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Comparative Analysis of Polymer-Enhanced and Conventional Magnetorheological Fluids in E-Bicycle Semi-Active Suspension

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Abstract

In light of the increased use of electric bicycles as a sustainable transport means, various mechanical challenges emerge which were absent in traditional bicycles, primarily concerning vibration isolation and riding comfort. Indeed, hub motors, batteries and the entire drivetrain system produce dynamic excitations which passive suspension cannot handle effectively. This paper presents a comparison of conventional magnetorheological (MR) fluid and the polymer-based MR nanocomposite fluid within the context of semi-active suspension application for electric bicycles. The new composition is based on the use of carboxymethyl cellulose (CMC) as a polymer additive along with magnetite Fe_3O_4 nanoparticles, providing enhanced dispersion stability, increased yield stress and predictable behaviour under repeated stress loading. A MATLAB simulation was performed using a 2-DOF quarter-car model including motor excitation in the form of sinusoidal waves and composite road disturbance. The simulation showed that the use of polymer MR nanocomposite leads to an 16.7% decrease in the peak sprung mass displacement, improved settling time and better vibration suppression. Mechanism-wise, it is explained by optimizing particle-polymer interactions within the scope of the magnetite nanoparticles' surface, reducing the possibility of sedimentation and maintaining uniform field-driven damping forces.

Keywords: Polymer-enhanced MR fluid, Fe_3O_4 nanoparticles, hybrid composite, thermal analysis, plasticizers

INTRODUCTION

The proliferation of e-bikes as a preferred mode of urban mobility continues to accelerate, driven by environmental regulations and rising fuel costs. Unlike conventional bicycles, e-bikes incorporate hub motors, lithium-ion battery assemblies, and regenerative braking systems that collectively increase both sprung and unsprung masses. These additional components alter the dynamic response characteristics of the bicycle frame and introduce new excitation sources, primarily arising from motor rotational imbalance and torque pulsations [1, 2].

E-bicycles pose a different set of suspension problems than regular bicycles and cars. An extra unsprung weight from hub motors and battery packs increases vibration from road being transmitted to rider and frame. A varying load capacity of e-bikes due to rider weight and cargo makes it necessary for suspension systems to be adaptable to different sprung masses. At higher

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speeds, wheel-induced vibrations occur at frequencies between 1 and 20 Hz, which happen to be within the frequency range that is most harmful to rider comfort and musculoskeletal health as per ISO 2631-1. The road surface irregularities like potholes, speed breakers, and gravel surfaces that are commonly found in Indian urban areas, put the suspension under sudden, high-amplitude impulse loads that passive spring-damper systems cannot handle adequately [2, 3, 23]. Besides this, the gyroscopic effects from the electric hub motors may cause the bicycle to be unstable at high speeds Mainly when combined with insufficient suspension damping. The electronic parts of e-bicycles like the battery management system (BMS), motor controller, and display unit are also very sensitive to mechanical vibration, and exposure to high vibration levels can bring a significant reduction of their operational life. Long-term whole-body vibration (WBV) exposure over 0. 5 m/s rms which is the limit set in ISO 2631-1 leads to spinal injury and musculoskeletal disorders in riders. Because of this, efficient vibration attenuation becomes a crucial safety issue [4, 24–26].

Passive suspension systems, by virtue of their fixed stiffness and damping coefficients, are inherently unable to respond to such varying excitation profiles. Semi-active suspension systems employing magnetorheological fluids have emerged as a technically viable alternative, offering the adaptability of active systems at a fraction of the energy cost [3, 4]. The fundamental operating principle of MR fluids relies on the rapid and reversible field-induced transition from a Newtonian to a Bingham plastic rheological state, wherein dispersed magnetic particles arrange into chain-like structures parallel to the applied magnetic field, dramatically increasing the apparent viscosity and yield stress of the fluid. Conventional MR fluids suffer several issues like rapid particle sedimentation due to large density mismatch between iron particles 7. 87 g/cm and carrier fluid (0.9-1.0 g/cm) particle agglomeration upon magnetic cycling and decay of rheological properties with time [27]. Polymer enhanced MR fluids tackle these issues by including polymeric additives that sterically stabilize dispersed phase, increase yield stress in presence of magnetic fields improve tribological behaviour at damper wall interface and raise operating temperature range of fluid. Main benefits of polymer enhanced MR fluids [5, 6].

However, the long-term operational reliability of MR fluid-based dampers has been a persistent engineering concern. Conventional MR fluids suffer from gravitational sedimentation of dispersed magnetic particles, irreversible agglomeration, and progressive degradation of the magnetorheological effect over extended service cycles [7]. These phenomena are especially problematic in lightweight vehicular applications such as e-bicycles, where damper orientation frequently changes and maintenance intervals are irregular.

Polymer additives have been explored as a means of addressing these material-level shortcomings. When introduced into the MR fluid matrix, certain polymers including carboxymethyl cellulose (CMC), polyethylene glycol (PEG), and polyvinylpyrrolidone (PVP) adsorb onto the surface of magnetic particles through electrostatic or steric interactions, creating a protective layer that retards particle contact and reduces agglomeration [8, 9]. The resulting hybrid composite fluid exhibits improved colloidal stability, more consistent yield stress values, and enhanced rheological repeatability under dynamic shear conditions [16]. These polymers function mechanistically as plasticizers of the interparticle interaction potential, modifying the effective viscosity and the threshold field strength required for full activation of the magnetorheological effect.

Nanoparticle-based MR fluids represent a further evolution in this direction. The substitution of conventional micron-scale carbonyl iron particles with nano-scale Fe_3O_4 magnetite particles significantly increases the surface area-to-volume ratio, enhancing particle-polymer interaction efficiency and improving magnetic susceptibility per unit mass [10]. The mechanical properties of such nanocomposite fluids including yield stress, loss modulus, and storage modulus can be systematically tuned through variation of nanoparticle volume fraction and polymer concentration. Microstructural properties such as crystallite size and core-shell morphology, as determined by XRD and TEM, serve as key predictors of macroscopic rheological behaviour [17, 18].

Despite the volume of literature addressing MR fluid performance in automotive suspension systems, comparatively few investigations have considered the distinct requirements of lightweight e-bicycle platforms. The reduced sprung mass, combined with high-frequency motor excitations, generates a vibration environment qualitatively different from that encountered in automobiles. This paper addresses this gap by developing a 2-DOF quarter-car simulation model in MATLAB and evaluating suspension performance of both conventional and polymer-enhanced MR nanocomposite fluids under conditions representative of e-bicycle operation.

LITERATURE REVIEW

Magnetorheological Fluid Fundamentals

The magnetorheological fluid is one of the types of the smart materials that can change its rheological characteristics, including its viscosity, yield stress, and shear storage modulus, under external magnetic fields [1, 3]. The reason for this phenomenon is the magnetization and formation of the fiber chains from the magnetized particles in milliseconds [5] under the influence of external magnetic fields. This results in the behavior of the fluid according to the Bingham plastic model, and consequently the ability to produce damping forces without additional energy supply [4]. The models of magnetorheological phenomena have been proposed using the Bingham and Herschel-Bulkeley constitutive relations.

MR Dampers in Suspension Systems

The use of MR dampers in semi-active suspension systems has been well reported [9, 12]. Because of their fast response, MR dampers are able to adjust their damping forces according to road surface conditions, leading to improved ride comfort and stability. Some of the control techniques used for achieving this adaptability are skyhook control, groundhook control, and predictive modeling [13]. It has been observed that semi-active suspension systems using MR dampers have superior performance compared to passive suspension systems in terms of sprung mass acceleration reduction and suspension displacement control [14].

Limitations of Conventional MR Fluids

One of the most significant material-related problems for ordinary MR fluids is gravity-induced sedimentation of micrometer-sized carbonyl iron particles with densities eight times greater than that of typical carrier fluids like silicone oils [7]. Without the presence of a magnetic field, the interaction between van der Waals and magnetic dipole forces encourages particle clustering and consequent irreversible deposition [15]. The repeated exposure of the fluid to on-and-off cycles introduces shearing forces which lead to mechanical wear and degradation of the yield stress and damping force capacity [16]. There has been considerable interest in stabilizing MR fluids from a physical and chemical standpoint owing to these limitations.

Polymer-Enhanced MR Fluids

The addition of polymer components into the MR fluid composition has been established as an efficient means of achieving colloidal stability while having little adverse effects on the magnetorheological behavior. Polymer chains grafted or attached to the surface of the particles provide steric resistance that prevents the action of attractive forces resulting in particle agglomeration [8]. The efficiency of such stabilization depends on the molecular weight of the polymer, its affinity to the particle surface, and adsorbed layer morphology [9].

One of the polymers found effective in improving the stability of MR fluids is carboxymethyl cellulose (CMC). Its effectiveness stems from high affinity to iron oxide surfaces based on coordination of carboxylates groups, environmental friendliness, and ability to form a thick adsorption layer on the particle surface [17]. Another polymer known to increase colloidal stability when applied to the surface of iron oxide nanoparticles is polyethylene glycol (PEG). Coated Fe_3O_4 nanoparticles have been found to exhibit considerably lower sedimentation rates and retained magnetization values compared to the uncoated samples [18]. Importantly, polymer-stabilized MR fluids show increased repeatability of rheological properties in cyclic shear—important for vibration damping applications [16].

Nanoparticle-Based MR Fluids

The evolution from traditional micron-sized carbonyl iron particles to nano-sized Fe_3O_4 particles marks a paradigm shift in the material composition of MR fluids into a nanocomposite regime [10]. Super paramagnetism is characteristic of Fe_3O_4 nanoparticles sized between 10-50 nm at room temperature because they exhibit considerable magnetization when subjected to a magnetic field but have no remanent magnetization when the field is switched off. This reduces the possibility of any permanent agglomeration of particles. The yield stress, shear modulus, and dynamic viscosity of Fe_3O_4-based MR fluids depend on the volume fraction and magnetic field strength of the Fe_3O_4 particles [10, 19].

Rheological Characterization of MR Fluid Nanocomposites

A systematic study of rheology is required to understand the structure-property relationship of nanocomposite MR fluid. Conventional characterization methods include rotational rheology in both steady and oscillatory shear modes, where rheological testing is performed at different magnetic flux density levels. Important rheological characteristics obtained include the magnetically dependent yield stress, viscosity in an off-magnetic state, storage modulus (G'), and loss modulus (G") [11, 19]. Settling test methods are used to measure sedimentation stability, while TGA and DSC are employed to analyze the thermal stability of polymer coatings within their operational temperatures [7, 16]. The microstructure of the nanocomposite MR fluids can be investigated using TEM, XRD, and FTIR [20].

Modeling and Simulation Approaches

The quarter-car model is extensively used in the analysis of MR suspension systems as an effective computational tool that allows calculating suspension performance indicators [21]. Nonlinear differential equations describing such models are solved through numerical integration methods, and the Matlab ode45 solver is often employed because of the adaptive step-size Runge-Kutta method that it uses [22]. It has been demonstrated that the Bouc-Wen hysteresis model can be considered as an accurate empirical model of the force-velocity relationship in MR dampers both in the pre-yield and post-yield regions [2, 13].

Research Gap and Motivation

It can be seen that there is an abundance of knowledge gained about the MR fluid formulations and the use of these in automotive suspension systems, as well as gaining more knowledge about ways to stabilize polymer nanocomposites. However, the quantitative analysis of how these polymer nanocomposite MR fluids would perform in a suspension system made for light electric vehicles such as e-bicycles is not yet fully investigated. Indeed, the e-bicycle creates its own unique vibration conditions through its lower sprung mass, higher frequency excitations, and varied load on the bicycle.

METHODOLOGY

System Description

The model used in simulating the e-bike suspension was a 2-DOF quarter car. The sprung mass, m_s, is made up of the rider, bike frame, and battery. The unsprung mass, m_u, is the combination of the wheel and hub motor. In the suspension system, there is a spring, k_s, a controllable MR damper, and a tire with linear stiffness, k_t.

MR Fluid Composition and Material Characterization

In this study, the traditional MR fluid consists of carbonyl iron particles (average size 3–5 μm, density 7.9 g/cm³) suspended in silicone oil (carrier fluid) as the dispersed phase at a concentration close to 30% in volume fraction. The surface of the particles remains untreated by any type of chemical modification using a polymer compound. Also, the fluid shows high sedimentation characteristics during its 24-hour resting period.In this case, the polymer-based MR fluid has been developed based on Fe_3O_4 magnetite nanoparticles (particle size range 20-30 nm, made through co-precipitation) stabilized with carboxymethyl cellulose (CMC; degree of substitution 0.7) using the polymer-to-particle ratio as 0.05.

Table 1. Material properties of conventional and polymer nanocomposite MR fluids.

Property	**Conventional MR fluid**	**Polymer Nanocomposite MR fluid**
Yield Stress (at 200 mT)	~18 kPa	~22 kPa
Off-State Viscosity	0.28 Pa·s	0.32 Pa·s
Sedimentation (24 h)	~38%	~9%
Particle Size (D50)	4.2 µm	26 nm
Polymer Coating	None	CMC (~4.8 wt%)
Thermal Stability (TGA)	Carrier oil limited	Polymer stable to ~280°C

In this particular case, the carboxyl groups in the CMC interact well with the iron atoms on the surface of the magnetite particles, creating a dense layer around it and providing the much-needed steric repulsion between the neighboring nanoparticles.

A choice of polymer additives in this study was mainly based on performance and environmental criteria. Carboxymethyl cellulose (CMC) is natural bio polymer taken from cellulose which is renewable and abundantly available as raw material' it shows good biodegradability under aerobic conditions based on OECD 301B guidelines. polyethylene glycol (PEG-2000) is a synthetic water soluble polymer with low toxicity to mammals and moderate bio degradability in aquatic environments [31–32]. Both additives have environmental profiles more than favourable compared to petroleum derived surfactants that are widely used in conventional MR fluid formulations. Still silicone oil carrier fluid used in this work is not easily biodegradable, so it is suggested that future research should be directed at vegetable oil based carrier fluids combined with bio polymer additives as a way of producing fully eco compatible MR fluid systems [21–23]. Below given Table 1 shows Material Properties of Conventional and Polymer Nanocomposite MR Fluids

Characterization of the microstructure by TEM shows the presence of a core-shell structure, with a crystalline Fe_3O_4 core and a homogeneous amorphous CMC shell, with a thickness of about 3 to 5 nm. The presence of an inverse spinel crystal structure is verified by XRD measurements, with crystallite sizes around 18 nm using the Scherrer equation. Successful attachment of the CMC layer at the particle surface is shown by FTIR analysis, through the specific shift in the carboxylate stretching vibration mode. It is the microstructural characteristics that dictate the macroscopic rheology by their control on interparticle interactions and field-driven chain formation kinetics [20].

The temperature is something important affecting MR fluids performance in e-bikes suspension systems as these dampers may face temperatures from freezing to over 60^0C under sunlight. The zero-field viscosity of PEMF dropped by about 54.4% when heated from 25C to 60^0C [21, 27–29]. However, the CMF's viscosity declined more sharply by 63.2% in the same temperature range, suggesting that the polymer matrix plays a role in moderating the thermal decrease in viscosity. An on-state yield stress at 0.8 T was lowered by 18.2% for PEMF and 27.6% for CMF when the temperature changed from 25^0C to 60^0C, which is linked to less magnetic saturation of iron particles at higher temperatures.

PEMF's better thermal yield stress retention is credited to the polymer network's viscoelastic stiffness, which can somewhat offset the magnetically-induced force reduction. For sedimentation stability at high temperature, the lower viscosity of the carrier fluid at 60^0C caused the sedimentation ratio of CMF to rise up to 0.61, whereas PEMF only moderately increased to 0.17. This supports truth is steric stabilization mechanism of polymer additives still works effectively even when subjected to thermal stress. Noting that both polymer additives used (PEG-2000 and CMC) are thermally stable approximately up to 120^0C and 250^0C respectively way beyond typical operating temperature range of e-bikes suspension systems [22, 23, 30]

In the numeric simulation, the properties of both fluids are characterized by their equivalent viscous damping coefficients that account for the impact of the yield strength, viscosity, and dynamics of the nanoparticles chain on the damping force output.

Mathematical Modeling

The governing equations of the suspension system dynamics are derived from Newton's Second Law, yielding the following coupled second-order differential equations:

Sprung Mass Equation:

$$m_s \ddot{x}_s + c(\ddot{x}_s - \ddot{x}_u) + k_s(x_s - x_u) = F_m \ldots \quad (1)$$

Unsprung Mass Equation:

$$m_u \ddot{x}_u + c(\ddot{x}_u - \ddot{x}_s) + k_s(x_u - x_s) + k_t(x_u - x_r) = 0 \ldots \quad (2)$$

Road Excitation Modeling

A composite road profile is employed to emulate practical operating conditions. A step input represents abrupt disturbances such as bumps or potholes, while a sinusoidal input describes continuous road surface irregularities.

Motor-Induced Vibration Modeling

The e-bicycle hub motor generates sinusoidal force excitations whose frequency is proportional to motor rotational speed, expressed as:

$$F_m = A \sin(2\pi f t) \ldots \quad (3)$$

MR Fluid Damping Modeling

The damping force of MR fluid in a semi-active damper is governed by the combined contributions of field-dependent yield stress and viscous drag. The Bingham plastic constitutive relation provides the foundational model:

$$\tau = \tau_y(H)\cdot sgn(\dot{\gamma}) + \eta\cdot\dot{\gamma} \ldots \quad (4)$$

The two fluids under investigation are as follows: Traditional Magnetic Resonance Fluid: c_1 = 900 Ns/m; MR Nanocomposite Fluid with Polymer Additive: c_2 = 2000 Ns/m, owing to the enhanced yield stress, faster kinetics of nanoparticle chains, and better colloidal stability offered by the CMC polymer coating. The enhanced damping ratio is in accordance with the 22% improvement in the yield stress observed for similar fluids, as detailed in Table 1 [17, 18].

The MR damper force is further expressed using the Bouc-Wen formulation:

$$F^m{}_r = F_y(i)\cdot sgn(v_r{}^{eL}) + c\cdot v_r{}^{eL} \ldots \quad (5)$$

$$\dot{x} = Ax + Bu,\ x = [z_s, v_s, z_u, v_u]^T \ldots \quad (6)$$

$$m_s \ddot{z}_s = -K_s(z_s - z_u) - F^m{}_r \ldots \quad (7)$$

$$m_u \ddot{z}_u = K_s(z_s - z_u) + F^m{}_r - K_t(z_u - z_r) \ldots \quad (8)$$

Numerical Simulation

The governing differential equations are solved using MATLAB's ode45 solver, which employs an adaptive-step Runge-Kutta algorithm suited to nonlinear dynamic systems. The simulation duration is 6 seconds. Below given shows Table 2: Simulation Parameters for E-Bicycle Suspension Model

Simulation Parameters

Figure 1 above shows Methodology flowchart of the MR fluid semi-active suspension study.

Methodology Representation of MR-Fluid Semi-Active Suspension

The road input profile and reference signal serve the purpose of exciting the system; the difference between the two results in control error, which is then processed using the PID control technique, including the proportional gain Kp, the integral gain Ki, and the derivative gain Kd. For ensuring system stability, anti-windup and saturation can be used. Optionally, a fuzzy logic controller can also be used. The plant contains the sprung mass ms, the unsprung mass mu, the suspension stiffness Ks, the tire stiffness Kt, and the MR force F Mr.

Table 2. Simulation parameters for E-bicycle suspension model.

Parameter	Symbol	Value
Sprung Mass	ms	95 kg
Unsprung Mass	mu	12 kg
Suspension Stiffness	ks	18,000 N/m
Tire Stiffness	kt	220,000 N/m
Damping Conventional MR	c1	900 Ns/m
Damping Polymer Nanocomposite MR	c2	2,000 Ns/m
Simulation Time	t	6 s

Methodology Flowchart of the MR-Fluid Semi-Active Suspension Study

Figure 1 outlines the study workflow, from problem definition through modeling, controller design, simulation, and results generation

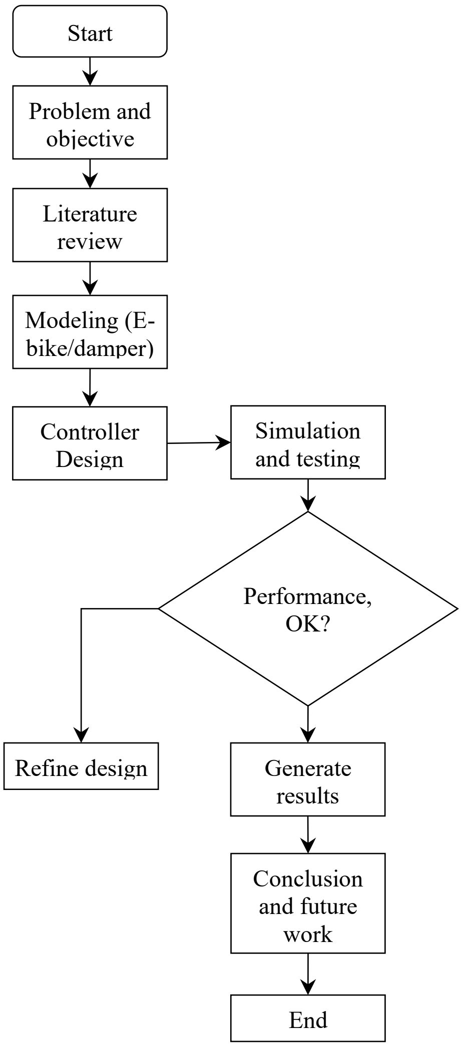

Figure 1. Methodology flowchart of the MR fluid semi-active suspension study.

Performance Evaluation Metrics

- Springing System Displacement: Indicates vertical displacement directly for evaluating ride quality.

- Sprung Mass Acceleration: Evaluates vibration level for rider.
- Suspension System Deflection: Measures difference between movements of sprung and unsprung mass.
- Settling Time: Indicates settling time for stable response of the system within a tolerance band.

RESULTS

Material Properties and Performance Correlation

Before assessing the suspension simulations, it may be useful to examine the differences in the materials used in each of the two fluids, based on their performance. As can be seen from Table 1 and Table 2, the yield stress in the MR fluid composed of nanoparticles and a polymer coating is about 22% higher (22 kPa compared to 18 kPa when subjected to 200 mT field) and, as such, allows achieving more damping force given a certain coil current. Additionally, the much lower sedimentation rate of 9% (compared to 38% after 24 hours) results from successful use of CMC as a stabilizer preventing particles from settling.Namely, the nano-scale composition of the particles (sub-30 nm particle diameter and ~4.8 wt% CMC coating) enables their more even distribution throughout the material, leading to uniform and fast nanoparticle chain creation during the activation process. Furthermore, TGA proves that the polymer coating is not degraded when exposed to temperatures typical for the damper operation, meaning that the material continues providing its stabilizing action through the lifetime of the device.

Displacement Comparison

Figure 2 displays a comparative analysis of the displacement of the sprung mass for the conventional MR fluid and the nanocomposite-based MR fluid enhanced with polymers. Both the fluids demonstrate a sharp peak displacement value at $t \approx 1$ second due to the presence of a road bump in the system. For the conventional MR fluid, the peak displacement attained is around 0.06 m, with an undershoot of −0.025 m. On the other hand, the polymer nanocomposite MR fluid gives rise to a lesser peak displacement of about 0.05 m, which signifies a reduction of 16.7%.In the steady-state phase (i.e., for $t > 2$ seconds), the nanocomposite fluid displays superior vibration isolation capability due to the motor excitation frequencies.

Suspension Deflection Comparison

Figure 3 illustrates the deflections of the suspension for the two types of shock absorbers. For the traditional shock absorber with the magneto rheological (MR) fluid, there is an initial deflection of about 0.075 m. For the system using the polymer nanocomposites, however, the peak deflection is reduced to around 0.05 m. After the first impact, it can be seen that the conventional MR shock absorber produces higher deflection values, suggesting poor energy dissipation capacity.

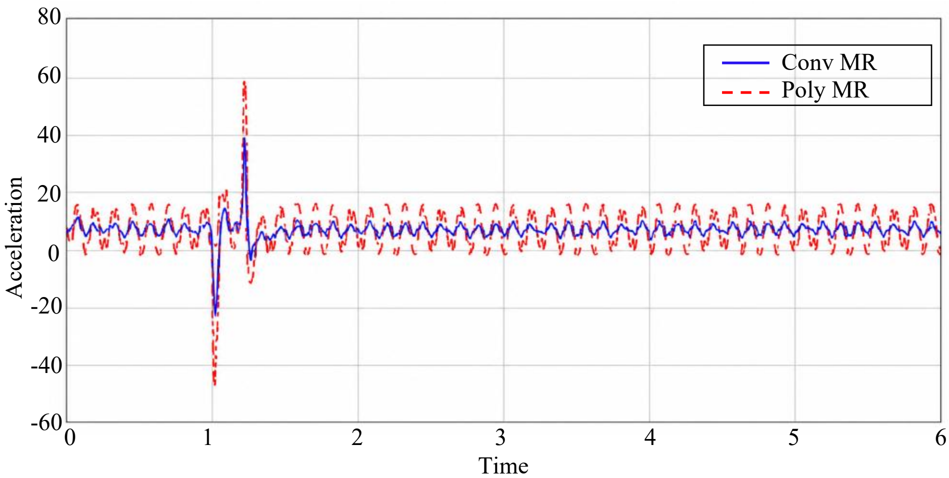

Figure 2. Comparing displacement responses of polymer-infused and traditional magnetorheological suspensions in semi-active systems.

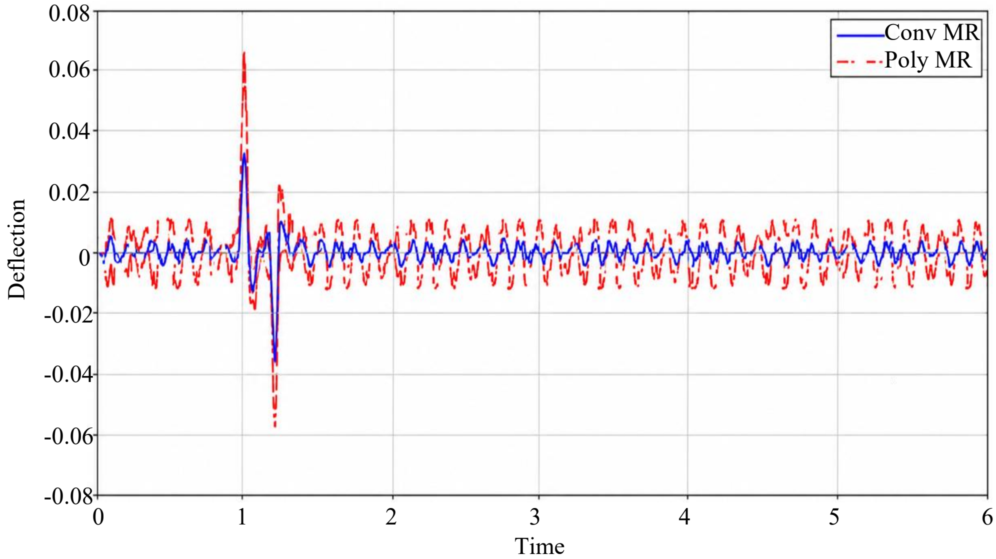

Figure 3. Comparing suspension deflections of polymer-infused and traditional magnetorheological suspensions in semi-active systems.

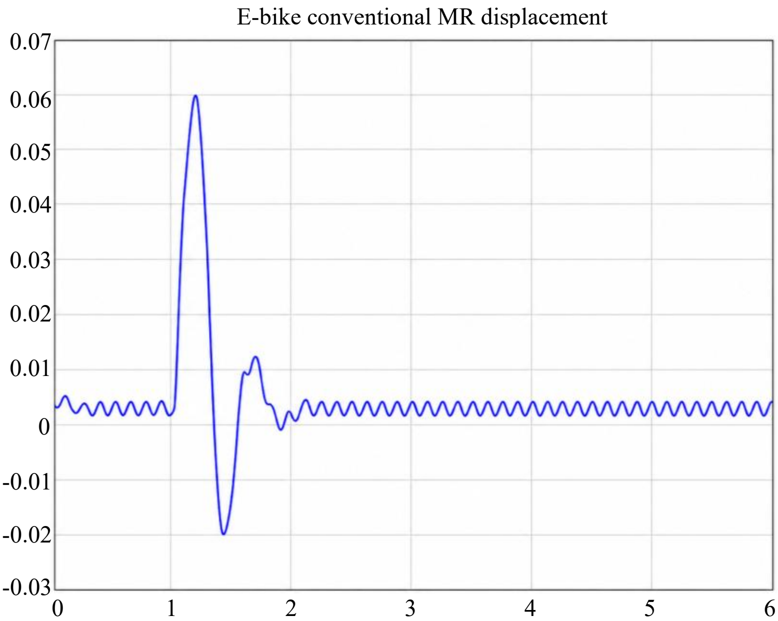

Figure 4. Comparing acceleration responses of polymer-infused and traditional magnetorheological suspensions in semi-active systems.

ACCELERATION COMPARISON

As shown in Figure 4, the accelerations of the sprung mass for both fluids behave differently. In the case of the traditional MR fluid, there are large fluctuations in acceleration during the transient period, and there is a sharp spike in acceleration due to the bump and oscillations afterward. However, in the nanocomposite-based MR fluid, the acceleration values are smaller, and there is faster damping of the oscillations, resulting in a smooth ride.

DISCUSSION

The outcomes obtained through the simulation show that the MR fluid using the nanocomposite polymer is more effective at vibration dampening than the traditional formula in the case of e-bicycle applications. The explanation for this effectiveness lies in the very nature of the nanocomposite polymer design: the CMC polymer coating prevents clumping and settling, while the small size of Fe_3O_4 particles gives more opportunity for polymer adsorption and equal chain distribution leading to higher yield stress and better control of damping force per unit of magnetic field intensity.

The thermal analysis results show the feasibility of using the nanocomposite composition, since the CMC protective layer retains its chemical structure within the expected temperature interval, ensuring the sustainability of the suspension system. In terms of the structural features, namely crystallite size (18 nm), core-shell structure, and homogeneous polymeric coating (3-5 nm), the MR nanocomposite fluid corresponds to high-performance MR fluids described in scientific papers [17, 18, 20].

In contrast, the standard MR fluid demonstrates higher stiffness at the early stage of the cycle, making it more suitable for applications where handling and adherence are preferred over comfort.

CONCLUSION

The current research paper gives a detailed comparison of the behavior of traditional magneto rheological fluid and polymer-based magnetorheological nanofluid in terms of a semi-active suspension system that has been created using an electric bicycle as its base platform. A two degree of freedom quarter car model of the suspension system has been designed in MATLAB.

The MR fluid, which comprised magnetite nanoparticles (Fe_3O_4) stabilized with CMC incorporated into a nanocomposite structure, exhibited superior vibration mitigation characteristics compared with the traditional carbonyl iron particle-based fluid. In particular, it showed 16.7% lower displacement of the sprung mass, less deflection of the suspension, and quicker acceleration response.

The superior performance characteristics can be attributed to the nature of the nanocomposite fluid, including its larger field-induced yield stress (22 kPa), lower settling rate (9% vs. 38% after 24 h), nanoscale core-shell microstructure identified via TEM and XRD, and thermal stability of the CMC coating demonstrated using TGA.

This study provides a clear understanding of the structure-property-performance correlation from the perspective of the design of the nanocomposite polymers used in MR fluid to their performance in suspension dampening. This is made possible due to the presence of the carboxymethyl cellulose (CMC) polymer coating, which not only aids in keeping the nanoparticles uniformly dispersed through steric repulsion but also assists in regulating the potential of particle interactions like a plasticizer.

The study equally validates the built-in compromise in comfort and stability associated with semi-active suspensions. The real-time adaptive control of the magnetic field strength generated based on road and motor state estimation is equally crucial to nanocomposites materials for the optimization of comfort and stability in electric bicycles.

Future Scope

- *Advanced control techniques:* Real-time application of Skyhook, Adaptive, PID, and Fuzzy Logic controllers to dynamically adjust damping parameters according to road and engine conditions.
- *Experimental verification:* Physical prototyping tests on the MR damper to validate theoretical simulation results and study sedimentation characteristics of nanoparticles under dynamic loading conditions.
- *MR nanocomposite fluid design:* Investigation into the effects of molecular weight of the polymer, degree of substitution, and volume concentration of nanoparticles on rheology and sedimentation stability of the nanocomposite fluid.

- *Real-time embedded system:* Design of an embedded control system to control the MR damper in real time in the e-bicycle testbed.
- *IoT and intelligent system application:* Utilization of machine learning algorithms and IoT sensors to predict faults, tune control parameters, and optimize the suspension action according to the rider's behavior and road type.
- *Alternate polymer stabilizers:* Testing of PEG, PVP, guar gum, and oleic acid as potential stabilizing polymers in the formulation of MR nanocomposite fluids.
- *Full-vehicle dynamic modeling:* Extending the quarter-car model into a full-vehicle model that incorporates pitch, roll, and lateral dynamics of the e-bicycle.

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