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Magnetic circuit optimization in designing Magnetorheological damper

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Abstract. This paper presents the materials analysis for combination of working modes of Magnetorheological (MR) damper. The materials were selected based on the optimum magnetic field strength at the effective areas in order to obtain a better design of MR damper. The design of electromagnetic circuit is one of the critical criteria in designing MR dampers besides the working mechanism and the types of MR damper. The increase in the magnetic field strength is an indication of the improvement in the damping performance of the MR damper. Eventually, the experimental test was performed under quasi-static loading to observe the performances of MR damper in shear mode, squeeze mode and mixed mode. The results showed that the increment of forces was obtained with the increased current due to higher magnetic flux density generated by electromagnetic coils. In general, it can be summarized that the combination of modes generates higher forces than single mode for the same experimental parameters throughout the study.

Keywords: Magnetorheological damper; mixed mode; electromagnetic design; magnetic material; non-magnetic material

1. Introduction

Magnetorheological (MR) dampers have been very widely studied and developed for commercial applications (Imaduddin *et al.* 2013). One of the most popular application is the semi-active suspension that performs according to the strength of the magnetic field. The mechanical properties of the suspension can be altered by changing the yield stress of the MR fluid to allow the damping characteristics of the device to be continuously controlled by varying the power of the electromagnet (Ahmadian and Norris 2008).

Recently, more MR dampers have been implemented successfully in various vibration control systems, such as vehicle suspension systems (Du *et al*. 2013, Bai *et al.* 2013, Choi *et al.* 2009), landing gear systems (Batterbee *et al.* 2007, Saxena and Rathore 2013), launcher vibration isolator

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systems (Jean *et al.* 2005), seismic protection systems (Li *et al.* 2013, Cha *et al.* 2013), haptic device systems (Kikuchi *et al.* 2009, Yang *et al.* 2012) and advanced prosthetic systems (Xie *et al.* 2013, Benoit and David 2012).

Basically, the MR dampers could be designed with different structural functions and configurations in the following fundamental aspects depend on the applications. The basic design of MR dampers can be divided into three criteria; types of MR damper, working mechanism and magnetic circuit design configuration of MR damper. There are three types of MR damper; monotube, twin tube and double-ended. In the case of the monotube MR damper, the damper is based on a single-rod cylinder structure with only one reservoir for the MR fluid. For the twin-tube, the damper has two fluid reservoirs for the MR fluid, while, for a double-ended MR damper, the configuration of the damper is based on a monotube damper, but the piston rod, which has the same diameter, protrudes from both ends of the damper cylinder. The MR damper can be operated in flow mode, shear mode, squeeze mode or any combination of these three different working modes depending on the application of the damper.

Electromagnetic circuit design is another important criteria in designing MR dampers. The electromagnetic coil in the MR damper is used to generate the magnetic circuits to control the damping forces by various input currents without mechanical moving parts. The increase in the magnetic field strength is an indication of the improvement in the damping performance of the MR damper. Sallom and Samad (2011) presented a new design of MR valve based on the simulation studies using Finite Element Method (FEM) to obtain a high value of magnetic field strength at the valve gap. They reported that the performance of the valve was dependent on the magnetic circuit design. Similarly, Yu *et al.* (2012) also studied the optimization of the magnetic circuit in MR dampers. They performed an analysis of the magnetic circuit model by adjusting the gap size in order to achieve a greater magnetic field strength. Moreover, Mei *et al.* (2005) developed a magnetic system in MR damper to obtain the high damping performance. They considered the parameter model of magnetic systems included radius of piston rod and piston, number of coil, thickness of piston cylinder, gap length of the annular orifice and effectual length of the annular orifice, in order to optimize the magnetic system in MR damper. Significant work has been done on the geometrical dimension optimization of MR damper to improve the damping performances by Yang *et al.* (2011).

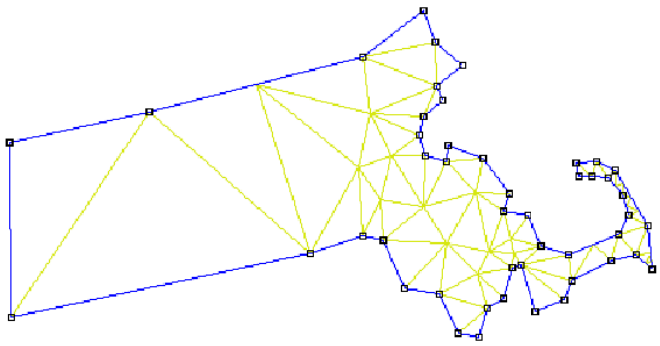
Nowadays, there are a lot of researches on the MR technology, however, the majority are limited in the development of high performance MR fluid, basic principle of MR damper and application of MR damper. The studies on the combination of the working mode of MR damper have not received much attention. In addition, a thorough study on magnetic field configurations in designing MR damper needs to be conducted.

Consequently, this work presents a design analysis of a new MR damper with the combination of modes; shear and squeeze mode. The selection of materials were considered in order to obtain a better design of MR damper with high magnetic field strength at the shear and squeeze area.

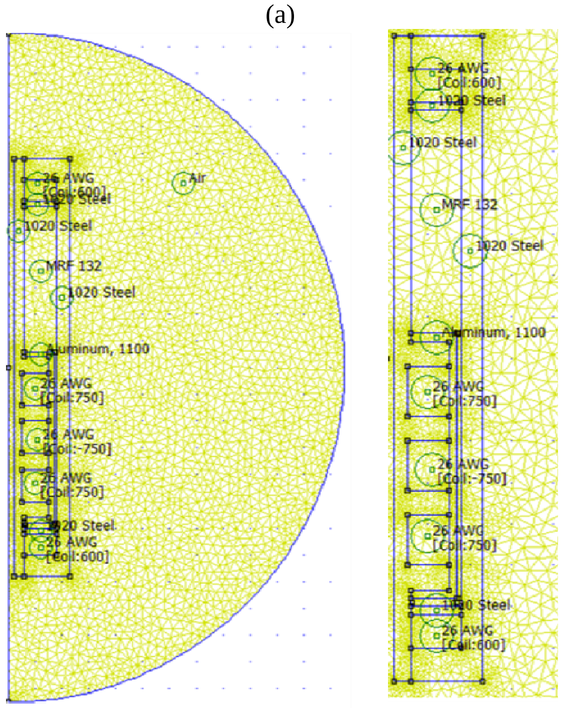
2. Simulation of magnetic circuit

In this study, Finite Element Method Magnetics (FEMM) version 4.2 was utilized to perform the electromagnetic circuit design in the MR damper (Meeker 2013, Ismail *et al.* 2010). FEMM is a finite element software package for solving low frequency electromagnetic problems on two-dimensional planar and axisymmetric domains. The idea of having a finite element analysis is to break the problem down into a large number of regions, each with a simple geometry. For example, Fig. 1 shows a map of the *Massachusetts* broken down into triangles. Over these simple regions, the solution for the desired potential is approximated by a very simple function. If enough small regions are used, the approximate potential closely matches the exact solution.

The advantage of breaking the domain down into a number of small elements is that the problem becomes transformed from a small but difficult to solve problem into a big, but relatively easy to solve problem. Through the process of discretization, a linear algebra problem is formed with perhaps tens of thousands of unknowns. However, algorithms exist that allow the resulting linear algebra problem to be solved, usually in a short amount of time.



(a)



(b)

Fig. 1 Triangulation of *Massachusetts* and (b) Meshed geometry in FEMM

Specifically, FEMM discretizes the problem domain using triangular elements. Over each element, the solution is approximated by linear interpolation from the values of potential in the three vertices of the triangle. The linear algebra problem is formed by minimizing a measure of the error between the exact differential equation and the approximate differential equation as written in terms of the linear trial functions. After giving all the material properties and applying the boundary conditions, the 2-Dimensional of MR damper model was eventually meshed with a coarse triangular mesh at the outside region and a finer triangular mesh at the significant regions, such as piston and cylinder to get more accurate results, as shown in Fig. 1.

The simulated magnetic flux density distribution in the MR damper is shown in Fig. 2. The non-magnetic materials properties, such as aluminum, copper wire and air were expected to be linear. The magnetic materials properties, such as 1020 steel and MRF-132DG were expected to follow the *B-H* curve given in the FEMM software package. This software package was correlated to the type of material for each component of the MR damper, type of coil, the number of turns of the coils wrapping around the piston rod and the values of the electric current supplied into the coils. These parameters were important to produce the best value of the magnetic field strength at the effective area, shear and squeeze area.

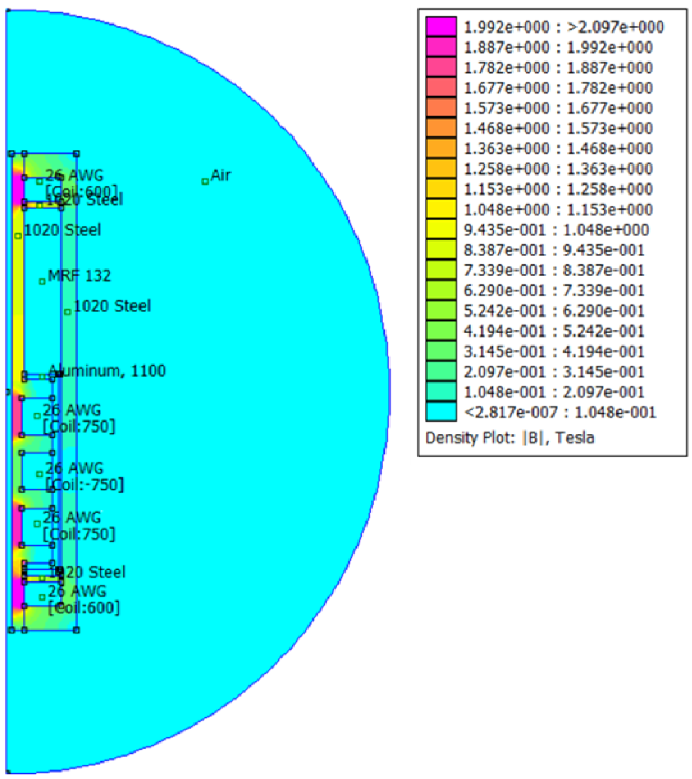


Fig. 2 The simulated of magnetic flux density in MR damper using FEMM

3. Design Analysis of MR damper

A schematic of the initial design concept of MR damper is shown in Fig. 3. At the beginning of the design, the MR damper consisted of five parts in which part 1 was the piston rod, part 2 was the piston pole, part 3 was the coils, part 4 was the coil cover and part 5 was the cylinder. Parts 1, 2 and 5 were made from magnetic materials which has a high magnetic permeability and magnetic saturation, while part 4 was made from non-magnetic material and part 3 was made from copper wire. The materials used to develop the MR damper were 1020 steel for magnetic materials, 1100 aluminum for non-magnetic materials and 26 AWG coated copper wire for coils. The selection of the coil has been briefly discussed in Yazid *et al.* 2013. The detailed list of each part is shown in Table 1.

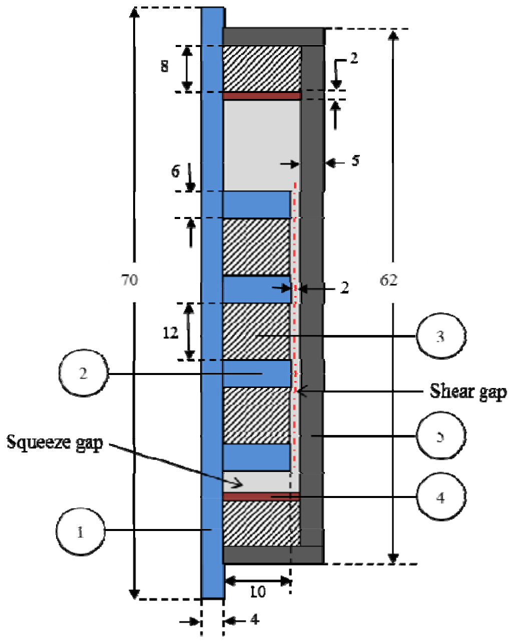
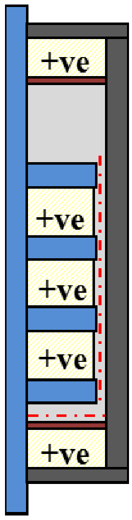
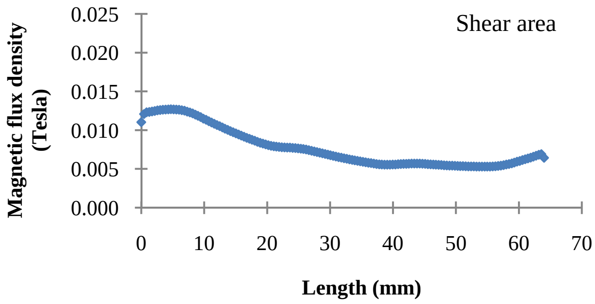
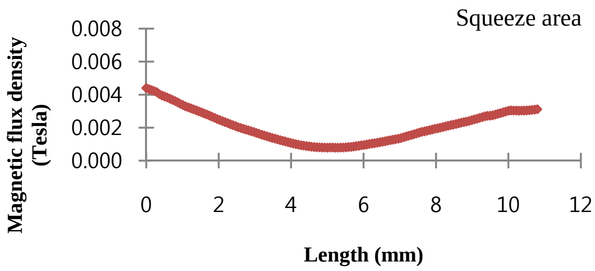
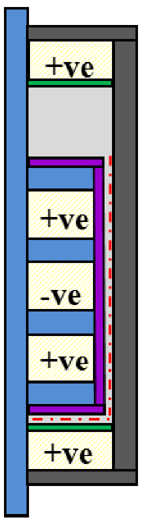
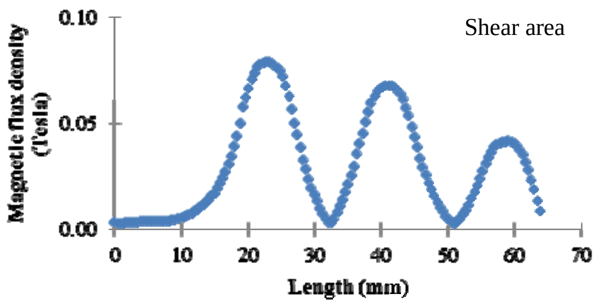
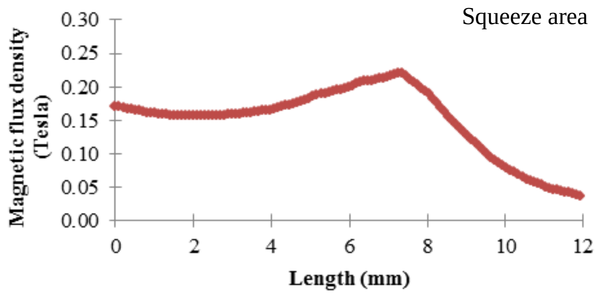


Fig. 3 Middle half of MR damper at the initial design concept

Table 1 List of parts and materials for MR damper

Part No.	Part name	Type of material	Material	Type
1	Piston rod	Magnetic	Low carbon steel	1020
2	Piston pole	Magnetic	Low carbon steel	1020
3	Coil	Non-magnetic	Copper wire	26AWG
4	Coil cover	Non-magnetic	Aluminum	1100
5	Housing	Magnetic	Low carbon steel	1020

Table 2 List of changes in the design concept

Design change	Sketch of damper	Magnetic flux density (Tesla) versus length taken at shear area and squeeze area
<u>Number 1</u> • First idea of the damper. • A positive sign was indicate that the coil turns were wrapped in a clockwise direction. • Average values magnetic flux density for Shear: 0.008 Tesla Squeeze: 0.002 Tesla		 
<u>Number 2</u> • From design number 1. • Add non-magnetic material for the piston cover. • Change material of the coil covers from non-magnetic (aluminum) to magnetic (steel) • A negative sign was indicate that the coil was wrapped in a counter-clockwise direction. • Average values of magnetic flux density for Shear: 0.030 Tesla Squeeze: 0.125 Tesla		 

A number of design changes were analyzed using the FEMM software package (Mazlan *et al.* 2009) and the example of the design changes are listed in Table 2. The number of turns of the coils, the initial gap size and the current value supplied were kept constant during the alterations. The average values of magnetic flux density were taken in the shear and the squeeze area, which were indicated by a red centered line.

Based on the simulation analysis, the damper in design number 2 was expected to produce the highest values for the magnetic flux density at the effective areas (red centered lines). In the final analysis, the damper were consisted of seven parts which including magnetic materials, non-magnetic materials and an electromagnetic circuit. Magnetic materials were used to make the piston rod (part 1), piston pole (part 2), coil cover (part 3) and housing (part 5) to guide the magnetic flux into the fluid gap effectively (Yazid *et al.* 2014). Meanwhile, non-magnetic materials were selected to make the piston cover (part 4). The introduction of a non-magnetic material as a piston cover produced a uniform distribution of the magnetic flux density. Therefore, the piston cover as shown in Fig. 4 was added to guide the magnetic fluxes into the effective area gap; shear and squeeze gap (Wang and Wang 2009). In addition, the piston cover would act as a protector to prevent the MR fluid making contact with the coils.

Fig. 5 shows the final design of the MR damper based on the simulation studies. Some modification has been made to the original concept of the MR damper because of the limitations of the manufacturing process.

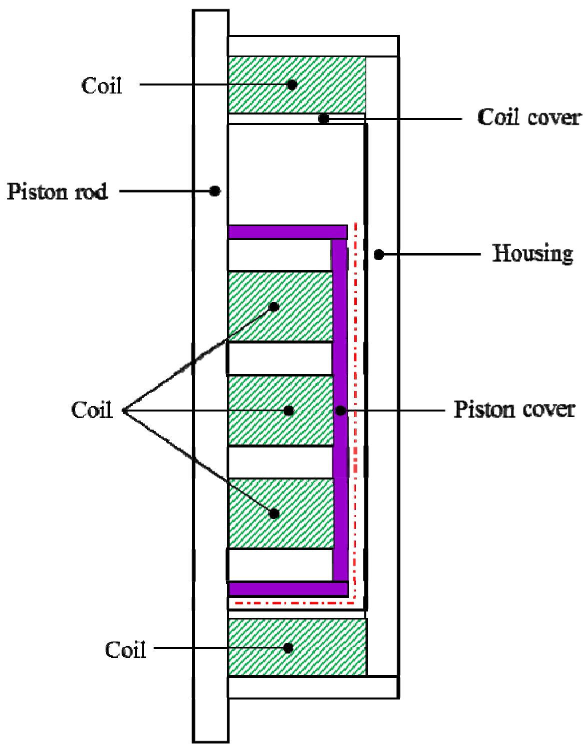


Fig. 4 The new concept of MR damper

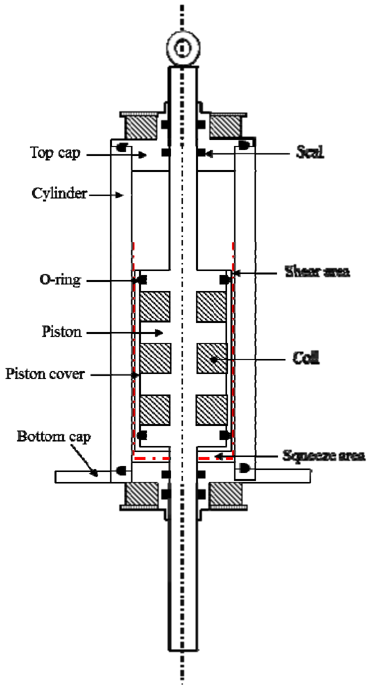
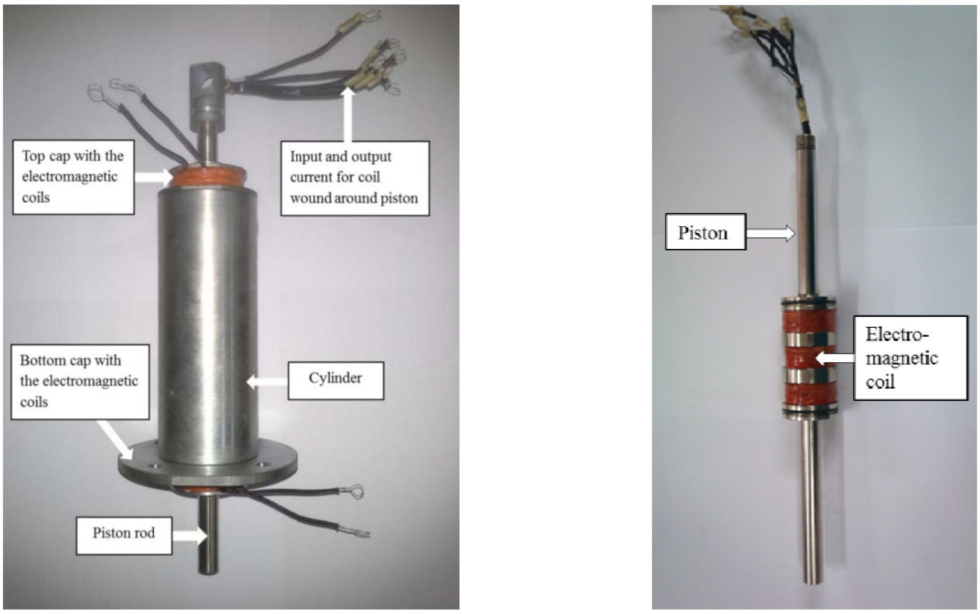


Fig. 5 Schematic of the mixed mode MR damper

The actual assembly damper, as shown in Fig. 6, was fabricated before performing the experiment. In this work, the piston rod has a hollow structure to accommodate the coils wires and separate them from the MR fluids. The coils were placed inside the MR damper which is referred to as an internal coil. Otherwise, the coils can be placed outside the MR damper which is called as an external coil. The magnetic circuit will guide the magnetic flux through the MR damper to the effective areas. The magnetic field strength generated by the electromagnetic coil will change the yield stress of the MR fluid. Therefore, the resultant damping force against the motion is activated under the control of the magnetic field strength. The detail list of each part is shown in Table 3.

Table 3 Design details and material for each component of the MR damper

Part Name	Type of Material	Material	Type
Piston	Magnetic	Low carbon steel	1020
Piston cover	Non-Magnetic	Aluminum	1100
Housing	Magnetic	Low carbon steel	1020
Top cap	Magnetic	Low carbon steel	1020
Bottom cap	Magnetic	Low carbon steel	1020
Coil	Non-magnetic	Copper wire	26AWG



(a) (b)

Fig. 6 The fabrication of (a) Mixed mode MR damper and (b) piston

4. Performance of MR damper

The experiment was conducted to observe the performance of a new mixed mode MR damper. A quasi-static loading test was used to investigate the fundamental behavior of mixed mode MR damper (Mazlan *et al.* 2011, Yang *et al.* 2002). The experiment was performed under compression and tension test to prove the existing of the combination of two working modes; shear and squeeze mode in MR damper (Mazlan *et al*. 2008). Fig. 7 shows the force versus the displacement of MR damper that has been developed in this work. The results showed the behavior of the force in compression mode under different applied currents. It was clearly observed that the forces increase as the applied current increases. Consequently, it was directly indicated that the damping forces could be effectively controlled by the applied current. In the absence of a magnetic field, the damping force of the damper would occurred according to the viscosity of the MR fluid itself. However, in the presence of a magnetic field, the MR damper produced a controlling damping force due to the yield stress of the MR fluid. It was identified that a damping force of 20 N in the absence of an input field was increased up to 100 N by applying the input current of 0.4 Amps.

Similar results of the behavior of the force has been reported by Nam and Park (2009) and Bai *et al.* (2013). Nam and Park (2009) assessed the performance of MR damper which was fabricated based on the electromagnetic circuit design. The results showed that the force could be effectively controlled by the applied currents. Bai *et al.* (2013) found the same phenomenon, which has been described that the forces have increase as the applied current increases which was due to the viscosity of the MR fluid.

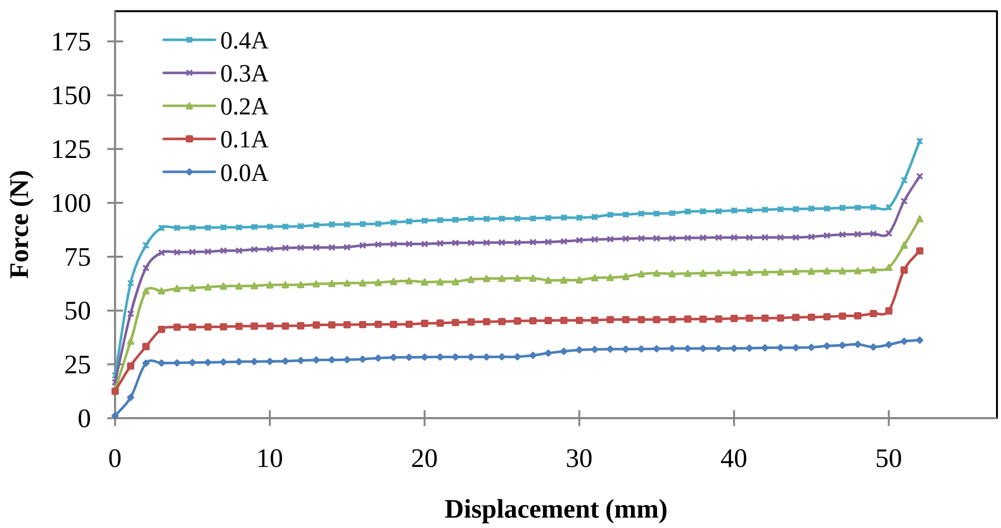


Fig. 7 Force versus displacement for MR damper under different current supplied

Fig. 8 shows the performance comparison of the damping force under different working modes. As seen from the figure, a high damping force was obtained in mixed modes compared to the shear and squeeze modes. The average increment of the damping forces in the mixed modes was increased by up to 53%. The results showed that under the mixed mode condition, with the same input current and test mode, the damping force could achieve up to 550 N. This proved that the mixed mode could produce a higher damping force than the single mode.

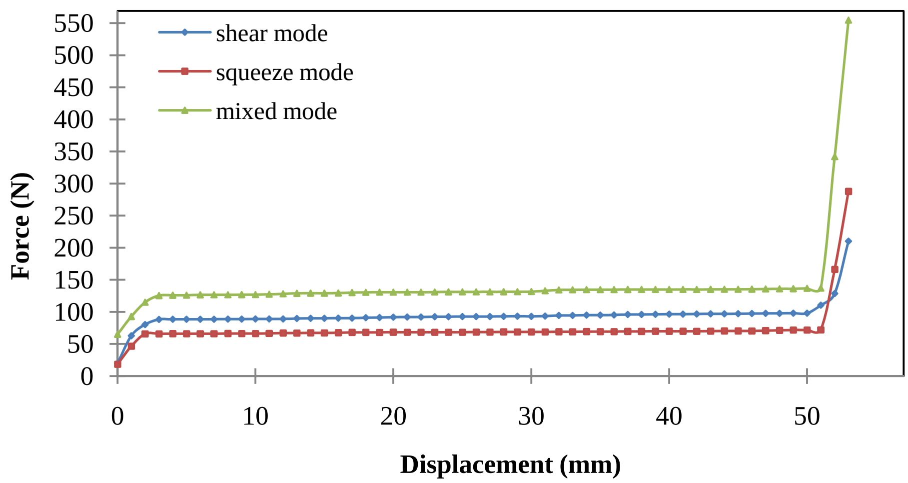


Fig. 8 Force versus displacement for MR damper in different modes under compression test

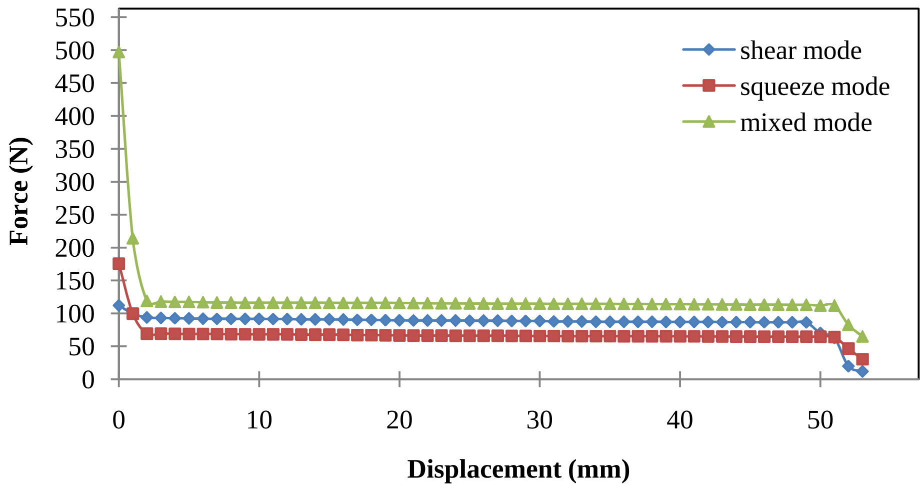


Fig. 9 Force versus displacement for MR damper in different modes under tension test

Fig. 9 shows the force versus displacement for the MR damper under tension mode. The tension test was carried out by moving the piston towards the top of the damper. In Fig. 10, the curves of the damping force under tension showed similar characteristics as in the compression mode, however, the curves were established in the opposite direction. This phenomenon was expected since a symmetrical design was constructed in the MR damper. In the tension process under the same applied current, piston speed and initial gap size, the forces were reduced as the piston move towards the top of the damper. From the results, the overall damping forces were increased with respect to the magnetic field strengths.

5. Conclusions

The selection of materials were considered and analyzed in order to obtain a better design of MR damper. From the simulation analysis, the final components of the mixed mode MR damper have seven parts consisted of three main categories which were magnetic materials, non-magnetic materials and electromagnetic circuit. A new mixed mode MR damper was designed and fabricated based on simulation studies. The experiment was performed to validate the performance of MR damper. Throughout this study, it was concluded that a mixed mode MR damper was capable of generating a higher damping force than a single mode MR damper.

Acknowledgments

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