

Research Paper

The Influence of Hard and Soft Magnetic Nanoparticle Additives in Magnetorheological Fluids on The Performance of Magnetorheological Dampers for Motorcycle

Rahmad Rizki Nur Arifin^{1,2}, Bhre Wangsa Lenggana³, Ubaidillah²✉, Irfan Bahiuddin⁴, Kacuk Cikal Nugroho^{2,5}, Fitrian Imaduddin⁶, Saiful Amri Mazlan⁷, Arjon Turnip⁸

¹Department of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi PETRONAS, Perak, Seri Iskandar, 32610, Malaysia

²Department of Mechanical Engineering, Faculty of Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia

³Department of Mechanical Engineering, Faculty of Engineering, Universitas Jenderal Soedirman, Purbalingga 53371, Indonesia

⁴Department of Mechanical Engineering, Vocational College, Universitas Gadjah Mada, Sleman 55281, Indonesia

⁵Department of Manufacture Engineering Technology, Akademi Inovasi Indonesia, Salatiga 50711, Indonesia

⁶Mechanical Engineering Department, Faculty of Engineering, Islamic University of Madinah, Al Madinah Al Munawwarah 42351, Saudi Arabia

⁷Engineering Materials & Structures (eMast) Ikohza, Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Kuala Lumpur 54100, Malaysia

⁸Department of Electrical Engineering, Universitas Padjadjaran, Sumedang 45363, Indonesia

✉ ubaidillah_ft@staff.uns.ac.id

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Abstract

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Magnetorheological Fluids (MRFs) are widely used in semi-active suspension systems due to their rapid field-dependent viscosity. However, conventional carbonyl iron particles (CIP)-based MRFs exhibit limited yield and shear stress due to weak interparticle interactions because of large particle spacing. This study aims to enhance the performance of CIP-based MRFs by incorporating hard (cobalt ferrite, CoFe_2O_4) and soft (manganese ferrite, MnFe_2O_4) magnetic nanoparticles for application in a motorcycle damper. The magnetic properties and viscosity (η) of the MRFs were characterized using vibrating sample magnetometer (VSM) and rheometer testing. The performance of magnetorheological damper (MRD) was analysed using finite element method magnetics (FEMM) simulations under various fluid gaps and MRF compositions. The optimal combination was achieved with MRF-CIP+ CoFe_2O_4 at 0.9 mm fluid gap, delivering a damping force (F_d) ranging from 0.941-3.858 kN (± 310 increase) under applied currents of 0-2 A. House of quality (HoQ) analysis further confirmed that the proposed magnetorheological damper (MRD) exhibits the highest weighted score compared to the benchmarked design in addressing customer requirements.

Keywords: Motorcycle suspension system; Magnetorheological damper; Magnetorheological fluids; Magnetic nanoparticles; Damping force

1. Introduction

Suspension system is a vital component that plays a critical role in delivering optimal ride comfort and maintaining the vehicle's stability [1], [2], [3]. Currently, many motorcycles utilise

passive-adjustable suspension systems because of their cost-effectiveness and design simplicity [4]. The components' features, such as springs and dampers, remain fixed. Consequently, the suspension system lacks the capacity to adapt



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dynamically to changes in road conditions or forces applied to the vehicle [5]. The suspension system has undergone significant development, incorporating active suspension systems that enable the vehicle to dynamically adapt the suspension level and reaction to road conditions and the driver's preferences [6], [7], [8]. Typically, these systems are furnished with sensors, actuators, and control systems that can react actively to information received [9], [10]. Despite its effectiveness, the active suspension system incurs high production costs.

Hence, the semi-active suspension system is considered a more affordable alternative. This system still allows for the adjustment of damping characteristics but does not carry production costs equivalent to those of active suspension systems [11]. One of the well-known semi-active suspensions is magnetorheological damper (MRD), which implements a magnetorheological valve (MRV) as a substitute for the piston [12], [13], [14], [15]. MRD offers a wider range of damping force (F_d) adjustment, allowing for greater flexibility compared to typical passive suspension system. The MRD is widely employed as a vibration-dampening component across numerous sectors, including UAV dampers, steering dampers, shock absorbers, mining applications, seismic control, and others [16], [17], [18], [19], [20], [21], [22].

The fluid utilised in the MRD is known as magnetorheological fluid (MRF). MRF demonstrates a high degree of responsiveness in changing their viscosity (η) and yield stress due to the applied external magnetic field [23], [24], [25], [26], [27], [28], [29]. This fluid consists of magnetic nanoparticles that are uniformly dispersed in liquid media, namely silicone oil. When a magnetic field is imposed on a fluid domain, magnetic particles align themselves parallel to the direction of the magnetic field, causing the fluid to exhibit solid-like behaviour [30]. The viscosity of this fluid can be adjusted by applying a magnetic field, allowing for active control over damping properties in suspension systems or vibration dampers. Moreover, the ability of MRF to generate different yield stresses is essential to advancing tuneable damping technologies [31].

The magnetic particle used in most MRF is carbonyl iron particle (CIP) which has high permeability, low remanent, and wide availability

[32]. Types of MRF CIP that have been commercialized and commonly used in numerous research were MRF-132DG and MRF-140CG from Lord Corporation [33], [34], [35], [36], [37]. These MRFs have been successfully applied to several MRD designs and demonstrated controllable damping forces. However, the use of CIP in MRFs poses a significant challenge in the limited interparticle interaction due to the large spacing among the CIPs, resulting in the restricted yield and shear stress value [38]. Consequently, the achievable damping force in MRD remains constrained. To address this issue, the incorporation of additional nanoparticles is considered to fill the space among the magnetic particles and enhances the linkage among particles, which is expected to enhance the damping capability [39].

Numerous researchers have investigated the influence of incorporating hard and soft magnetic nanoparticles to increase the performance of the MRFs [40], [41], [42], [43], [44], [45]. Nugroho *et al.* [46] examined the impact of hard magnetic nanoparticles (CoFe_2O_4) on the MRF properties. The findings showed that the combination of CIP- CoFe_2O_4 can increase the shear stress and the viscosity of the MRFs. Furthermore, Hajalilou *et al.* [47] incorporated the soft magnetic nanoparticles (ZnFe_2O_4) into the MRF-CIP. This results in the enhancing yield stress by $\pm 12\%$ at 500 mT conditions. Although the magnetic saturation of the hard magnetic (CoFe_2O_4) and soft magnetic (ZnFe_2O_4) were lower compared to the CIP, the combination of CIP and these nanoparticles can increase the shear and yield stress, as well as the viscosity of the MRFs. However, as far as discernable, no research has been done on the comparison and estimation of the damping force (F_d) caused by the MRFs modification with nanoparticle additives, especially hard and soft magnetic nanoparticles. Incorporating magnetic nanoparticles into MRF is considered necessary to improve the damping capability of the MRD.

In this research, cobalt ferrite (CoFe_2O_4 , as hard magnetic) and manganese ferrite (MnFe_2O_4 , as soft magnetic) nanoparticles were utilised as an additive of the CIP-based MRFs. This study aims to evaluate the effect of additional hard (CoFe_2O_4) and soft (MnFe_2O_4) magnetic nanoparticles in CIP-based MRF to the damping force performance of

the MRD for application in a motorcycle damper system. This paper is organized as follows: first, this study examines a new design that involves varying the fluid gap range between 0.5 to 1 mm. Then, the different types of MRFs were synthesised and characterised their properties in the laboratory. The finite element method magnetics (FEMM) simulations was conducted to analyse the magnetic flux density obtained in the MRV design under varying fluid gaps and MRFs. Furthermore, the F_d performance was determined using the applicable formulas and the optimal fluid gap design and MRF type were selected according to the required F_d on the MRD for the motorcycle suspension system. Finally, the house of Quality (HoQ) analysis was conducted to evaluate the alignment between costumer requirements with technical specification of the proposed MRD, as well as to compare the proposed MRD design with the benchmarked competitors.

2. Methods

2.1. Sample Fabrication

In this experiment, the nanoparticle additives, CoFe_2O_4 and MnFe_2O_4 , were created using co-precipitation method, as it can produce more

uniform nanoparticles at room temperature compared to hydrothermal or sol-gel methods [48], [49]. The uniform size maintain homogenous particle distribution within the MRFs, resulting in more stable performance when exposed to varying magnetic fields. The nanoparticles fabrication process is shown in Figure 1. For manufactured nanoparticles of CoFe_2O_4 and or MnFe_2O_4 , cobalt nitrite ($\text{Co}(\text{NO}_3)_2$) or manganese nitrite ($\text{Mn}(\text{NO}_3)_2$) was mixed with 100 ml of water using a magnetic stirrer. Next, the solution was titrated with 4.8 M sodium hydroxide (NaOH) at 95 °C using a magnetic stirrer speed of 1000 rpm. The sediment particles were washed using ethanol ($\text{C}_2\text{H}_6\text{O}$) and were calcined at 1000 °C for five hours. The balanced chemical equations for the fabricated CoFe_2O_4 and MnFe_2O_4 nanoparticles are shown in Eq. (1) and Eq. (2).

Among the various types of MRFs utilised in this research were MRF-CIP, MRF-CIP+ CoFe_2O_4 , and MRF-CIP+ MnFe_2O_4 . The MRF CIP was made by mixing 70 weight percent (wt%) CIP and 30 wt% silicone oil. MRF-CIP+ CoFe_2O_4 was made by mixing 1 wt% CoFe_2O_4 nanoparticle, 69 wt% CIP, and 30 wt% silicone oil, whereas MRF-CIP+ MnFe_2O_4 was made by mixing 1 wt% MnFe_2O_4 nanoparticle, 69 wt% CIP, and 30 wt% silicone oil.

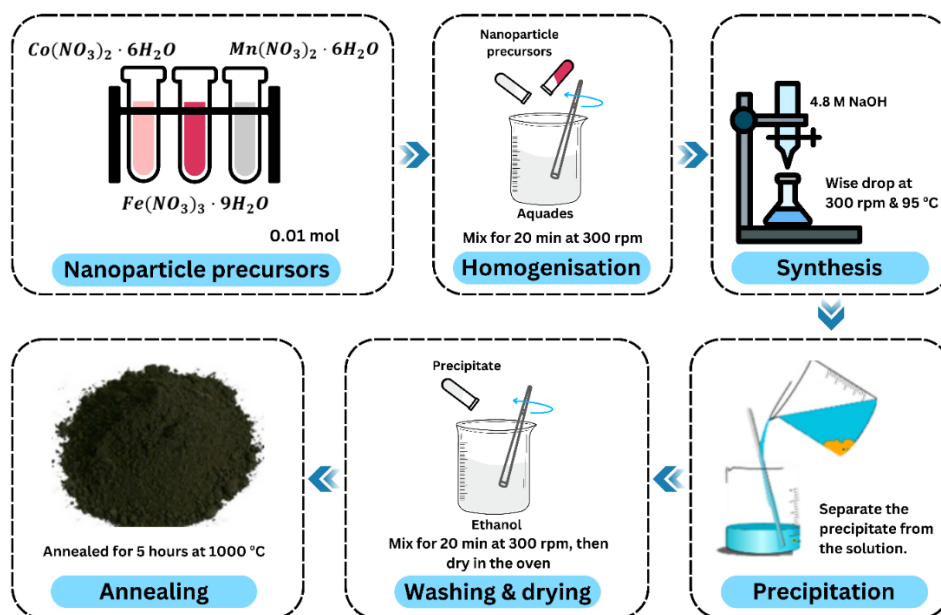
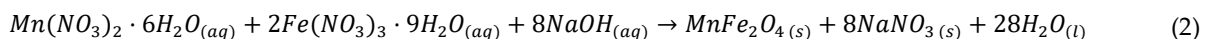
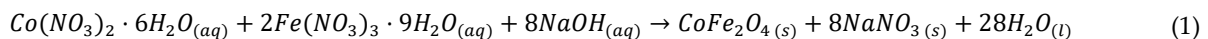


Figure 1. Fabrication process of magnetic nanoparticles

2.2. Sample Characterisation

In this study, the sample were characterised through three analytical approach, including microstructural and particle size analysis, magnetic properties analysis, and rheological characteristics analysis, as presented in [Figure 2](#). Field emission scanning electron microscopy (FESEM, Zeiss Supra 55 Vp) was utilised to analyse the morphological structure of the magnetic nanoparticles. ImageJ software was then used to figure out the particle size distribution based on the FESEM results. Particle size measurement was established by measuring 30 random particle points. Furthermore, the magnetic characteristics of MRFs were analysed using a vibrating sample magnetometer (VSM, microsense) test. The magnetic characteristics data were utilised to determine the M-H and B-H curve of each MRF. Additionally, the rheological characteristics of MRFs were examined using the Anton Paar MCR302 rheometer testing apparatus. The test temperature was kept constant at 25 °C while maintaining a plate spacing of 1 mm. Rheological testing was performed in the off-state conditions (0 A) to determine the η of MRFs at a specific shear rate. The η data was utilised to calculate viscous pressure drop ($\Delta P_{viscous}$) on the MRV. Furthermore, oscillatory test were conducted to evaluate the shear stress vs shear rate of each MRFs in both off-state and on-state conditions. The shear rate was ramped constantly ranging from 0-300 s^{-1} , while the current input ranging from 0-2 A (with 0.5 intervals) was applied to generate the magnetic flux density ranging from 0-0.484 T. The shear stress vs shear

rate data were then extracted using the Bingham-plastic model to obtain the yield stress vs magnetic flux density of each MRFs [\[32\]](#), which was used to determine the yield pressure drop (ΔP_{yield}) on the MRV.

2.3. Magnetorheological Damper's (MRD's) Design Principles

The design requirements and objectives (DRO) were centred on emphasising user experience, maximising functionality, and assuring the usage of appropriate F_d values. The DRO is shown in [Figure 3](#). The structural design of the MRV is essential for improving its performance. Developing the MRV's structural design must be customised to fulfil the ΔP specifications. The structural design should be conducive for effortless assembly and impervious to MRF seepage. The structural design of the MRV should consider several elements, such as size, fluid flow characteristics, fluid flow gap, fluid properties, the number of coil windings, and material composition. These various parameters can affect the magnetic flux density that is communicated to the MRF, resulting in changes in the ΔP across the MRV.

The structural configuration and material selection for the MRV must be customised to correspond to this specific range of F_d . The MRV, presented in [Figure 4](#), consists of four primary components: the bobbin, coil, valve casing, and fluid gap. The MRV utilises a composite of both magnetic and non-magnetic materials. Magnetic materials are used to amplify the magnetic flux density emitted from the coil, while non-magnetic

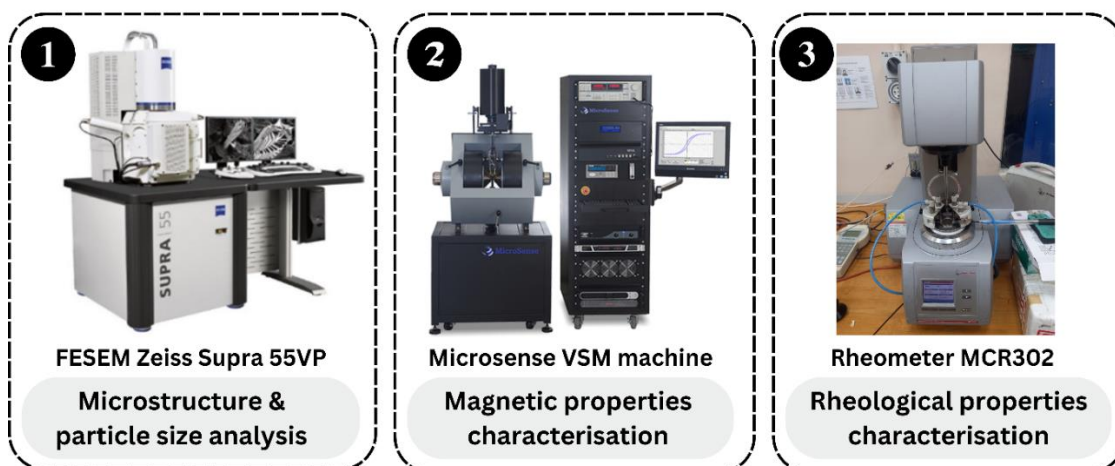


Figure 2. Sample characterisation procedures

DESIGN REQUIREMENTS AND OBJECTIVES		
MR Valve for Motorcycle Damper		
Parameters	Description	Demand/ Wishes
ERGONOMICS	- Provide adjustable damping levels for enhanced comfort - Has dimensions of 325 mm, fluid gap range 0.5-1 mm, easy to assemble, and applicable to various motorcycles models	D W
OPERATION	- Minimise energy consumption (0-2 A) for improved overall vehicle efficiency. - Adhere to safety regulations in both manufacturing and product usage.	W D
DAMPING PROPERTIES	- Provide a large damping forces range 1-3 KN. - Ensure durability for long-lasting and reliable performance	W D
PERFORMANCE CONTROL	- Enable electronic control for dynamic adjustment of damper performance - Achieve a broad performance range for effective operation across varied road conditions	D W
MANUFACTURING COST	- Develop a design conducive to cost-efficient mass production - Consider cost-effective production methods for market competitiveness	D D

Figure 3. Design requirements and objectives of the MRD

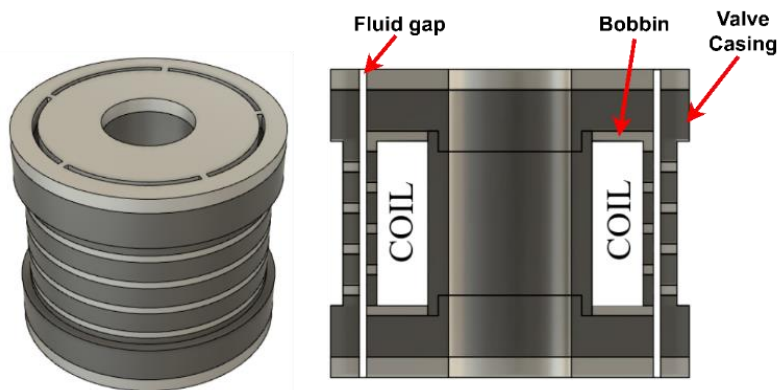


Figure 4. The design of magnetorheological valve

materials restrict the magnetic flux density to focus on the fluid domain. This arrangement can lead to a greater range of pressure decreases [30].

The MRV's main structure comprises five components, as depicted in Figure 5. All these components were fabricated from AISI 1020 Steel as a soft magnetic material and aluminum 6061 as a non-magnetic material. The coil utilises 28 American wire gauge (AWG) copper wire. Based on the Farnell datasheets, the conductor has a diameter of 0.315 mm and an electrical resistance of 0.219 Ω /m. The wire is coiled around the bobbin region for a total of 350 turns. The MRV was

incorporated into the MRD for the motorcycle suspension system, as seen in Figure 6. The MRD has a bore diameter of 35 mm, a stroke length of 57.11 mm, and a rod diameter of 14 mm.

The proposed MRV layout parameters are shown in Table 1. Figure 7 presents the detailed dimensions and variables of an MRV.

Table 1. Magnetorheological valve design parameters

Parameters	Description	Value (mm)
Da	Annular gap size	0.5-1
La	Upper/bottom annular	26
Ra	Gap	14
Rp	Radius of piston	17.5

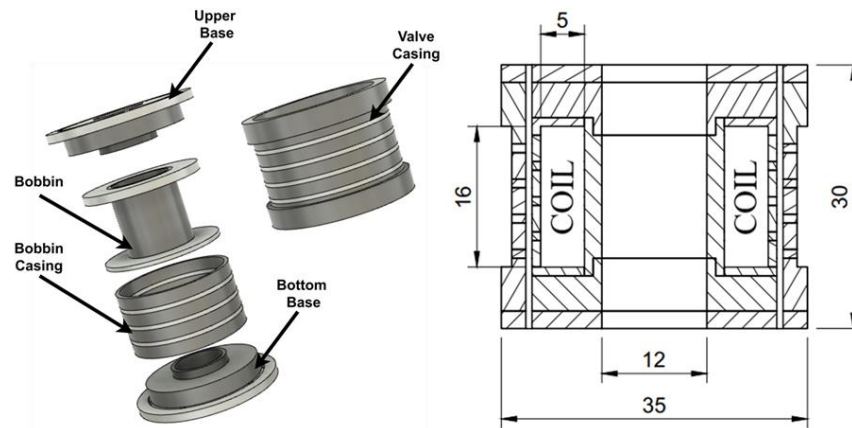


Figure 5. Exploded view and dimensions of the magnetorheological valve components

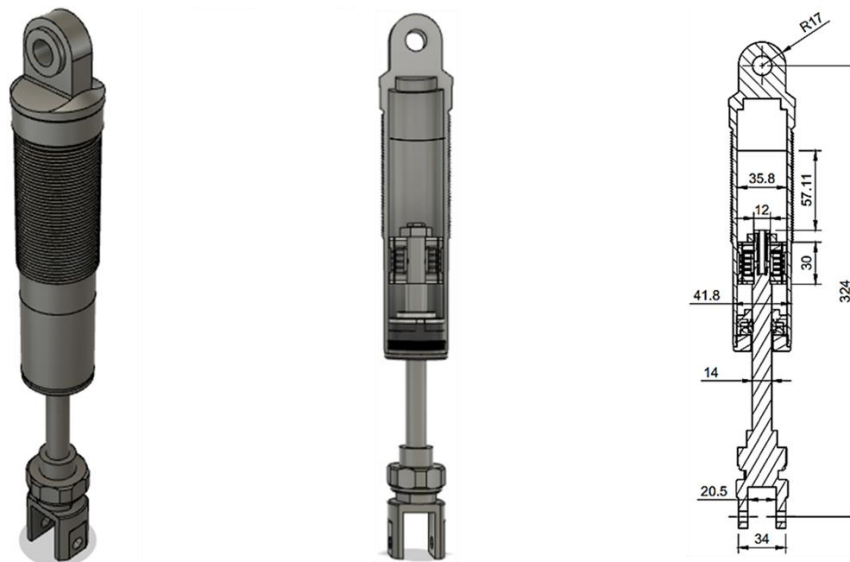


Figure 6. The assembly of magnetorheological valve in the magnetorheological damper

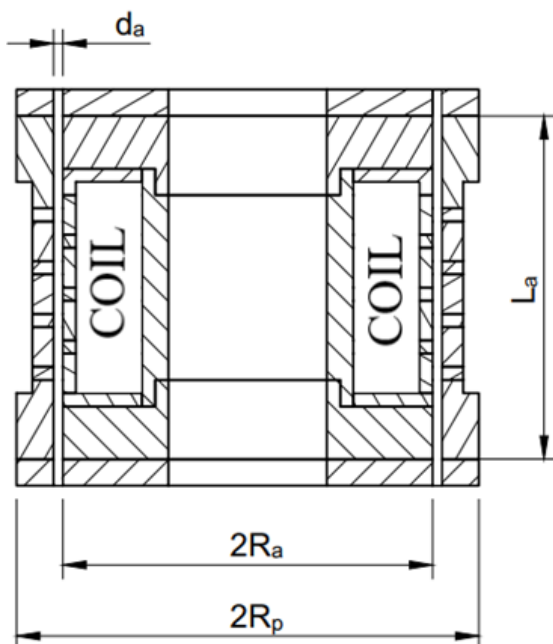


Figure 7. Dimensions and variables of the magnetorheological valve

2.4. Simulation and Governing Equations

The data analysis technique comprised two stages: simulation, which aimed to ascertain the magnetic flux levels within the MRV gaps, and mathematical modelling analysis to calculate the F_d . The FEMM was utilised to conduct magnetic simulations, as illustrated in [Figure 8](#). The simulation stage is essential and should come before the MRD production process. Simulating magnetic field strength is crucial due to the difficulty of direct measurement using experimental methods. The simulation results were used to calculate the yield stress in the MRF by utilising the magnetic flux density values. Each region of the MRF exhibits varying magnetic flux density values, leading to unique yield stress values. The properties of each MRF influence the yield stress value. This analysis of MRV performance emphasises its capacity to generate and control pressure differential between the up-

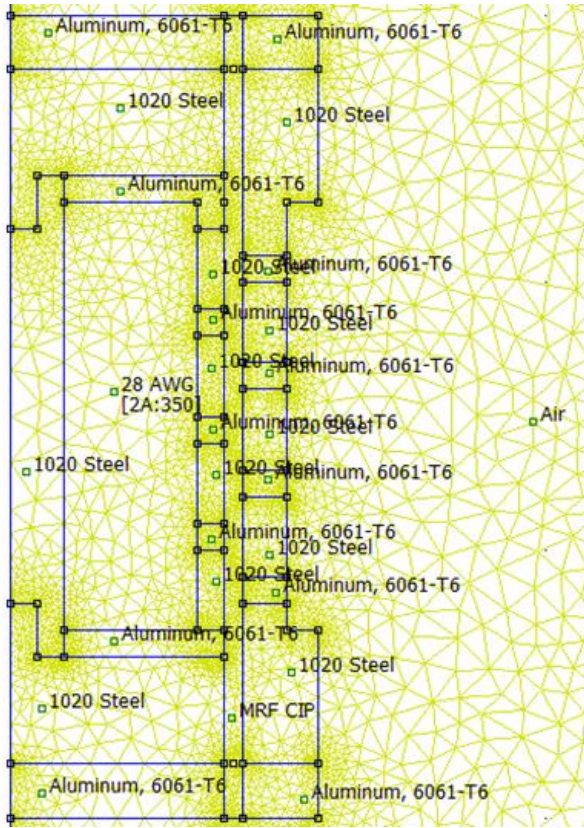


Figure 8. The meshed model of the 2D axisymmetric MRV in the FEMM simulations

stream and downstream sections. The ΔP in the MRV comprises two factors: viscous ΔP and yield ΔP . The viscous ΔP is determined exclusively by the viscous characteristics of the MRF, or in cases when the coil does not conduct an electromagnetic current (off state condition). Conversely, decreases in pressure are influenced by the fluid's yield stress or when the coil receives an electromagnetic current (on state condition). The pressure decreases in a MRV can be mathematically represented by the Eq. (3).

$$\Delta P = \Delta P_{viscous} + \Delta P_{yield} \quad (3)$$

Due to the specific characteristics of the annular gaps, the mathematical modelling of their ΔP values also vary. Eq. (4) and Eq. (5) depict the mathematical expressions for ΔP caused by viscous resistance and field dependence in annular gaps [14].

$$\Delta P_{viscous} = \frac{6\eta QL}{\pi d^3 R} \quad (4)$$

$$\Delta P_{yield} = \frac{c\tau(B)L}{d} \quad (5)$$

The variables that affect the viscous ΔP are η , flow rate (Q), L (length of the annular channel), d

(gap size of the channel), R (channel radius), $\tau(B)$ (yield stress), and c (flow velocity profile coefficient). Variable c can be determined by computing the ratio between the viscous ΔP and the total ΔP or employing the approximation function as demonstrated in Eq. (6).

$$c = 2.07 + \frac{12Q\eta}{12Q\eta + 0.8\pi R d^2 \tau(B)} \quad (6)$$

By utilising the mathematical formulas for the annular and radial ΔP as stated in Eq. (3) to Eq. (6), the mathematical representation of ΔP for the MRV with the proposed concept flow channel can be further defined using Eq. (7).

$$\begin{aligned} \Delta P_{total} &= \Delta P_{viscous} + \Delta P_{yield} \\ &= \frac{6\eta QL_a}{\pi d_a^3 R} + \frac{c_a \tau_a(B) L_a}{d_a} \end{aligned} \quad (7)$$

The ability of the MRD applications in the motorcycle shock absorber can be seen in the value of the F_d prediction. The F_d of MRV depends on the ΔP and the cross-section of MRV (A_p). The F_d calculation of the MRD is shown in Eq. (8).

$$F_d = \Delta P \times A_p \quad (8)$$

3. Results and Discussion

3.1. Magnetorheological Fluid (MRF) Characteristics

The characteristics of the nanoparticles and MRFs are essential to analyse because the performance of the MRD depends on them. Figure 9 depicts the morphological structures of the nanoparticles. The particle size distribution has been analysed and illustrated in Figure 10. These figures indicate that the particle size range of CoFe_2O_4 and MnFe_2O_4 were 147-211 nm and 230-459 nm, respectively.

The viscosity and magnetic properties of the related MRFs have been investigated. The viscosity of MRF samples was determined using shear rheological measurement in rheometer MCR 302. The MRFs were examined at a shear rate of 300 sec^{-1} in off-state conditions (0 A). This testing was conducted with three repetitions to ensure the accuracy of the data, subsequently the average value of the three data was utilised as a representation of more consistent and reliable results. Table 2 shows the viscosity of the MRFs.

The magnetic properties of MRFs were measured by VSM testing. The magnetic properties, such as the M-H curve and B-H curve,

are shown in [Figure 11](#), while the yield stress curve is shown in [Figure 12](#). The results of the M-H curve and B-H curves of the three types of MRFs had almost similar values. Among the samples examined, the MRF-CIP exhibited the highest magnetic saturation, with a maximum of 128 Am²/kg of magnetisation and 1.661 T of magnetic flux density. The MRF-CIP+CoFe₂O₄ and MRF-CIP+MnFe₂O₄ had a maximum of 120.6 Am²/kg, 125.5 Am²/kg of magnetisation and 1.651 T, 1.658 T of magnetic flux density, respectively. From this

data, adding nanoparticle additives can decrease the magnetisation and magnetic flux density of MRFs on the same applied magnetic field, which is similarly reported by Leong *et al.* [50].

Table 2. Fluid viscosity (η) of the MRFs at a shear rate of 300 sec⁻¹

MRF Type	Viscosity (Pa-s)
MRF CIP	1.21
MRF CIP+CoFe ₂ O ₄	1.3421
MRF CIP+MnFe ₂ O ₄	1.1848

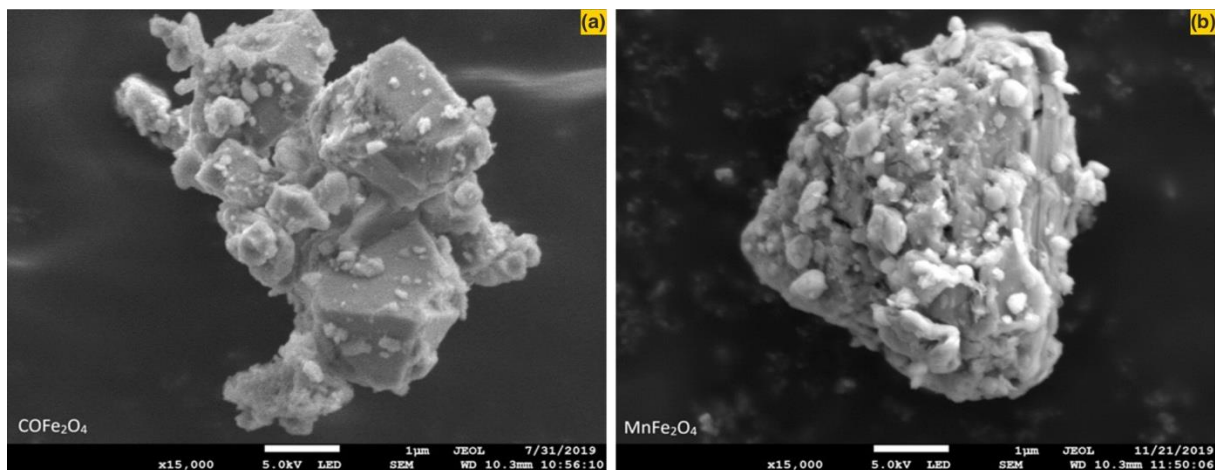


Figure 9. Morphological structure of nanoparticles: (a) CoFe₂O₄ and (b) MnFe₂O₄

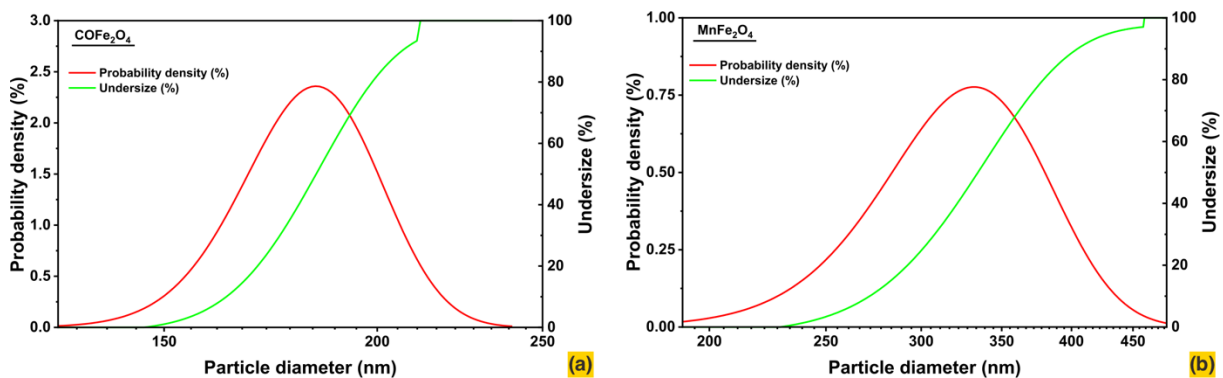


Figure 10. Size distribution of nanoparticles: (a) CoFe₂O₄ and (b) MnFe₂O₄

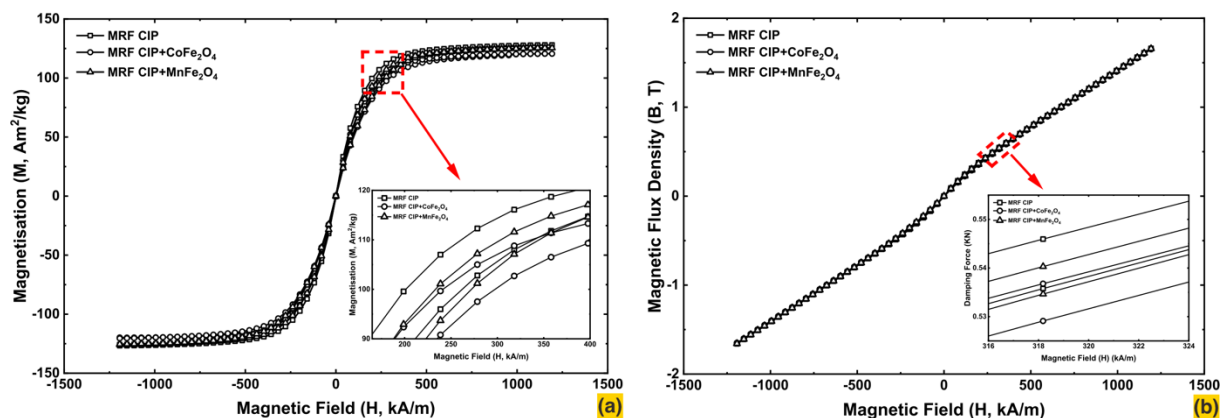


Figure 11. The magnetic properties of the magnetorheological fluids (MRFs): (a) M-H curves and (b) B-H curves

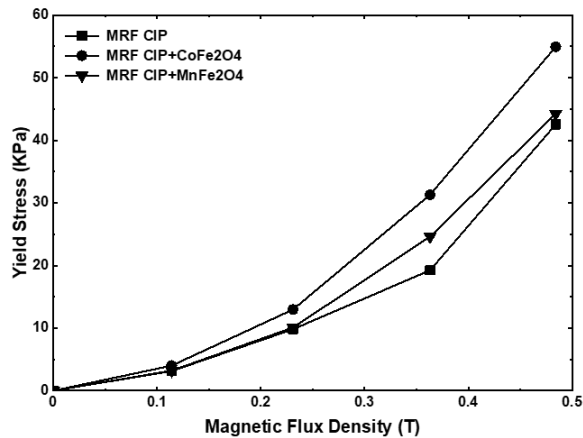


Figure 12. The correlation between yield stress and magnetic flux density of the MRFs

As shown in [Figure 12](#), MRF-CIP+CoFe₂O₄ exhibited the highest value, followed by MRF-CIP+MnFe₂O₄, and lastly, MRF-CIP. Although the addition of nanoparticles reduces the magnetic saturation, it enhances the yield stress of MRF-CIP. The incorporation of nanoparticles enlarges the contact area among the particles within the MRFs, as similarly reported by Leong *et al.* [50]. Since the CIPs have a larger particle size (3.9-5.2 μm) compared to CoFe₂O₄ (147-211 nm) and MnFe₂O₄ (230-459 nm) nanoparticles, the smaller nanoparticles fill the gaps between the CIP and enhance the magnetic dipole interaction force under an applied magnetic field. As a results, the particle chains within the MRFs become more compact and mechanically stable, thereby increasing the yield stress. Furthermore, the smaller particle size correspond to a stronger interstitial filling effect, resulting in the higher yield stress observed in MRF-CIP+CoFe₂O₄ compared to MRF-CIP+MnFe₂O₄. The yield stress polynomial equations of each MRFs is shown in [Table 3](#). The fitness value of these equations was also demonstrated in the table.

To strengthen the reliability of the experimental and analytical results, a brief uncertainty assessment was conducted. For magnetorheological fluids, measurement

variability is dominated by field-induced particle microstructure, shear history, and possible sedimentation rather than by instrument resolution alone. Therefore, all rheological tests were performed using a standardized protocol involving thorough sample homogenization, fixed pre-shear and rest conditions, controlled temperature, and identical geometry and magnetic field settings. Selected measurements were repeated under identical conditions, showing good repeatability with only minor variability compared to the magnitude of the measured shear stress and viscosity. This repeatability-based variability represents the combined uncertainty relevant for engineering applications.

The rheological parameters used in the MR damper design were obtained from curve fitting of complete flow curves rather than individual data points, thereby reducing the influence of random measurement fluctuations. Furthermore, the calculated damping forces depend primarily on field-dependent yield stress and post-yield viscosity, which exhibited consistent trends across all tested conditions. These considerations indicate that the measured and calculated parameters are sufficiently reliable for the intended engineering analysis and design conclusions.

3.2. Pressure Drop and Damping Force Calculation

The magnetic flux density values in the MRV gap zones were determined using FEMM simulations. [Figure 13](#) displays the simulation results of the FEMM, while [Figure 14](#) illustrates the magnetic flux density charting different gaps of the MRV. The current was set to a constant value of 2 A. [Figure 14](#) illustrates a positive correlation between the gap value and the magnetic flux density value. The maximum magnetic flux density was obtained at a gap of 0.5 mm. This suggests that when the gap value lowers, the

Table 3. Yield stress polynomial formula and fitness value for the MRFs

MRF Type	Yield stress formula		R ²
MRF CIP	$\tau_y(B) = \begin{cases} 522.3B^3 + 176.67B^2 + 51.137B - 0.2432, & \text{for } \tau_y(B) > 0 \\ 0, & \text{for } \tau_y(B) \leq 0 \end{cases}$		0.9973
MRF CIP+CoFe ₂ O ₄	$\tau_y(B) = \begin{cases} 50.116B^3 + 187.28B^2 + 11.13B - 0.0483, & \text{for } \tau_y(B) > 0 \\ 0, & \text{for } \tau_y(B) \leq 0 \end{cases}$		0.9999
MRF CIP+MnFe ₂ O ₄	$\tau_y(B) = \begin{cases} 92.637B^3 + 119.67B^2 + 11.79B - 0.0354, & \text{for } \tau_y(B) > 0 \\ 0, & \text{for } \tau_y(B) \leq 0 \end{cases}$		1

magnetic flux density value increases. There is no substantial disparity in the magnetic flux across the three types of MRFs. The average magnetic flux density ranges from around 0.31 to 0.51 T.

3.3. Pressure Drop (ΔP) Calculation

The ΔP value was utilised to determine the performance of the MRV. The ΔP can be classified into three components: viscous ΔP (off-state conditions), yield ΔP (on-state conditions), and total ΔP . The results indicate the ΔP between the compressed position and the expanded position for different piston speeds. During extended or rebound conditions, the speed value becomes negative, and the cross-sectional area of the MRV becomes smaller compared to the cross-sectional area in compressed conditions. The cross-sectional area of the MRV decreases due to the presence of the piston rod, resulting in a reduced Q compared to the compressed condition. Figure 15 illustrates the changes in viscous ΔP on the MRV with various types of MRF.

In off-state conditions, the ΔP is influenced by the design effectiveness and properties of the

MRF. The higher the piston speed, the higher the viscous ΔP . The MRV design with a gap of 0.5 mm has the highest ΔP value in line with Eq. (4). It shows that the smaller the gap value, the greater the viscous ΔP . Of the three types of MRF used,

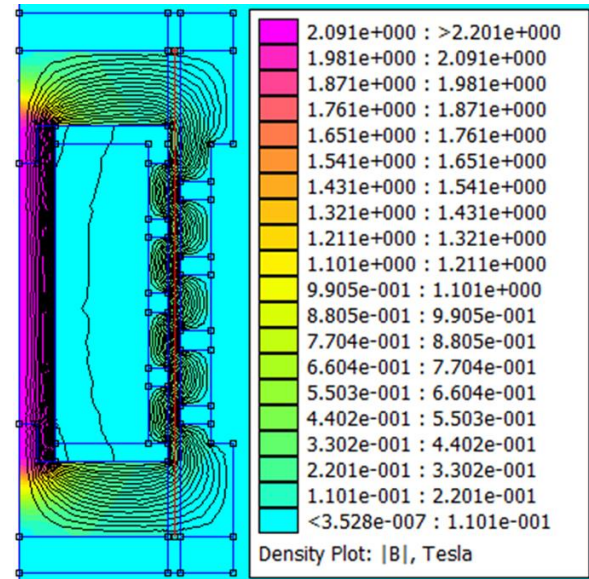


Figure 13. The correlation between yield stress and magnetic flux density of the MRFs

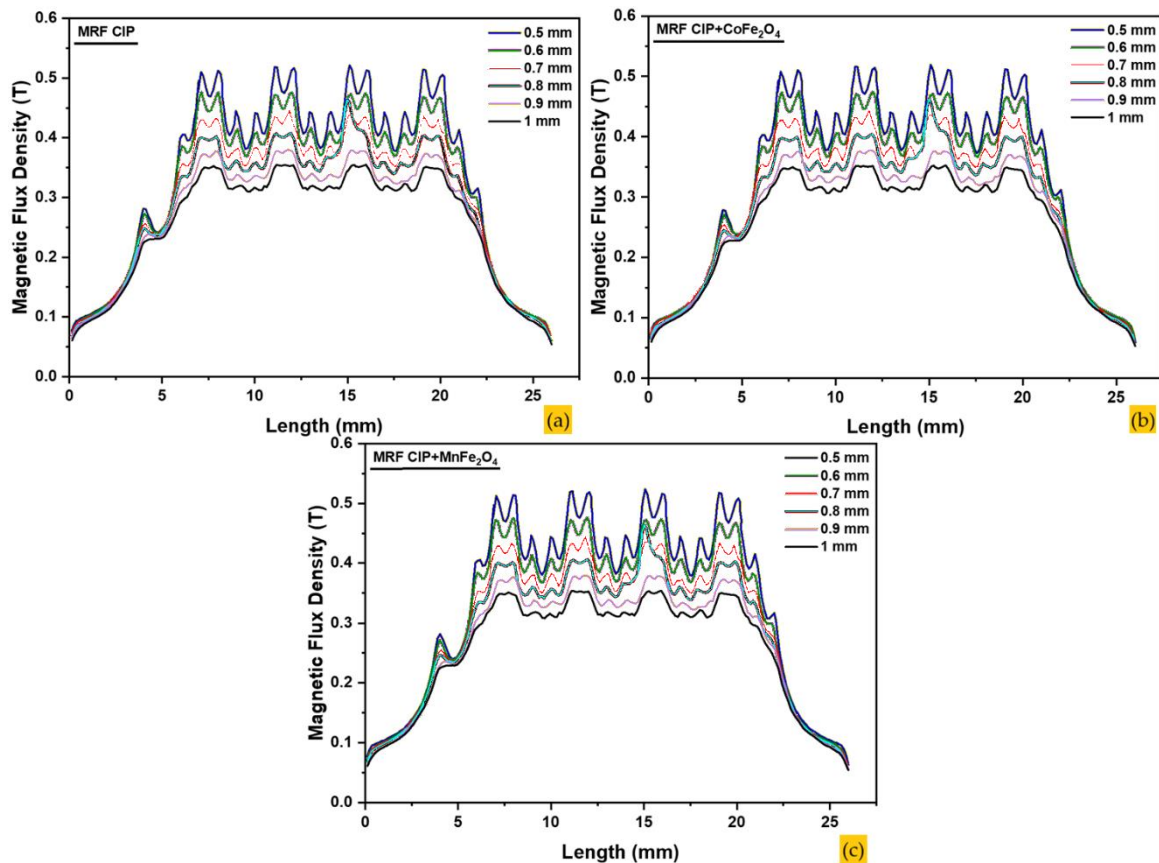


Figure 14. Distribution of the magnetic flux density from FEMM simulations: (a) MRF-CIP, (b) MRF-CIP+CoFe₂O₄, and (c) MRF-CIP+MnFe₂O₄

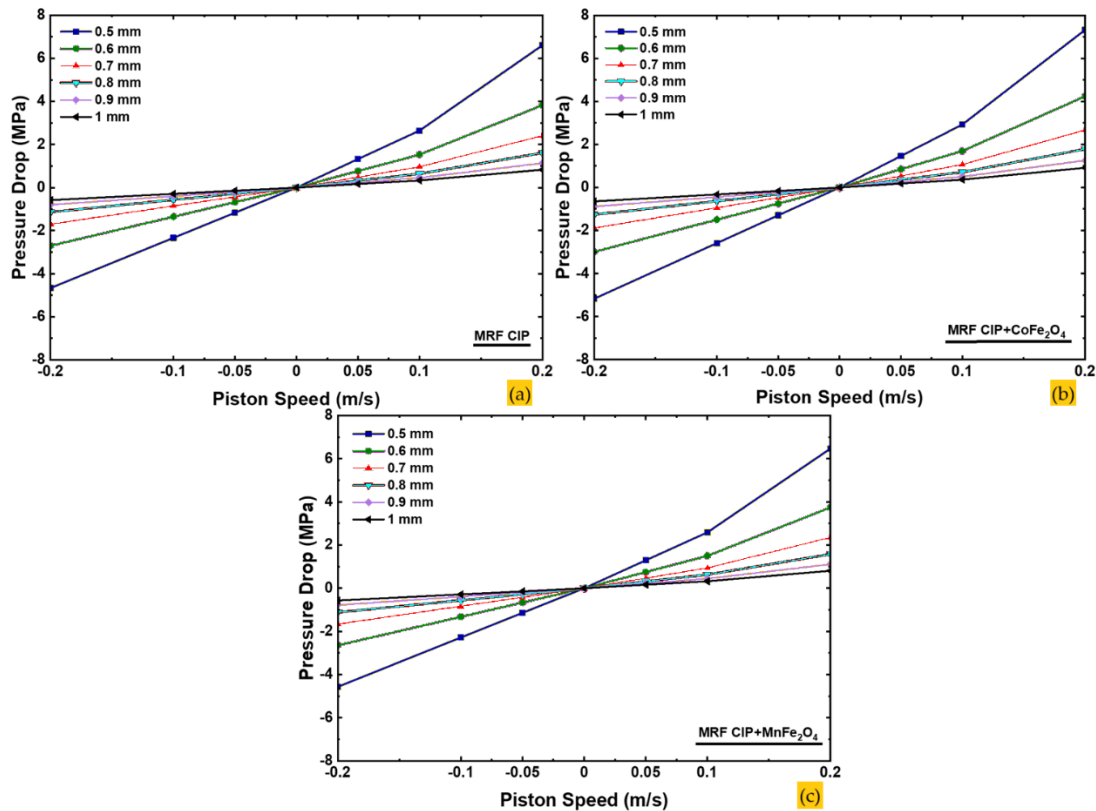


Figure 15. Pressure drop results in the off-state condition: (a) MRF-CIP, (b) MRF-CIP+CoFe₂O₄, and (c) MRF-CIP+MnFe₂O₄

MRF-CIP+CoFe₂O₄ had the highest average value at a 0.5 mm gap of 7.33 MPa. Whereas the viscous ΔP values of MRF-CIP and MRF-CIP+MnFe₂O₄ were 6.61 MPa and 6.47 MPa, respectively. Figure 16 illustrates the decrease in yield pressure (on-state conditions) for three different types of MRFs at various gap sizes. The result was obtained from the calculations in Eq. (5). The MRF-CIP+CoFe₂O₄ has the highest ΔP value at a gap of 0.5 mm, amounting to 9.61 MPa. The viscous ΔP values for MRF-CIP and MRF-CIP+MnFe₂O₄ were 7.99 and 7.96 MPa, respectively.

The total ΔP can be calculated by tabulating the viscous ΔP and yield ΔP , as indicated in Eq. (3) and Eq. (7). Figure 17 demonstrates the total ΔP across different piston speeds and variations in the MRV fluid gap. As the MRV fluid gap increased, the total ΔP decreased. The MRF-CIP+CoFe₂O₄ had the highest viscous ΔP at a gap of 0.5 mm and a piston speed of 0.2 m/s at 16.93 MPa. Meanwhile, the viscous ΔP values of MRF-CIP and MRF-CIP+MnFe₂O₄ were 14.6 and 14.43 MPa, respectively.

According to the results, there is a significant increase in the total ΔP (on-state conditions) compared to the pressure decrease caused by

viscosity in the off-state condition. Adding the current input can raise the pressure difference between the passive and active systems. Table 4 presents a comparison of ΔP between a passive system and an active system, with a piston speed of 0.2 m/s and a current input of 2 A.

3.4. Damping Force (F_d) Calculation

The prediction of F_d can be determined using Eq. (8). The F_d values determine the performance of an MRD. Figure 18 illustrates the relationship between the predicted F_d and the piston speeds of the MRD when using MRF-CIP, MRF-CIP+CoFe₂O₄, and MRF-CIP+MnFe₂O₄. The F_d values gradually increased in correlation with the piston speeds for all variations of MRFs, which has a same trend reported by Ubaidillah *et al.* [16]. The MRV that utilised MRF-CIP+CoFe₂O₄ and had a fluid gap of 0.5 mm exhibited the highest F_d , measuring 16.28 KN. Meanwhile, the maximum F_d of MRF-CIP and MRF-CIP+MnFe₂O₄ were 14.04 and 13.88 KN, respectively.

Based on the ΔP and F_d prediction results, as the fluid gap in the MRV decreases, the ΔP and F_d rise. This observation is in accordance with Eq. (4), Eq. (5), Eq. (6), and Eq. (7). The MRF-CIP+CoFe₂O₄

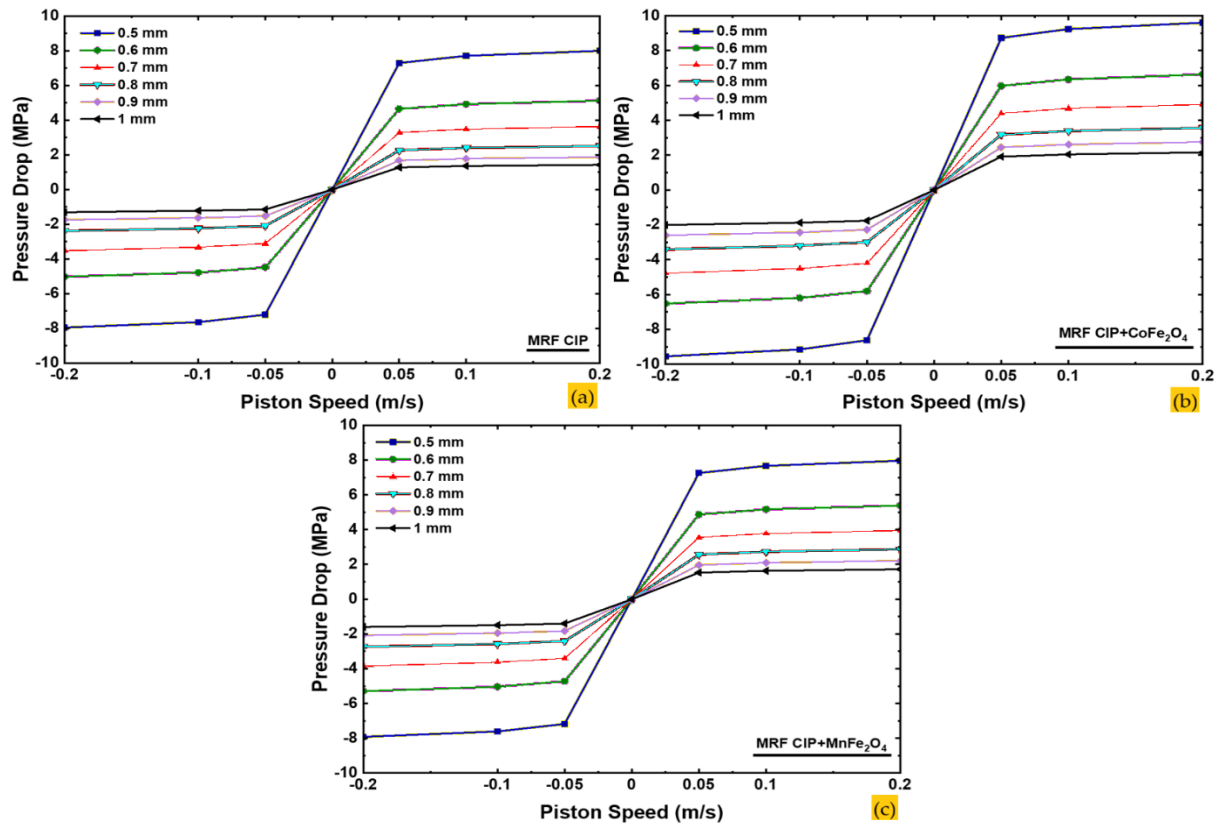


Figure 16. Pressure drop (Δp) results in the on-state condition (2 A): (a) MRF-CIP, (b) MRF-CIP+CoFe₂O₄, and (c) MRF-CIP+MnFe₂O₄

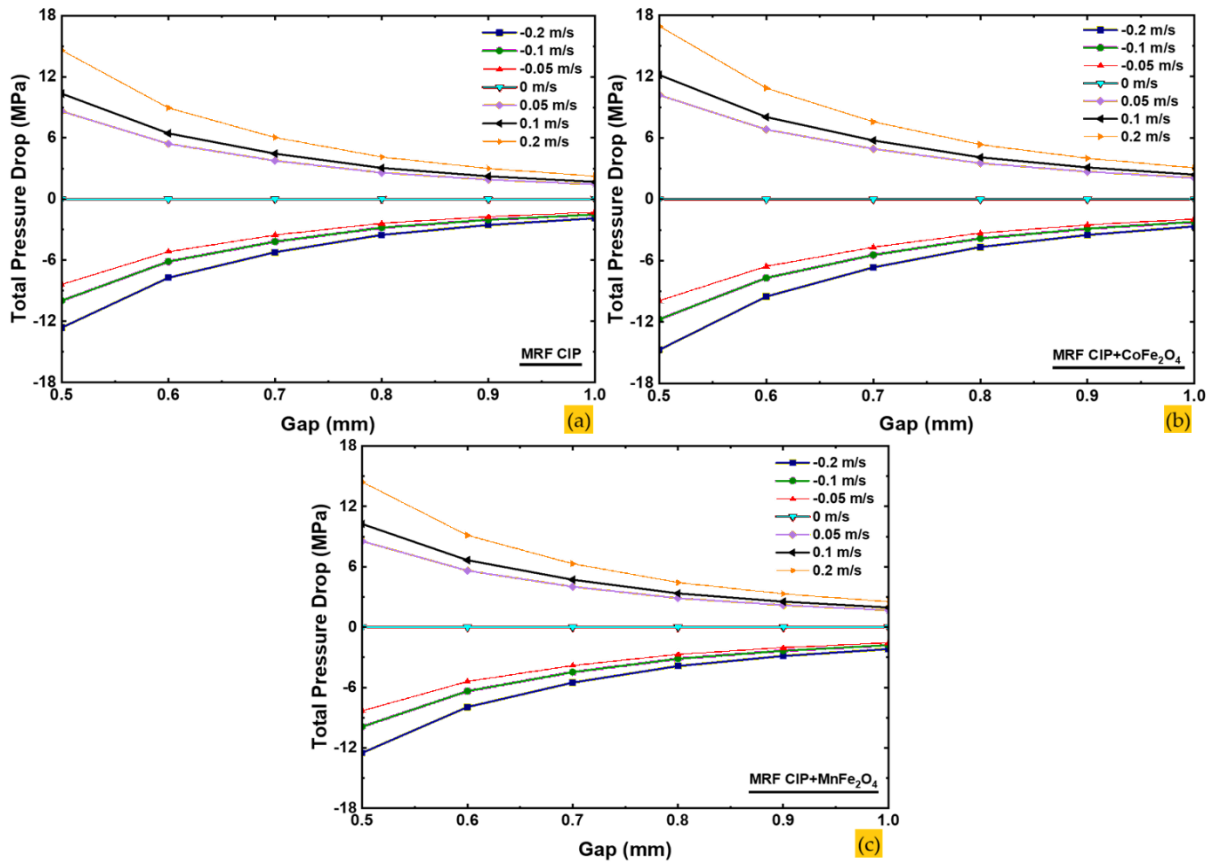


Figure 17. Effect of fluid gap on the total pressure drop: (a) MRF-CIP, (b) MRF-CIP+CoFe₂O₄, and (c) MRF-CIP+MnFe₂O₄

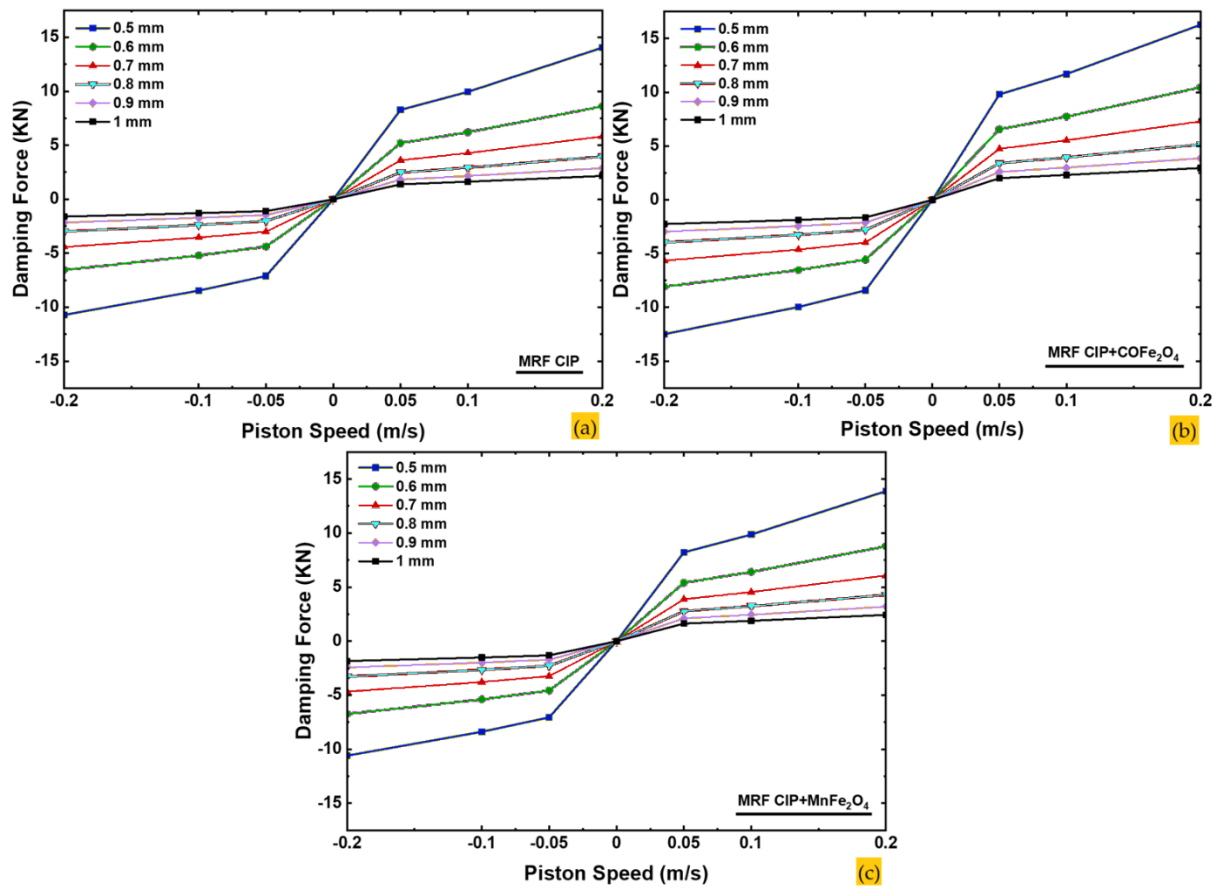


Figure 18. Damping force results in varying piston speeds and gap sizes: (a) MRF-CIP, (b) MRF-CIP+ CoFe₂O₄, and (c) MRF-CIP+ MnFe₂O₄

Table 4. Pressure drop comparison between viscous and total pressure drop (2 A) with a piston speed of 0.2 m/s

MRF Type	Viscous pressure drop (MPa)	Total pressure drop (MPa)	Enhancement (%)
MRF CIP	6.61	14.6	121%
MRF CIP+CoFe ₂ O ₄	7.33	16.93	131%
MRF CIP+MnFe ₂ O ₄	6.49	14.43	122%

exhibited better characteristics than MRF-CIP and MRF-CIP+MnFe₂O₄. The magnetic characteristics of CoFe₂O₄ nanoparticles are far superior than that of MnFe₂O₄. Furthermore, the addition of CoFe₂O₄ nanoparticles may enhance the magnetic characteristics of MRF and improve the performance of MRVs. As seen in Figure 3, the DRO of MRD for motorcycles requires only a maximum F_d of 1-3 kN. Based on Figure 18, the MRV with a fluid gap of 0.9 mm and MRF-CIP+CoFe₂O₄ could fulfil the required F_d for the MRD for motorcycles. It is necessary to evaluate the F_d for each current input variation and off-state conditions.

Figure 19 shows the MRV's F_d when the fluid gap is 0.9 mm and using MRF-CIP+CoFe₂O₄. The F_d increase proportionally with the rise in piston speeds and current inputs. The maximum

achieved F_d was 3.858 kN when the piston speed was 0.2 m/s and the current input was 2 A. Conversely, the minimum F_d attained was 0.941 kN

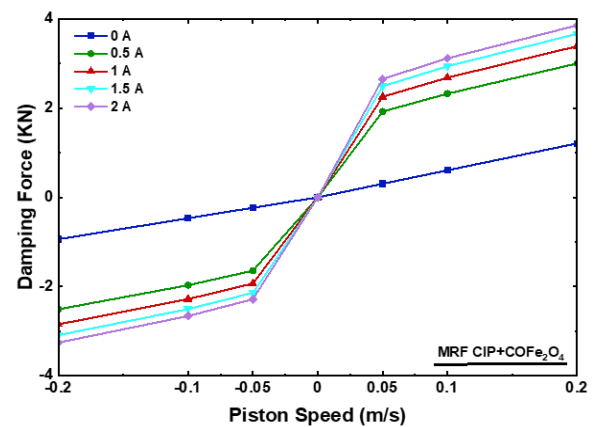


Figure 19. Damping force results in varying piston speeds and current inputs using a fluid gap of 0.9 mm

when the position was extended at a velocity of 0.2 m/s without any electrical current input (0 A). When the velocity was 0.05 m/s, the F_d was 0.235 kN when the system was in an extended position with no current (0 A), and 1.923 kN when the system was in a compressed position with a current of 2 A. Therefore, a greater F_d range directly correlated with improved MRD performance.

Table 5 presents an overview of the existing designs and developments analyses of different MRDs. In general, prior works have primarily focused on the enhancement of the damping performance without orienting the proposed design configuration toward specific practical implementation. Furthermore, the MRFs used were mostly based on commercial MRF-CIP without any modification to meets with specific operational requirements. In contrast, the proposed MRV design is primarily oriented for implementation in a motorcycle damper, incorporating MRF modification to achieve the

desired damping force range. The proposed MRV has a proportional dimensions, a wider F_d range (0.941 to 3.858 kN), and a 310% increase in F_d with small applied current of 0-2 A.

3.5. House of Quality (HoQ)

The house of quality (HoQ) is a tool that ensures alignment between costumer needs and the technical processes used in design development [51]. **Figure 20** displays the HoQ for the proposed MRD. The primary focus is on key performance parameters such as an F_d range of 1 to 3 kN, reduced energy consumption, suitability for diverse motorcycle types, and a compact design. These characteristics facilitate accurate manipulation, effectiveness, and seamless incorporation into various motorcycle systems.

The proposed MRD exhibits superior performance compared to three competing products, achieves an average rating of 4.32 (29%), and showcases exceptional capabilities and potential for extensive use.

Table 5. Comparison of prior works on magnetorheological dampers

Lead author, year	Effective area (mm ²)	Dimension s (mm)	Current (A)	Piston speed (m/s)	Coil type	MRF Type	Off-state damping force (KN)	Total damping force (KN)	Increment
Sohn, [52]	37.1	H=35, D=37.5	1	0.1	Copper, 100 turns	MRF CIP	0.154	0.875	468%
Desai, [35]	38.4	H=56, D=40.9	1.5	0.5	26 AWG, 500 turns	MRF-132DG	0.55	0.9	64% at 0.2 T
Ubaidillah, [16]	32	H= 30, D=30	0.5	0.2	28 AWG, 350 turns	MRF-132DG	0.114	0.415	264% at 0.1 T
Abdalaziz, [34]	138.96	H=60, D=64.5	2	0.0125	24 AWG, 215 turns	MRF-132DG	1.31	6.61	405%
Munyaneza, [53]	52	H=48, D=40	1.5	0.25	Electromagnetic coil, 304 turns	MRF-132DG	0.446	3.754	706% at 0.5 T
Current Design	46.8	H=30, D=35	2	0.2	28 AWG, 350 turns	MRF CIP+CoFe ₂ O ₄	0.941	3.858	310% at 0.35 T

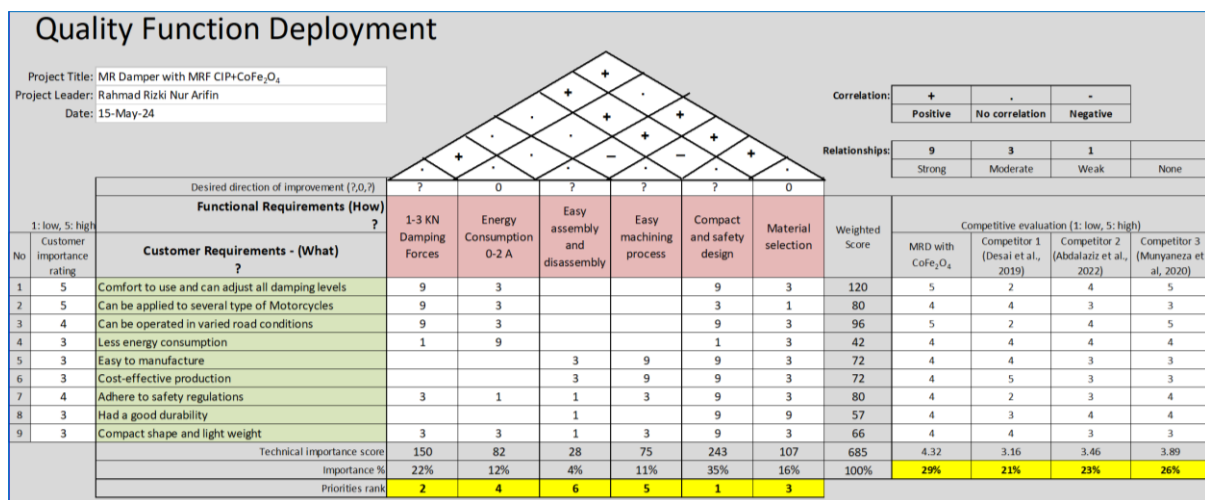


Figure 20. HoQ of the proposed MR damper

4. Conclusion

The MRF was successfully synthesised by incorporating soft and hard magnetic nanoparticles. The characterisation results were implemented in the MRD design. The MRV performance was evaluated using FEMM simulations. The MRFs utilised in this study were MRF-CIP, MRF-CIP+CoFe₂O₄, and MRF-CIP+MnFe₂O₄. The results demonstrate that, as the fluid gap of the MRV increases, the total ΔP decreases. Furthermore, the nanoparticle additives affect the F_d performance of the MRD. The addition of hard magnetic nanoparticles (CoFe₂O₄) enhanced the performance of the MRD. Conversely, the addition of soft magnetic nanoparticles (MnFe₂O₄) decreases the F_d of the MRF. The MRV with a fluid gap of 0.9 mm and MRF-CIP+CoFe₂O₄ exhibited the characteristics required to fulfil the DRO of MRD for a motorcycle suspension system, which requires an F_d range of 1 to 3 kN. The proposed MRV exhibited proportional dimensions, an extensive range, and an increase in F_d . The F_d ranged from 0.941 to 3.858 kN, demonstrating a rise of approximately 310%. This study provides evidence that the proposed MRV design and MRF alterations improve the performance of a motorcycle damping system, as supported by both the experimental and simulation findings.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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The authors declare no competing interest.

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