intelligent Material Systems and Structures, vol. 11, pp. 936-944, 2000.

[3] D. Simon and M. Ahmadian, "Vehicle evaluation of the performance of magneto rheological dampers for heavy truck suspensions," TRANSACTIONS-AMERICAN SOCIETY OF MECHANICAL ENGINEERS JOURNAL OF VIBRATION AND ACOUSTICS, vol. 123, pp. 365-375, 2001.

[4] A. H.-F. Lam and W.-H. Liao, "Semi-active control of automotive suspension systems with magneto-rheological dampers," International Journal of Vehicle Design, vol. 33, pp. 50-75, 2003.

[5] W. Hu and N. M. Wereley, "Magnetorheological fluid and elastomeric lag damper for helicopter stability augmentation," International Journal of Modern Physics B, vol. 19, pp. 1471-1477, 2005.

[6] H. Jung, B. Spencer Jr, Y. Ni, and I. Lee, "State-of-the-art of semiactive control systems using MR fluid dampers in civil engineering applications," Structural Engineering and Mechanics, vol. 17, pp. 493-526, 2004.

[7] M. Liu, V. Sethi, G. Song, and H. Li, "Investigation of locking force for stay cable vibration control using magnetorheological fluid damper," Journal of Vibration and Acoustics, vol. 130, pp. 054504, 2008.

[8] F. Gordaninejad, X. Wang, G. Hitchcock, K. Bangrakulur, S. Ruan, and M. Siino, "Modular high-force seismic magneto-rheological fluid damper," Journal of structural engineering, vol. 136, pp. 135-143, 2010.

[9] C. Guo, X. Gong, L. Zong, C. Peng, and S. Xuan, "Twin-tube-and bypass-containing magneto-rheological damper for use in railway vehicles," Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, vol. 229, pp. 48-57, 2015.

[10] Y.-J. Shin, W.-H. You, H.-M. Hur, J.-H. Park, and G.-S. Lee, "Improvement of ride quality of railway vehicle by semiactive secondary suspension system on roller rig using magnetorheological damper," Advances in Mechanical Engineering, vol. 6, p. 298382, 2014.

[11] G. H. Hitchcock, F. Gordaninejad, and X. Wang, "A new by-pass, fail-safe, magnetorheological fluid damper," in Proceedings of SPIE Conference on Smart Systems for Bridges, Structures, and Highways, 2002, pp. 345-351.

[12] J.-H. Yoo and N. M. Wereley, "Design of a high-efficiency magnetorheological valve," Journal of Intelligent Material Systems and Structures, vol. 13, pp. 679-685, 2002.

[13] N. M. Wereley and L. Pang, "Nondimensional analysis of semi-active electrorheological and magnetorheological dampers using approximate parallel plate models," Smart Materials and Structures, vol. 7, p. 732, 1998.

[14] X.-X. Bai, W. Hu, and N. M. Wereley, "Magnetorheological damper utilizing an inner bypass for ground vehicle suspensions," Magnetics, IEEE Transactions on, vol. 49, pp. 3422-3425, 2013.

[15] X.-X. Bai, N. M. Wereley, W. Hu, and D.-H. Wang, "A Bidirectional-Controllable Magnetorheological Energy Absorber for Shock and Vibration Isolation Systems," in ASME 2012 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, 2012, pp. 485-495.

[16] X.-X. Bai, N. M. Wereley, and W. Hu, "Maximizing semi-active vibration isolation utilizing a magnetorheological damper with an inner bypass configuration," Journal of Applied Physics, vol. 117, p. 17C711, 2015.
[17] X.-X. Bai, D.-H. Wang, and H. Fu, "Principle, modeling, and testing of an annular-radial-duct magnetorheological damper," Sensors and Actuators A: Physical, vol. 201, pp. 302-309, 2013.

[18] M. Mao, W. Hu, Y.-T. Choi, and N. M. Wereley, "A magnetorheological damper with bifold valves for shock and vibration mitigation," Journal of Intelligent Material Systems and Structures, vol. 18, pp. 1227-1232, 2007.

[19] R. M. Robinson, W. Hu, and N. M. Wereley, "Adaptive Dampers Employing Magnetorheological Valves Filled with Porous Media," in 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 18th AIAA/ASME/AHS Adaptive Structures Conference 12th, 2010, p. 3068.

[20] E. Cook, W. Hu, and N. M. Wereley, "Magnetorheological bypass damper exploiting flow through a porous channel," Journal of Intelligent Material Systems and Structures, vol. 18, pp. 1197-1203, 2007.