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Sliding Mode Control of Magnetorheological Fluid Damper to Mitigate Impact Loads in Semi Active Isolation Systems

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ABSTRACT

This paper presents a robust sliding mode control (SMC) strategy for regulating a magnetorheological fluid damper (MRFD) in a semi-active impact isolation system subjected to high-intensity transient loads. Conventional passive and proportional–integral–derivative (PID)based damping systems often exhibit limited adaptability and reduced robustness under rapidly varying nonlinear impact conditions. To address these limitations, a single-degree-of-freedom (SDOF) recoil-type impact isolation model integrated with an Adaptive Neuro-Fuzzy Inference System (ANFIS) based MRFD model is developed. Experimental data obtained under varying impact energies and input currents are utilised to characterise the nonlinear and field-dependent behaviour of the MRFD. The proposed SMC algorithm regulates the input current supplied to the damper in real-time to enhance dynamic response suppression and improve system robustness against uncertainties. Numerical simulations are conducted under low-, medium-, and high-impact energy conditions, and the proposed controller is compared with passive and PID controlled systems. The performance evaluation is based on jerk, acceleration, and transmitted force using root mean square (RMS) analysis. The results demonstrate that the SMC-controlled MRFD consistently outperforms the passive and PID controllers, achieving average reductions of approximately 42%, 41%, and 42% in jerk, acceleration, and transmitted force, respectively. The proposed approach exhibits superior effectiveness under high-impact energy conditions while maintaining a simple control structure and low computational complexity. These findings highlight the strong potential of the proposed SMC strategy for real-time impact mitigation applications, particularly in military recoil systems and industrial shock isolation environments.

Keywords: Magneto-rheological fluid damper; impact loads; control strategy; sliding mode control

INTRODUCTION

High-intensity impact loads often arise in dynamic systems, where sudden forces are transmitted through mechanical structures, such as during high-speed actuation, industrial pressing operations, and rapid deceleration events. Failure to adequately manage transient forces can compromise operational precision, increase vibration, and lead to long-term structural degradation. Traditional passive damping solutions, such as hydraulic shock absorbers, are frequently employed to attenuate such impacts by using fluid resistance to dissipate kinetic energy. However, these conventional systems are limited by their fixed damping characteristics, vulnerability to fluid leakage, and high maintenance requirements, making them insufficient for modern engineering applications that demand adaptive, high-performance, and low-maintenance solutions in rapidly changing dynamic environments.

Researchers have investigated the potential of semi-active control devices, particularly magnetorheological fluid dampers (MRFDs), to address these limitations due to their field-dependent rheological properties. The increasing interest in MRFDs is due to their swift response, tunable damping capability, and potential applications in high-impact environments. Researchers continuously explored various control approaches and structural implementations to enhance the effectiveness of MRFDs under impact loading conditions. MRFDs offer greater real-time, adaptable control of damping behaviour by regulating magnetic field intensity across varying loading conditions. Researchers have made significant progress in utilising with these smart materials in various fields, such as vehicle suspension (W. Li, Bai, Jiang, Yuan, Liu, Gao, and Pan 2023; Aghasizade, Mirzaei, and Rafatnia 2019; Chauhan, Kumar, and Sham 2024), seismic isolation (Gu et al. 2019; Xu et al. 2022; Nikpey, Khatibinia, and Eliasi 2024; Guzmán Prado 2022), railway (Mohamad Hafiz Harun et al. 2015; M Hafiz Harun et al. 2017; M Hanif Harun et al. 2014), and vibration control (Zou et al. 2024; Bai et al. 2020; Sharma, Gladston, and Ebanezer 2023; Shakir Yusoff et al. 2024). However, their applications in high-impact, fast-response environments, such as gun recoil systems, remain underexplored.

Jeyasenthil et al. (2019) investigated the time-response characteristics of MR dampers under impact conditions, emphasising the critical need for rapid force adaptation in recoil systems to avoid structural overshoot and instability. Min Sun et al. (2022) developed a dynamic model for MRFD under impact loads and implemented a fuzzy logic-based control strategy. Their simulations confirmed that smart control can significantly reduce recoil, particularly in military-grade applications. Phan et al. (2022) designed an efficient electrorheological (ER) damper for minimising recoil length. They demonstrated the ability of the simplified controller design to reduce the computational burden for real-time implementations. Ouyang et al. (2020) conducted a feasibility study on integrating MR absorbers into artillery systems. The study outcomes demonstrated that MRFDs are efficient in absorbing high-intensity recoil forces, highlighting their value in mobile and fixed artillery platforms. Choi et al. (2024) introduced a high-viscosity MR damper for impact applications and validated the system experimentally using a 600 kg drop mass. They employed a fuzzy neural controller to improve the damping stability under extreme loads. Rahmat et al. (2021) introduced a hybrid skyhook active force control for MR elastomer systems to mitigate impact. The experimental study confirmed that such hybrid control could suppress impact-induced vibrations with high precision. In another study, the researchers investigated the feasibility of using adaptive force control in the MR dampers for gun recoil, which offered enhanced robustness and accuracy compared to passive solutions. Abdul Aziz et al. (2022) published a book discussing recent advancements in large stroke MR actuators, laying the groundwork for their use in industrial presses and robotic arms exposed to sudden external loads.

The focus of the most recent research has shifted to more refined damping control and application-specific optimisations. Lenggana et al. (2021) published a comprehensive review of MR systems in high speed impact applications, citing the importance of real-time feedback and low-latency control responses. Li et al. (2023) emphasised the significance of accurate modelling and adaptive control to capture nonlinear damper behaviour under transient impact loads. Most recently, Phu et al. (2020) proposed a damper design for recoil systems using simplified control algorithms to balance real-time responsiveness and low computational cost, which is crucial for embedded applications, such as weapon systems or industrial shock isolators. Previous studies consistently demonstrated that MRFDs offer promising potential for managing impact loads. The selected control strategy, whether fuzzy logic, neural networks, or sliding mode control, directly influences the damper real time responsiveness and adaptability. However, conventional Proportional-Integral-Derivative (PID) controllers are widely used due to their simple implementation and low computational cost. However, PID controllers often suffer from performance degradation under highly nonlinear and rapidly varying transient impact conditions due to fixed gain parameters and limited robustness against uncertainties and disturbances. In high-intensity impact environments, PID controllers may experience overshoot and residual oscillations, reducing their effectiveness in real-time impact mitigation applications. Therefore, robust nonlinear control approaches such as Sliding Mode Control (SMC) are more suitable for ensuring stable and fast dynamic response under severe impact loading conditions.

This study developed an SMC control approach for regulating a magnetorheological fluid damper (MRFD) in an SDOF recoil impact isolation model. It characterised the damper, an RD-8040-1 unit manufactured by LORD Corporation, experimentally under impact conditions with input currents ranging from 0.5 to 2 amperes. It then used the collected data to develop a non-parametric MRFD model employing the ANFIS in MATLAB Simulink, effectively capturing its nonlinear behaviour. The SMC algorithm was designed to deliver fast response and robust control performance, particularly in mitigating high-magnitude transient impact loads. The algorithm was integrated into the SDOF dynamic system and tested across various impact scenarios. Comparison of the simulation results with passive and a Proportional-Integral-Derivative (PID) controller revealed that the SMC control strategy

significantly enhanced damping effectiveness and reduced undesirable responses, such as jerk, acceleration, and transmitted force. These findings confirmed the controller's potential for real-time applications, ensuring fast-response performance for a semi-active impact isolation system.

METHODOLOGY

CHARACTERISATION OF MAGNETORHEOLOGICAL DAMPER

This study investigated the performance of the RD-8040-1 MRFD developed by LORD Corporation and Mid-Atlantic Co. The damper features a mono-tube structure comprising a piston, magnetic coil circuit, pressurised gas accumulator, and MR fluid. Applying electric current causes the iron particles within the MR fluid to align into chain-like formations, changing the fluid's behaviour from linear viscous to semi-solid and generating a variable, non-linear damping force. The damper has a maximum extended length of 248 mm, a stroke length of 74 mm, and operates continuously at up to 1 ampere, with intermittent operation permitted at up to 2 amperes.

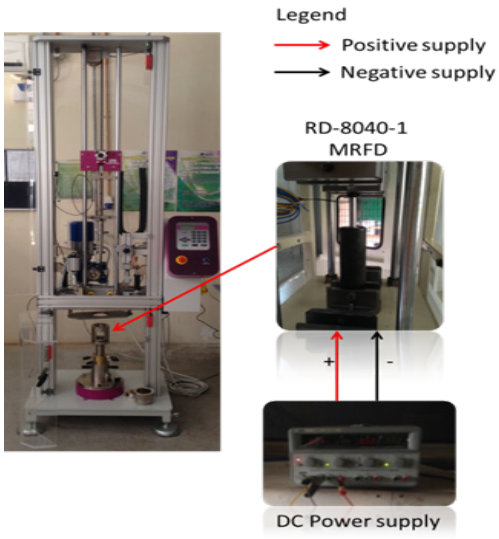


FIGURE 1. Characteristics of the MRFD in the impact tower machine

Figure 1 shows the impact testing machine used to evaluate the dynamic response and energy absorption characteristics of MRFD. The system consists of a vertical drop weight impact frame, a guided striker mechanism and a base support to ensure controlled and repeatable impact loading. The specimen is positioned at the lower test zone, where impact force is transferred through a calibrated loading head. A control panel is integrated into the main frame to regulate test parameters and monitor system operation. The setup is connected to a DC power supply, which provides stable electrical input for sensors, data acquisition units, and MRFD. During testing, the drop mass generates a predefined impact energy based on its height and mass, allowing precise evaluation of stiffness, damping performance, and impact mitigation capability. This configuration supports high fidelity data collection for validating mathematical and numerical impact models. The input current was gradually increased by 0.5 amperes from 0.5 to 2 amperes. The gathered data was used to train an ANFIS employing MATLAB-SIMULINK. The ANFIS model comprises three input parameters (current, displacement, and pendulum kinetic energy) and one output parameter (damping force). A five-layer fuzzy neural network architecture (Figure 2) was employed to interpret the data, optimise membership function parameters, and simulate the damper's dynamic behaviour (Mohd Sabirin Rahmat, Hudha, Abd Kadir, et al. 2021; Mohd Sabirin Rahmat, Hudha, Kadir, et al. 2021).

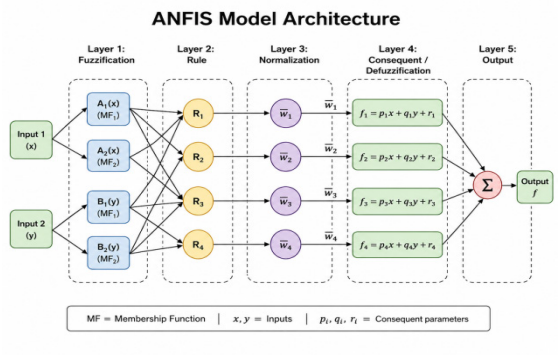


FIGURE 2. Schematic diagram of the ANFIS model.

Figure 3 shows a single-degree-of-freedom impact isolation system comprising an MRF damper and a spring. The MRF damper provides a passive damping force and a field-dependent controlled damping force. The impact isolation system was derived as follows.

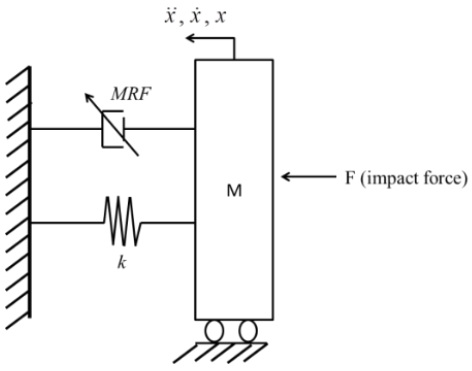


FIGURE 3. Schematic of the SDOF impact isolation system

The force of the MRF damper was calculated using the following equations.

$$M\ddot{x} + MRF + \mathrm{kx} = F_{impact} \quad (1)$$

$$MRF = C_{controllable} \times \dot{x} \quad (2)$$

Where M is the mass, k is the effect of spring stiffness on the MRF damper, $C_{controllable}$ is the damping of the MRF damper, and x, $\dot{x}$, and $\ddot{x}$ are the displacement, velocity, and acceleration of the mass, respectively. It should be noted that the damping force of the MRF damper corresponds with the magnitude of the current applied to the MRF damper and demonstrates the time response of a practical application.

IMPACT ISOLATION SYSTEM

This study employed an SMC control approach to enhance the performance of an MRF damper in reducing impact loads in an SDOF impact isolation system. The control objective is to regulate the input current $I(t)$ to the MRFD such that the system velocity tracks the desired dynamic response while minimising the effects of external disturbances. The sliding surface $s(t)$ is defined as follows:

$$s(t) = \dot{e}(t) + \dot{\lambda} e(t) \quad (3)$$

where $e(t)$=$\dot{x}$(t)-$\dot{x}_d$(t) is the tracking error of the MRFD velocity, and λ is a positive design parameter.

The SMC control law is given by Equation (4).

$$I(t) = F_{estimation}(t) - K.sign(s(t))/\phi \quad (4)$$

where,$F_{estimation}$ is the force generated during impact from the impact isolation system of the MRFD, K is the control gain tuned to ensure finite time convergence, $sign(s(t))$ is the sliding function enforcing the sliding motion, and ϕ is the boundary layer thickness to mitigate chattering of the controller. The control gain K was selected through a tuning process based on system response stability and convergence performance under different impact energy conditions. Higher values of K improve convergence speed and robustness against disturbances; however, excessively large gains may increase control chattering. Therefore, an optimal gain was selected to balance response speed, robustness, and smooth control performance. The proposed SMC approach was implemented in the SDOF model using an ANFIS-based MRFD. The effectiveness of the control law is evaluated through simulation scenarios under varying impact energies (low, medium, and high). The performance metrics are jerk reduction, acceleration suppression, and transmitted force attenuation. Figure 4 shows the control structure of SMC for MRFD in impact isolation.

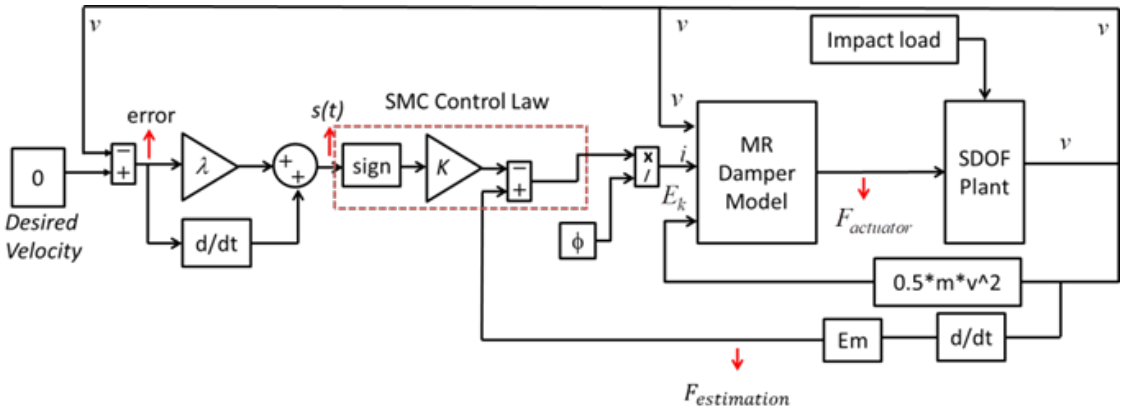


FIGURE 4. Control structure of the SMC controller

RESULTS AND DISCUSSION

CONTROL STRATEGY PERFORMANCE

The performance of the proposed SMC was evaluated through a comparative simulation study against a passive damper system and a conventional PID controlled MRFD. The passive configuration serves as the baseline reference to quantify the level of vibration mitigation achieved through active control. Meanwhile, the PID controller is introduced as a benchmark to assess the relative advantages of the proposed nonlinear control strategy. The evaluation focuses on the jerk response in the time domain under three

impact energy levels: low, medium, and high. Since jerk represents the rate of change of acceleration, it is a critical parameter for assessing impact severity and structural comfort performance.

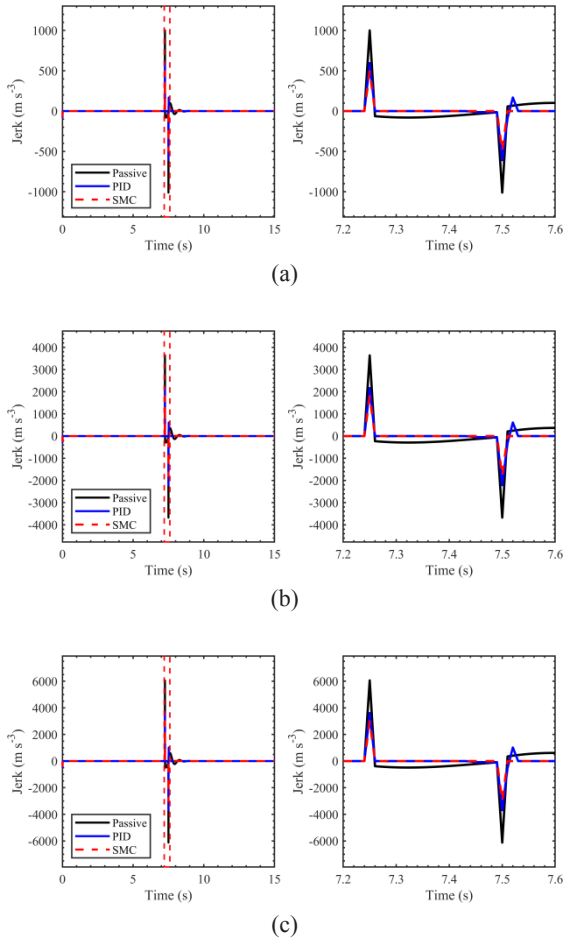


FIGURE 5. Simulation results for the jerk response under (a) low-impact energy, (b) medium-impact energy, and (c) high-impact energy

Figure 5 illustrates the simulated jerk responses for all three impact levels. Across low, medium and high energy conditions, the SMC controlled MRFD demonstrates superior suppression of peak jerk compared to both the passive and PID systems. The passive damper exhibits the highest jerk magnitude, particularly near the impact instant, indicating limited adaptability to sudden dynamic excitation. The PID controller reduces the peak response; however, residual oscillations remain noticeable. In contrast, the SMC controller achieves approximately 40% reduction in jerk magnitude relative to the passive system across all impact levels. This consistent performance indicates improved robustness and stability. The enhanced control is attributed to the SMC ability to regulate coil current effectively as the magnetorheological material properties vary under transient impact loading.

TABLE 3. RMS values for the jerk response

Impact energy	RMS value				
	Passive	PID	Percentage of Improvement (%)	SMC	Percentage of Improvement (%)
Low	0.0298	0.0253	15.05	0.0176	40.94
Medium	0.1009	0.0845	16.24	0.0583	42.22
High	0.1632	0.1342	17.76	0.0924	43.38

The RMS values for the jerk response show that the proposed controller is 43.38% more effective in dissipating unwanted jerk response under high-impact energy. The enhanced performance confirms the superior performance of the proposed SMC controller when the isolation system was subjected to high-impact energy.

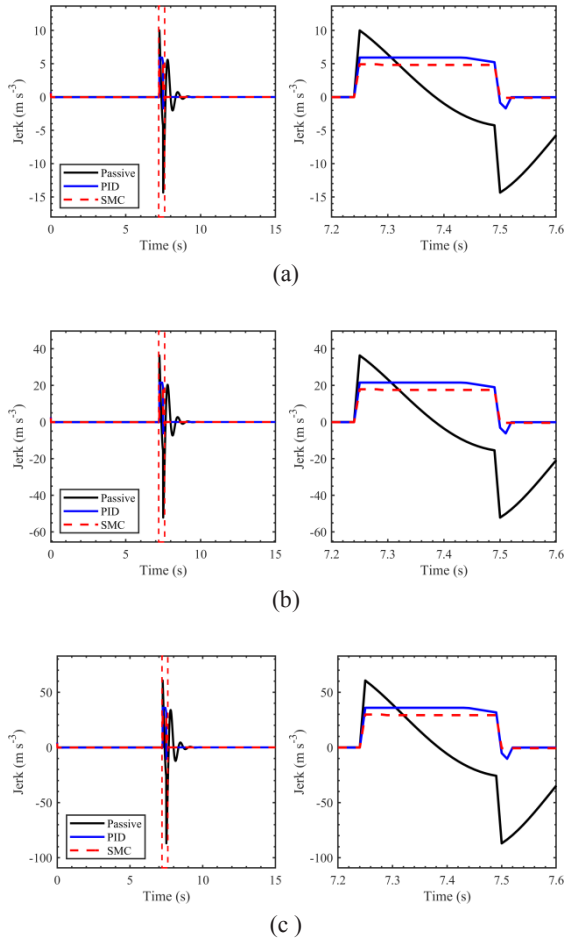


FIGURE 6. Simulation results for acceleration response under (a) low impact energy, (b) medium impact energy, and (c) high impact energy

Figure 6 presents the simulated acceleration response to varying impact energies. Figure 6 (a) shows the acceleration response of the SDOF impact isolation system in the time domain under low-impact energy. The SMC controller enhances the MRFD ability to mitigate unwanted acceleration in the SDOF impact isolation system. The MRFD with an SMC controller is more effective in attenuating acceleration responses under high-impact energy than low- and medium-impact energies. The root mean square (RMS) was used to evaluate the effectiveness of the SMC controller in regulating the input current to the MRFD coil, and the results are summarised in Table 4.

TABLE 4. RMS values for the acceleration response

Impact energy	RMS value				
	Passive	PID	Percentage of Improvement (%)	SMC	Percentage of Improvement (%)
Low	0.1320	0.1120	15.12	0.0788	40.30
Medium	0.4632	0.3875	16.35	0.2710	41.49
High	0.7819	0.6452	17.48	0.4424	43.42

Table 4 presents the RMS acceleration responses under three impact energy levels (low, medium, and high) for passive, PID controlled, and SMC controlled conditions. As expected, the passive system exhibits a progressive increase in RMS values from 0.1320 (low) to 0.7819 (high), indicating a direct correlation between impact energy and vibration severity. The implementation of the PID controller results in consistent reductions across all impact levels, achieving improvements of 15.12%, 16.35%, and 17.48% for low, medium, and high energies, respectively. Although PID demonstrates stable vibration mitigation, its effectiveness remains moderate under higher impact loads. In contrast, the SMC strategy significantly outperforms both passive and PID control, reducing RMS values to 0.0788, 0.2710, and 0.4424 for low, medium, and high impacts, corresponding to improvements of 40.30%, 41.49%, and 43.42%. Notably, the performance advantage of SMC increases with impact severity, highlighting its robustness and superior capability in suppressing nonlinear dynamic responses under high-energy impact conditions.

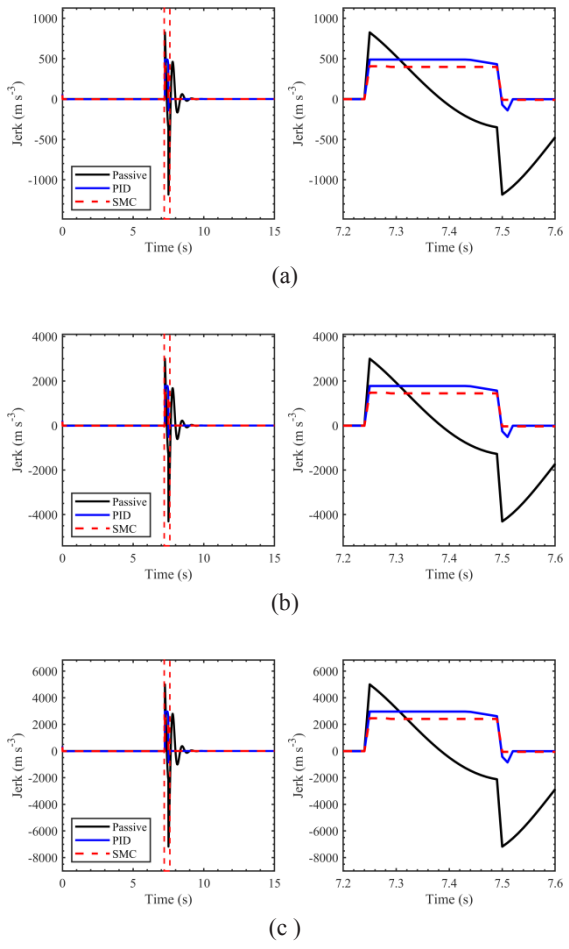


FIGURE 7. Simulation results for transmitted force under (a) low-impact energy, (b) medium-impact energy, and (c) high-impact energy

Figure 7 presents the performance of the MRFD controlled by SMC under low-, medium-, and high-impact energy. The results indicate that the MRFD with SMC is effective in rejecting unwanted transmitted forces, particularly under low and medium impact energies, where peak forces and post-impact oscillations are significantly reduced compared to the passive and PID-controlled systems. The SMC strategy enhances the MRFD's capability to rapidly adapt the damping force, leading to improved impact isolation performance. Despite the higher force due to physical limitations under high-impact energy, the SMC controlled MRFD maintains a more stable transient response. Generally, the MRFD with SMC controller demonstrates superior performance over the PID controller, achieving improvements of 41.25%, 41.86%, and 43.15% under low-, medium-, and high-impact energies, respectively.

TABLE 5. RMS of the transmitted force

Impact energy	RMS value				
	Passive	PID	Percentage of Improvement (%)	SMC	Percentage of Improvement (%)
Low	0.0499	0.0412	17.53	0.0293	41.25
Medium	0.0786	0.0646	17.81	0.0457	41.86
High	0.1143	0.0935	18.20	0.0649	43.15

The RMS values for the transmitted force (Table 5) were employed to evaluate the performance of the SMC controller. The SMC controller outperforms the passive damper by rejecting 41.25% of the unwanted force under low-impact energy. The percentage of enhancement increased slightly for medium-impact energy, and the unwanted force is significantly lower under high-impact energy, indicating the effectiveness of the SMC controller as a fast-response controller for impact load applications to control the damping force of MRFD.

CONCLUSION

This study developed a sliding mode control (SMC) approach and evaluated its effectiveness in enhancing the damping performance of a magnetorheological fluid damper (MRFD) in handling impact loads. It employed a single-degree-of-freedom (SDOF) dynamic model to represent an impact isolation system and conducted experimental tests to characterise the system's MRDF. The study used an Adaptive Neuro-Fuzzy Inference System (ANFIS) to model the damper's nonlinear behaviour based on input current, displacement, and impact energy. The SMC controller was designed to regulate the input current to the MRFD during impact events. The study conducted simulations to test the SMC controller under three different impact energy conditions: low, medium, and high impact energies. It compared the performance of the SMC controller against two benchmarks: a passive damping system and a PID-controlled MRFD system. The evaluation was based on three key performance indicators: jerk suppression, acceleration reduction, and transmitted force mitigation.

The simulation results showed that the SMC controller consistently outperformed the passive and PID controllers. For jerk response, the SMC achieved an improvement of 42.18% across all impact levels compared to the passive system. The reduced jerk response improves comfort and mechanical stability in systems subjected to sudden impacts. The SMC controller performed 25% better than the PID. It exhibited superior performance in acceleration response, which directly reflects the force experienced by the isolated body. The average enhanced performance compared to the passive damper was 41.73%, with the highest reduction observed under high-impact energy. Compared to the PID controller, the SMC reduced acceleration by an average of 24%. For transmitted force (the amount of impact force passing through a structure or chassis), the SMC controller achieved an improvement of 42.09% over passive damping. The transmitted force is about 23% lower than that for the PID controller. These reductions indicate that the proposed SMC approach effectively protects structures or systems from shock-related damage. One of the benefits of the SMC design is its fast response and simple structure. The control law employed in this study requires minimal computational resources, making it suitable for real-time applications. Additionally, the boundary layer method was applied to reduce chattering and ensure smoother control of signal generation.

In summary, the proposed SMC approach provides a practical and effective solution for controlling MRFDs in systems exposed to sudden and high-energy impacts. It improves system stability and reduces unwanted motion and the forces transmitted to the protected structure. The consistent performance provided by the simulations suggests that this control method is feasible for real-time embedded systems. Future research should experimentally validate these results using a hardware-in-the-loop simulation (HILS) setup to confirm the study outcomes. Furthermore, they could refine and validate the robustness of the controller in practical conditions by considering additional uncertainties and disturbances or introducing new parameters. Although the proposed SMC approach demonstrated excellent performance through simulation studies, experimental real time validation using hardware implementation was not conducted in this work. Future studies should focus on hardware-in-the-loop simulation and practical implementation to further evaluate the robustness of the controller under real operational disturbances and uncertainties.

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DECLARATION OF COMPETING INTEREST

None.

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