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Three-Degree-of-Freedom Semi-Active Seat Suspension System based on Magnetorheological Dampers

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Abstract

In this study, the parameters of the Bouc-Wen model were identified using Particle Swarm Optimization (PSO) based on experimental data regarding the damping characteristics of magnetorheological (MR) dampers. By analyzing the dynamic characteristics of seat suspension systems, a three-degree-of-freedom (3-DOF) semi-active seat suspension model was developed. To overcome the inherent limitations of traditional passive suspensions in adapting to diverse road conditions, a semi-active suspension system was designed. Numerical simulations were subsequently conducted to evaluate the dynamic performance of both passive and semi-active suspension systems under random road excitation. The comparative analysis demonstrates that the proposed semi-active seat suspension significantly outperforms the passive system in vibration mitigation.

Keywords

Intelligent Magnetorheological Materials; Bouc-Wen Simulation Model; Three-degree-of-freedom (3-DOF) Seat Suspension; Vibration Reduction.

1. Introduction

Vehicle suspension systems, comprising tires, primary vehicle suspensions, and seat suspensions, are essential for ensuring occupant ride comfort and driving safety. Tires, as the direct interface with the road, absorb initial vibrations and impacts. The primary suspension connects the vehicle body and wheels, further mitigating road-induced shocks through spring and damper systems. The seat suspension serves as the critical barrier directly influencing occupant comfort. An optimized seat suspension system can enhance both ride comfort and handling stability, thereby providing a superior experience for drivers and passengers.

Extensive literature indicates that the natural frequencies of the human torso and vehicle seats typically range from 2 to 10 Hz, commonly referred to as the first natural frequency of the human body [1]. If road-induced vibrations transmitted to the vehicle body reach the 2 to 12 Hz range, resonance may occur in the seat and the occupant’s body. This resonance not only risks minor structural damage to the seat but also poses potential health threats to the driver and passengers [2]. To improve the vibration isolation performance of seat suspensions, researchers have continuously explored optimization schemes. Methods such as reducing tire stiffness and increasing suspension damping ratios have been widely investigated. However, modifying key components like tires and primary suspensions is a non-trivial challenge, as altering these parameters may adversely affect other vehicle performance metrics. Compared to primary suspension modifications, enhancing passenger comfort via seat suspension is more cost-effective and has a negligible impact on the overall performance of the vehicle.

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Seat suspension systems are generally categorized into three types based on their operating modes: passive, active, and semi-active. A passive seat suspension is a complete system consisting of a fixed mechanical frame, multiple vibration-isolating spring sets, and dampers with constant parameters. Recently, advancements in smart material technology have provided new opportunities for seat suspension design. Semi-active seat suspensions, in particular, have garnered significant attention because they combine the advantages of the previous two types: they offer higher stability and lower energy consumption than active systems, while providing the flexibility and controllability that passive systems lack. Consequently, this approach has become a prominent research focus. As a novel semi-active device, the magnetorheological (MR) damper is integrated into seat suspension systems by leveraging the rapid and reversible rheological properties of MR fluids under magnetic fields [3]. Generally, MR dampers are characterized by low power consumption, excellent controllability, fast response times, and stable performance.

The selection of control strategies is paramount to system performance. For nonlinear systems, researchers typically focus on strategies that offer superior robustness and stability [4]. In this context, Ding et al. proposed a delay-dependent $H\infty$ robust control scheme to mitigate the adverse effects of MR damper response lag on low-frequency vibration control in semi-active suspensions [5]. To improve the ride comfort of intelligent electric vehicles, Liao et al. developed an intelligent chassis coordinated control algorithm integrated with wheel-ground tangential force control. This algorithm specifically addresses the increased incidence of motion sickness, and its efficacy in vibration reduction has been validated through simulations and experimental trials [6].

In this paper, experimental data from the mechanical performance testing of an MR damper are utilized, and Particle Swarm Optimization (PSO) is employed to identify the parameters of the Bouc-Wen model. Subsequently, a three-degree-of-freedom (3-DOF) seat suspension model is established based on its kinematic characteristics. A PID-based control strategy is implemented for simulation to achieve effective control of the semi-active seat suspension system. Using time-domain signals of random road excitation as the system input, the results demonstrate that the proposed semi-active control strategy significantly enhances seat suspension performance compared to traditional passive schemes.

2. Magnetorheological (MR) Damper Model

2.1 Experimental Characterization of MR Damper Damping Properties

During the experiments, the MR damper was subjected to controlled sinusoidal displacement excitations within a frequency range of 0.5–2.0 Hz under specific input currents. The MR damper (Fig. 3) operates in a shear-valve mode and features a single-rod, mono-tube configuration comprising the damper housing, a piston unit, and a piston rod.

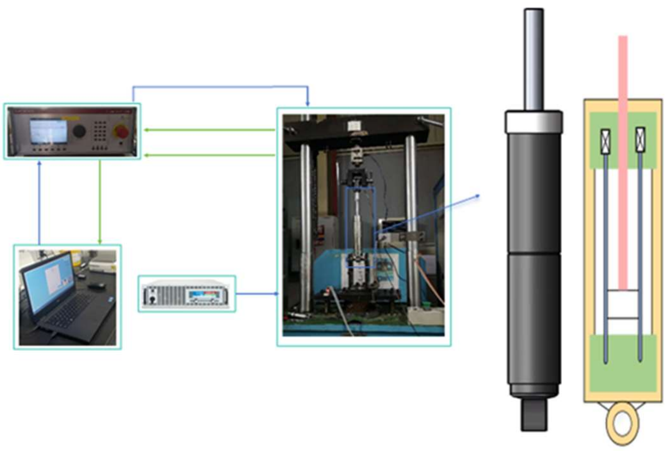

Fig. 1 Test rig for the damping characterization of the MR damper

Throughout the testing process, the MR damper was driven by harmonic motions generated by the servo-hydraulic actuator of a universal tensile testing machine. A force sensor was employed to measure the output damping force, while the damper displacement was recorded using a Linear Variable Differential Transformer (LVDT).The hysteretic force-displacement (F-x) and force-velocity (F-v) characteristics were measured under various control currents, ranging from 0 to 2.0 A with an increment of 0.5 A. Furthermore, tests were conducted at three displacement amplitudes (5, 7.5 , and 10 mm) and four frequencies (0 ,1 ,1.5 , and 2 Hz), covering the typical operating envelope for vehicle suspension applications. Figure 3 illustrates the F-x and F-v loops under an excitation amplitude of A = 10 mm and f = 1 Hz.

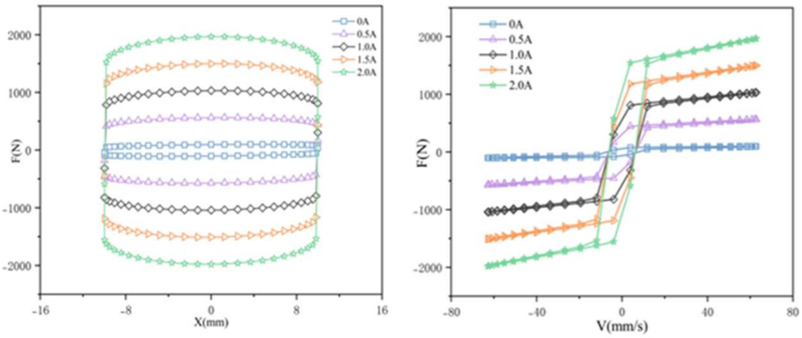

Fig. 2 Experimental damping characteristic curves of the MR damper

2.2 Bouc-Wen Model

The establishment of a high-fidelity mechanical model is paramount for the implementation of semi-active control, particularly when utilizing magnetorheological (MR) dampers. The accuracy of this model directly determines the validity of the performance evaluation for the proposed vibration mitigation strategies. Furthermore, it provides the essential framework for subsequent parameter identification and numerical simulation of damping characteristics. The Bouc-Wen model, originally proposed by Bouc and Wen in the mid-1970s, is a widely recognized phenomenological model[7]. It can be abstracted as a parallel configuration of three primary components: a hysteretic element, a viscous damping element, and a spring element, as illustrated in Fig. 3. The governing mathematical expressions are defined as follows in Equation (1):

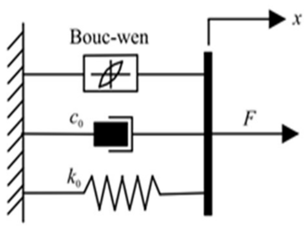

Fig. 3 Bouc-Wen model

$$\begin{cases} F = c_0\dot{x} + k_0(x - x_0) + \alpha z \\ \dot{z} = -\gamma|\dot{x}|z|z|^{n-1} - \beta\dot{x}|z|^n + A\dot{x} \end{cases} \tag{1}$$

Where F denotes the output damping force; c_0 is the post-yield viscous damping coefficient of the MR material; k_0 represents the spring stiffness; x_0 is the initial displacement of the damper; α signifies the ratio of post-yield to pre-yield stiffness; z is the evolutionary (hysteretic) displacement; γ is the parameter governing the linearity of the transition region; n determines the smoothness of the

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transition from the linear to the nonlinear region; β and A are factors influencing the shape and amplitude of the hysteresis loop, respectively.

2.3 Parameter Identification

According to previous studies, the Bouc-Wen model for MR dampers involves eight parameters to be determined. To reduce the computational complexity of the identification process, the initial displacement x_0 is set to zero. Furthermore, for specific MR fluids, the variation in the parameter n is negligible; thus, it is fixed at a constant value of 2 [8]. Consequently, the number of parameters to be identified is reduced to six.

Particle Swarm Optimization (PSO) is a population-based meta-heuristic optimization technique inspired by the collective foraging behavior of bird flocks. In PSO, each candidate solution in the search space is abstracted as a "particle" characterized by its position and velocity. By iteratively updating these attributes, the PSO algorithm effectively searches for the global optimum. PSO is widely utilized in engineering optimization due to its simplicity, ease of implementation, and high computational efficiency [9]. Similar to Genetic Algorithms (GA), the procedure begins with a set of stochastic initial solutions, evaluates them using a fitness function, and iteratively converges toward the optimal parameter set. In this study, the identification was performed using experimental data obtained under sinusoidal excitation with an amplitude of A = 10 mm and 1 Hz , spanning an input current range from 0 to 2 A. The six unknown parameters of the Bouc-Wen model were successfully identified, and the results are summarized in Table 1.

Table 1. Identified parameters of the Bouc-Wen model

I/A	γ	β	A	k_0	c_0	α
0	85	150	147	24	1.6	259
0.5	12	112	195	30	42	255
1.0	10	96	234	27	51	354
1.5	15	28	512	49	15	230
2.0	22	50	421	89	147	695

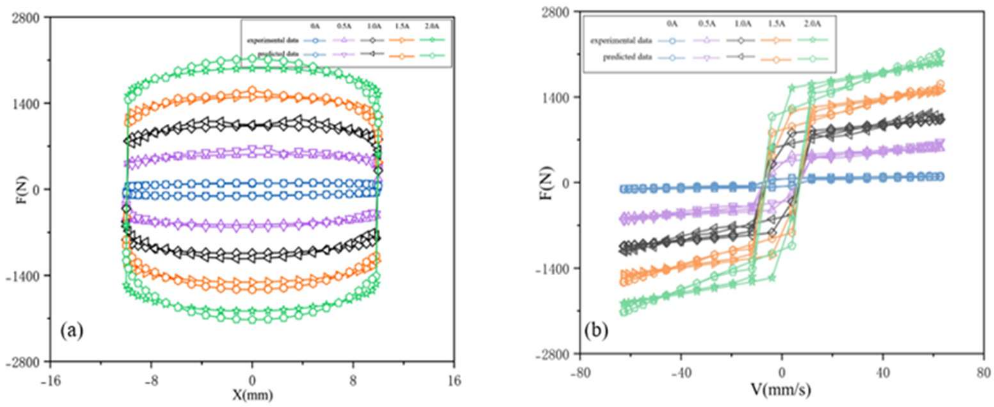

Fig. 4 Comparison between simulation and experimental results

Based on the identification results in Table 1, the parameters exhibit distinct dependency patterns relative to the excitation current. To further characterize these relationships, the Polynomial Fitting Toolbox in MATLAB was employed to derive the specific functional expressions between each parameter and the applied current. Fig. 4 presents a comparative analysis of the force-displacement *F-x* and force-velocity *F-v* characteristics between the simulated and experimental data across

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different current levels. As illustrated in Fig. 4, the simulation results are in close agreement with the experimental measurements for both F-x and F-v loops. These findings demonstrate that both the parameter identification and the curve-fitting results satisfy the accuracy requirements for subsequent analysis.

3. Design of the Three-Degree-of-Freedom (3-DOF) Semi-Active Seat Suspension

3.1 Seat Suspension Modeling

A three-degree-of-freedom (3-DOF) quarter-car seat suspension model was developed, encompassing the vertical motions of the seat, the vehicle body, and the tire. This model is characterized by a streamlined structure and ease of implementation, making it highly effective for simulating the vertical dynamic response of the suspension system under road surface irregularities.

In this study, the human body and the seat are treated as a single integrated mass, simplified using equivalent stiffness and damping elements. Similarly, the vehicle body and wheel are represented as discrete mass elements. To simplify the mechanical analysis, the damping effect of the tire is neglected. The specific parameters of the selected 3-DOF semi-active seat suspension system are summarized in Table 2. Based on Newton's second law of motion, the dynamic governing equations are derived as follows:

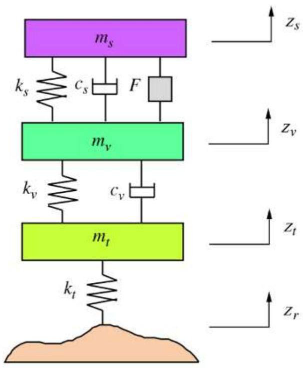

Fig. 5 Three-DOF semi-active seat suspension system

$$\begin{cases} m_s\ddot{z}_s = -c_s(\dot{z}_s - \dot{z}_v) - k_s(z_s - z_v) - F \\ m_v\ddot{z}_v = c_s(\dot{z}_s - \dot{z}_v) + k_s(z_s - z_v) + F - c_v(\dot{z}_v - \dot{z}_t) - k_v(z_v - z_t) \\ m_t\ddot{z}_t = c_v(\dot{z}_v - \dot{z}_t) + k_v(z_v - z_t) - k_t(t - z_r) \end{cases} \tag{2}$$

Table 2. Parameters of the 3-DOF semi-active seat suspension system.

Coefficient	Description	Value
m_s	Driver and seat mass	80kg
m_v	Sprung mass	400kg
m_t	Un sprung mas	40kg
ks	Cushion stiffness	8,000N/m
kv	Suspension stiffness	10,000N/m
kt	Stiffness of tire	180,000N/m
cs	damping coefficient of driver	200Ns/m
c_v	damping coefficient of suspension	1500 Ns/m

3.2 Time-Domain Model of Random Road Excitation

Road surface roughness, defined as the profile irregularities existing on a road surface, serves as one of the primary excitation sources for vehicles during operation. In the investigation of control strategies for active and semi-active suspensions, system feedback is typically processed in the form of time-domain signals, necessitating comprehensive time-domain analysis. Modeling road profiles in the time domain is a critical technique for obtaining accurate road roughness information. Currently, researchers have primarily utilized methods such as harmonic superposition, filtered white noise, inverse Fourier transform, and time-series modeling for road profile generation.

The filtered white noise method demonstrates distinct advantages in simulating road irregularities. By treating road roughness as a stochastic process, this approach utilizes filtered white noise to replicate its inherent randomness and auto-correlation, thereby effectively characterizing the realistic state of road fluctuations [10]. Equation (7) presents the differential form of the road time-domain model based on white noise, providing a robust and reliable methodology for generating vibration signals that reflect actual driving conditions.

$$\dot{z}_{\mathrm{g}}(t) = -2\pi n_1 u z_{\mathrm{g}}(t) + 2\pi n_0 \sqrt{G_{\mathrm{q}}(n_0) u}\, w(t) \tag{3}$$

Where, n_1= 0.01 m^{-1} denotes the lower cut-off spatial frequency, and n_0 = 0.1 m^{-1} is the reference spatial frequency. The parameter $G_q(n_0)$represents the road roughness coefficient, which is assigned the standard value corresponding to C road profiles according to ISO 8608 standards. Numerical simulations were performed for a C road surface at a constant vehicle speed of v = 10 m/s The generated time-varying road elevation profile is illustrated in Fig. 6.

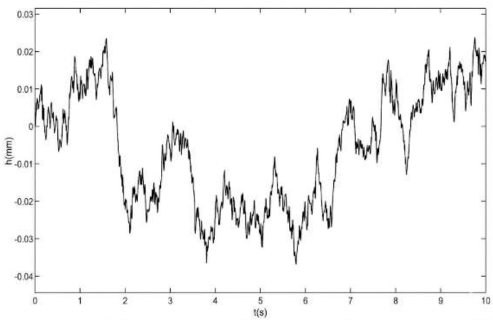

Fig. 6 road elevation profile

4. Control Strategy and Simulation Analysis

4.1 PID Control Strategy

The selection of an appropriate control strategy is one of the most critical factors determining the vibration isolation performance of semi-active seat suspension systems. In recent years, the Proportional-Integral-Derivative (PID) control strategy has remained a cornerstone of control engineering due to its straightforward structure, the clear physical significance of its parameters, and its exceptional reliability in practical applications[11]. Despite the proliferation of advanced intelligent control methods, PID control retains significant value for semi-active seat suspensions, particularly in its ability to be tuned to accommodate specific system dynamics. Unlike intelligent controllers that rely on expert knowledge or fuzzy inference, PID control is a linear feedback mechanism that eliminates deviations and enhances response speed by performing proportional, integral, and derivative operations on the error signal. The efficacy of this approach centers on the design and optimization of the three primary gain parameters.

To optimize the comfort and safety of the vehicle seat suspension, the vertical displacement and velocity are utilized as key indicators of ride quality, as they are relatively easy to measure.

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Consequently, the error between the vertical seat displacement and its desired value is selected as the input for the PID controller. The controller then calculates the ideal control signal through its P, I, and D components. The control current *I* for the MR damper is chosen as the output variable, with an upper limit of 2 A to prevent electromagnetic coil overheating [12].

4.2 Simulation Results and Discussion

Numerical simulations were conducted under random road excitations to evaluate the vibration reduction efficacy of the proposed PID-controlled semi-active suspension in comparison with a conventional passive system. Fig. 7 illustrates the time-domain response of the seat vertical acceleration under random road excitation. The results demonstrate that the parameter-optimized PID control strategy significantly outperforms the passive seat suspension, yielding a substantial improvement in vibration mitigation performance.

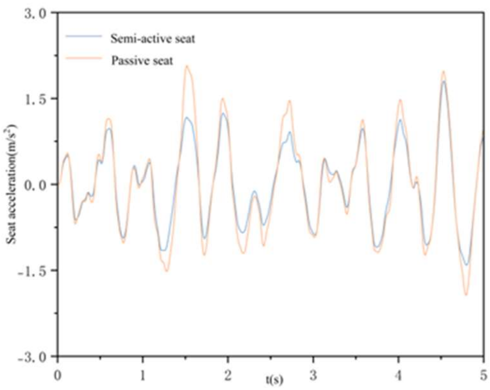

Fig. 7 The time-domain response of the seat

5. Conclusion

This study investigated a three-degree-of-freedom (3-DOF) semi-active seat suspension system integrated with magnetorheological (MR) dampers. The parameters of the Bouc-Wen model were successfully identified using the Particle Swarm Optimization (PSO) algorithm based on experimental damping characteristics. Comparative analysis of the *F-x* and *F-v* hysteretic loops demonstrated high fidelity between the identified model and experimental data, providing a robust foundation for control system design.

A PID-based semi-active control strategy was developed and evaluated through numerical simulations under random road excitations. The results indicate that the proposed semi-active suspension system significantly outperforms traditional passive suspensions in terms of vibration mitigation. Specifically, the system effectively isolates road-induced disturbances and reduces seat vertical acceleration, thereby substantially enhancing ride comfort and occupant safety. This research provides a reliable modeling and control framework for the development of advanced intelligent seat suspension systems, demonstrating the superior potential of MR-based semi-active control in automotive engineering applications.

References

[1] Harrison, Donald D., et al. "Sitting biomechanics, part II: optimal car driver's seat and optimal driver's spinal model." Journal of manipulative and physiological therapeutics 23.1 (2000): 37-47.

[2] Troup, J. D. G. "Driver's back pain and its prevention: A review of the postural, vibratory and muscular factors, together with the problem of transmitted road-shock." Applied Ergonomics 9.4 (1978): 207-214.

[3] Phule, Pradeep P. "Magnetorheological (MR) fluids: principles and applications." Smart Materials Bulletin 2001.2 (2001): 7-10.

[4] Sastry, Shankar. Nonlinear systems: analysis, stability, and control. Vol. 10. Springer Science & Business Media, 2013.

[5] Ding, Renkai, et al. "H∞ control and experimental study of MR semi-active suspension with actuator response delay." Metrology and Measurement Systems 31.4 (2024).

[6] Liao, Jianfeng, Zheng Chen, and Bin Yao. "Model-based coordinated control of four-wheel independently driven skid steer mobile robot with wheel–ground interaction and wheel dynamics." IEEE Transactions on Industrial Informatics 15.3 (2018): 1742-1752.

[7] Cai, Jingnan, Wei Dong, and Ryozo Nagamune. "A survey of Bouc-Wen hysteretic models applied to piezo-actuated mechanical systems: Modeling, identification, and control." Journal of Intelligent Material Systems and Structures 34.16 (2023): 1843-1863.

[8] Heredia-Pérez, Michael, Diego A. Alvarez, and Daniel Bedoya-Ruiz. "A State-of-the-Art Review of the Bouc-Wen Class Model of Hysteresis: Origin, Evolution and Current State: M. Heredia-Pérez et al." Archives of Computational Methods in Engineering (2025): 1-51.

[9] Zaini, Farah Anishah, et al. "A review on the applications of PSO-based algorithm in demand side management: challenges and opportunities." IEEE Access 11 (2023): 53373-53400.

[10] Li, Junqing, et al. "Road roughness detection based on discrete kalman filter model with driving vibration data input." International Journal of Pavement Research and Technology 18.2 (2025): 480-492.

[11] Mumuni, Q. A., A. I. Olayiwola-Mumuni, and A. A. Yussouff. "The advent of the proportional integral derivative controller: a review." Journal of Advances in Engineering Technology 2 (2023): 5-22.

[12] Kozieł, Arkadiusz, Łukasz Jastrzębski, and Bogdan Sapiński. "Advanced prototype of an electrical control unit for an MR damper powered by energy harvested from vibrations." Energies 15.13 (2022): 4537.