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A Review of Modeling, Control, and Optimization of Electric Vehicle Suspension Systems

Vu Van Hai [1], **Ngo Thanh Trung** [2], **Dam Huu Vu** [3*]
[1,3] Faculty of Vehicle and Energy Engineering, Thai Nguyen University of Technology, Thai Nguyen, Vietnam
[2] Faculty of Basic and Applied Sciences, Thai Nguyen University of Technology, Thai Nguyen, Vietnam

* Corresponding Author: **Dam Huu Vu**

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Abstract

The suspension design problem in electric vehicles is no longer a direct extension of that in conventional vehicles. In addition to conventional objectives such as ride comfort, road holding, suspension working space, and vehicle stability, electric vehicle suspensions must also deal with battery-induced mass redistribution, increased unsprung mass caused by in-wheel motors, electromechanical coupling effects, and the demand for energy-efficient chassis control. This paper reviews recent studies on the modeling, control, and optimization of electric vehicle suspension systems. First, representative suspension models are discussed, ranging from quarter-car and half-car models to full-vehicle and electromechanically coupled models for in-wheel-motor electric vehicles. Second, passive, semi-active, and active suspension control strategies are analyzed, including skyhook, groundhook, acceleration-driven damping, PID, LQR, H∞, sliding mode, fuzzy control, and model predictive control. Third, parameter optimization methods based on genetic algorithms, particle swarm optimization, artificial fish swarm algorithms, firefly algorithms, and multi-objective optimization are summarized. The review shows that current research is moving from isolated suspension design toward integrated chassis control, in which suspension dynamics, electric powertrain characteristics, ride comfort, road friendliness, and energy consumption are considered simultaneously. Finally, the main research gaps are identified, including limited full-vehicle experimental validation, insufficient consideration of real road conditions, and the need for robust multi-objective control strategies for electric vehicles operating under variable loads and road excitations.

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1. Introduction

Vehicle vibration is mainly induced by road irregularities, tire–road interaction, powertrain excitation, and structural coupling. In electric vehicles, these excitation sources become more complex because the battery layout, motor configuration, and chassis control architecture may alter the vibration transmission path. However, the structural layout of electric vehicles differs significantly from that of conventional internal combustion engine vehicles. The battery pack is usually mounted under the floor, which changes the total vehicle mass, the center of gravity, and the pitch and roll moments of inertia. In addition, electric vehicles equipped with in-wheel motors may suffer from a considerable increase in unsprung mass, which directly affects ride comfort, tire dynamic load, and suspension durability.

Vehicle suspension systems have traditionally been designed to balance three conflicting requirements: improving ride comfort, maintaining road holding, and limiting suspension deflection. The fundamental concept of semi-active vibration control was established by Karnopp *et al.* [1], and later studies further demonstrated that semi-active suspension can offer a practical compromise between passive reliability and active control performance [2].

Recent reviews have also shown that automotive suspension systems are gradually moving toward electronically controlled and intelligent configurations, in which sensors, actuators, and control algorithms are integrated into the chassis system [3], [4].

For electric vehicles, this problem becomes more complex. In conventional vehicles, the suspension is mainly affected by road excitation and body motion. In electric vehicles, additional factors such as battery mass distribution, hub-motor excitation, regenerative braking, and powertrain–chassis coupling may influence suspension performance. Earlier studies on ride comfort and suspension design for heavy vehicles and buses provided useful modeling and assessment methods for vertical dynamics, road friendliness, and vibration isolation [5]–[9]. These studies form an important methodological basis for extending suspension modeling and optimization to electric vehicles.

Among different electric vehicle architectures, in-wheel-motor electric vehicles have attracted considerable attention because they allow independent wheel torque control and simplify the driveline structure. However, the motor installed inside the wheel increases the unsprung mass and may introduce additional electromagnetic excitation. Quynh *et al*. investigated the influence of an in-wheel motor suspension system on electric vehicle ride comfort and showed that the motor–wheel assembly should not be neglected in dynamic modeling [10]. Tan *et al*. applied a dual-loop PID control strategy optimized by particle swarm optimization to improve the active suspension performance of in-wheel-motor electric vehicles [11]. Other studies further analyzed vibration-absorbing structures and vertical–longitudinal coupling effects in in-wheel-motor suspension systems [12, 13].

Control and optimization are therefore essential for improving electric vehicle suspension performance. Semi-active control strategies, such as modified skyhook control and acceleration-driven damping, have been developed for electric vehicle suspensions [14, 16]. Parameter optimization methods, including improved artificial fish swarm algorithms and firefly algorithms, have also been used to improve ride comfort and reduce pitching vibration in electric vehicle models [15, 16]. These studies indicate that electric vehicle suspension design should not be treated only as a mechanical parameter selection problem, but as an integrated modeling–control–optimization problem.

The purpose of this paper is to provide a structured review of modeling, control, and optimization methods for electric vehicle suspension systems. The remainder of the paper is organized as follows. Section 2 reviews modeling approaches for electric vehicle suspension systems. Section 3 discusses passive, semi-active, and active control strategies. Section 4 summarizes optimization methods and performance criteria. Section 5 identifies research gaps and presents future research directions.

2. Modeling of Electric Vehicle Suspension Systems

Modeling is the foundation for suspension analysis, controller design, and parameter optimization. Depending on the research objective, electric vehicle suspension models can be classified into quarter-car, half-car, full-vehicle, and electromechanically coupled models.

The quarter-car model is the simplest and most widely used model in suspension research. It usually includes the sprung mass, unsprung mass, suspension spring, damper, tire stiffness, and road excitation. This model is suitable for investigating vertical ride comfort, suspension deflection, and tire dynamic load. Because of its simplicity, the quarter-car model is often used in the early stage of controller design and parameter optimization. For electric vehicles, this model can be extended by adding the mass of the in-wheel motor or an additional vibration-absorbing structure between the motor and the wheel. This extension is important because the in-wheel motor changes the dynamic characteristics of the unsprung system [10, 13].

The half-car model is more suitable when both vertical and pitch motions of the vehicle body need to be considered. This type of model can describe the influence of front and rear suspension parameters, axle load distribution, wheelbase, and road input phase difference. For electric vehicles, the half-car model is useful because the battery pack may significantly affect pitch inertia and load distribution. Dung *et al*. used a half-car electric vehicle model and optimized both the vehicle suspension and driver seat suspension parameters using an improved artificial fish swarm algorithm [15]. This approach is meaningful because ride comfort is affected not only by the vehicle suspension but also by the vibration transmitted to the driver.

The full-vehicle model is usually developed with seven or more degrees of freedom, including vertical, pitch, and roll motions of the vehicle body and vertical motions of four unsprung masses. Compared with quarter-car and half-car models, the full-vehicle model can better describe asymmetric road excitation, roll dynamics, and the interaction among four suspension units. This model is particularly important for electric vehicles because the battery pack changes the vehicle mass distribution and may influence both pitch and roll dynamics. Moreover, if the vehicle uses independent wheel motors, the suspension model may need to be coupled with wheel torque control and tire dynamics.

Electromechanically coupled models have become increasingly important in studies on in-wheel-motor electric vehicles. In these models, the suspension is not treated as an isolated mechanical system. Instead, the motor, wheel, tire, and suspension are considered together. Qin *et al*. analyzed dynamic vibration-absorbing structures for in-wheel-motor-driven electric vehicles, while Zhao *et al*. studied the vertical–longitudinal coupling effect and multi-objective optimization of suspension-in-wheel-motor systems [12, 13]. Such models are closer to the real dynamic behavior of electric vehicles because they consider the interaction between road excitation, motor mass, and longitudinal motion.

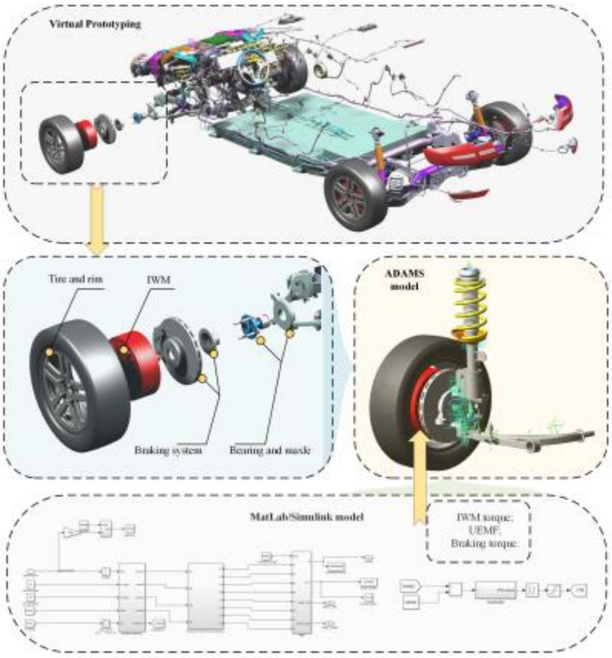

Fig. 1: ADAMS–MATLAB/Simulink co-simulation model of an in-wheel-motor electric vehicle [13]

In addition to vehicle-level modeling, component-level modeling is also important. The dynamic characteristics of dampers, springs, bushings, tires, and actuators can affect the accuracy of simulation results. For example, magnetorheological dampers and electrically controlled dampers exhibit nonlinear and hysteretic behavior, which should be considered in semi-active suspension design. Similarly, active suspension actuators are limited by force capacity, bandwidth, delay, and energy consumption. Therefore, a high-quality electric vehicle suspension model should include not only the vehicle body and wheels, but also realistic actuator and tire characteristics.

To clarify the role of different modeling levels in electric vehicle suspension studies the representative models used in the literature are summarized in Table 1. The comparison shows that each model has its own suitable application range, from simple vertical vibration analysis to integrated full-vehicle dynamic evaluation.

Table 1: Representative modeling directions for electric vehicle suspension systems

Modeling direction	Typical model	Main advantage	Main limitation	Representative references
Conventional vertical vibration model	Quarter-car model	Simple, transparent, suitable for controller comparison	Cannot describe pitch, roll, or left–right coupling	[1], [2], [5]–[7]
Ride comfort and vibration isolation model	Quarter-car or cab/seat isolation model	Useful for RMS acceleration, vibration transmission, and comfort evaluation	Usually limited to vertical vibration	[8], [9], [14]
Electric vehicle half-car model	Sprung mass with vertical and pitch motions	Can capture front–rear suspension effects and pitch response	Cannot describe roll and asymmetric road input	[15], [16]
In-wheel-motor suspension model	Quarter-car or half-car with motor mass/absorber	Captures increased unsprung mass and motor-side vibration	Electromagnetic effects are often simplified	[10]–[13], [31]–[33]
Full-vehicle model	Seven or more degrees of freedom	Suitable for pitch, roll, asymmetric roads, and integrated chassis control	Requires many parameters and experimental validation	[24], [36], [39]
Electromechanical/regenerative model	Suspension plus actuator or energy recovery unit	Can evaluate comfort and energy performance together	Control and validation are more difficult	[25], [34], [35]

As shown in Table 1, quarter-car and half-car models are still widely used because of their simplicity and suitability for controller development. However, these models cannot fully represent the coupled effects among pitch, roll, tire dynamics, and in-wheel motor excitation. Therefore, full-vehicle or electro-mechanical integrated models are increasingly required when the suspension system is studied together with electric powertrain dynamics and ride-comfort constraints.

Overall, modeling studies show that there is no single model suitable for all suspension problems. The quarter-car model is efficient for theoretical analysis and controller comparison; the half-car model is suitable for pitch and ride comfort studies; the full-vehicle model is necessary for roll and asymmetric road excitation; and electromechanically coupled models are essential for in-wheel-motor electric vehicles

3. Control Strategies for Electric Vehicle Suspension Systems

Suspension control aims to reduce vehicle body vibration, maintain tire contact with the road, and keep suspension deflection within allowable limits. For electric vehicles, suspension control may also need to reduce the negative effects of increased unsprung mass and improve energy efficiency.

Passive suspension systems have fixed spring and damping characteristics. Their main advantages are simple structure, low cost, and high reliability. However, passive suspension cannot adapt to different road conditions, vehicle speeds, and loading states. A soft suspension can improve ride comfort but may increase suspension deflection and reduce handling stability. A stiff suspension can improve road holding but may transmit more vibration to the vehicle body. Therefore, passive suspension systems always involve a compromise.

Semi-active suspension systems provide a practical solution by adjusting damping force according to the vehicle dynamic state. Unlike active suspension, semi-active suspension does not inject large external energy into the system; instead, it changes the damping characteristics in real time. This makes it more energy-efficient and easier to implement. Skyhook control is one of the most widely used semi-active control strategies. It aims to connect the vehicle body to an imaginary fixed reference in the sky, thereby reducing body vibration. Quynh *et al*. proposed a modified skyhook control strategy for semi-active electric vehicle suspension and demonstrated its potential for improving ride comfort [14].

Acceleration-driven damping is another effective semi-active control strategy. This method adjusts damping according to the acceleration state of the sprung mass and is often used to reduce vertical vibration. Cuong *et al*. analyzed a semi-active suspension system in an electric vehicle using acceleration-driven damping and optimized the control performance using a firefly algorithm [16]. The results indicate that combining semi-active control with intelligent optimization can improve ride comfort more effectively than using fixed control parameters.

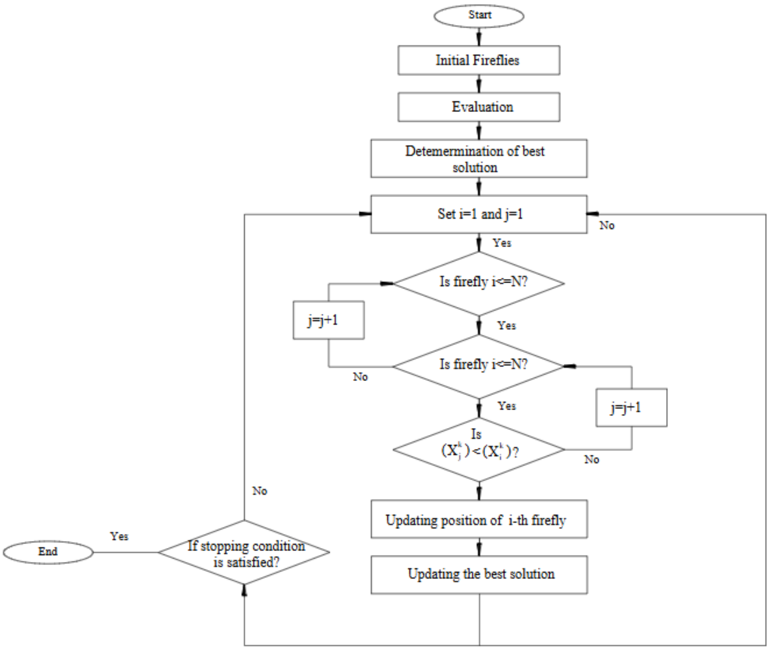

Fig 2: Flowchart of the optimization/control procedure for the in-wheel-motor electric vehicle suspension system [13]

Active suspension systems can generate control forces directly between the sprung and unsprung masses. Therefore, they can provide better performance than passive and semi-active systems. PID control is simple and easy to implement, but its performance depends strongly on parameter tuning. Tan *et al*. used a dual-loop PID controller with particle swarm optimization for the active suspension of an electric vehicle driven by in-wheel motors [11]. This study showed that optimized PID control can reduce the negative influence of in-wheel motors on vehicle ride comfort.

More advanced control methods have also been applied to active suspension systems. H∞ control is suitable for systems with uncertainty, disturbance, actuator faults, and input delay. Shao *et al*. developed an output feedback H∞ control method for the active suspension of in-wheel-motor-driven electric vehicles, considering control faults and input delay [17]. Intelligent control methods, such as fuzzy control and neural-network-based control, have also been used to improve nonlinear suspension performance [18]. Sliding mode control has strong robustness and has been applied to quarter-car active suspension systems [19].

LQR control is another common optimal control method for active suspension systems. It allows the designer to balance ride comfort, suspension deflection, tire dynamic load, and control effort by selecting appropriate weighting matrices. Hybrid optimization methods have been used to tune LQR parameters. Zhao *et al*. proposed a hybrid particle swarm optimization–genetic LQR control method for active suspension systems [26]. This type of method is suitable for suspension systems because the performance indices are strongly coupled and difficult to tune manually.

Model predictive control has recently attracted attention because it can explicitly handle system constraints. In suspension systems, constraints may include actuator force limits, suspension stroke limits, and tire load requirements. Jiang *et al*. developed a hybrid model predictive control strategy for a semi-active suspension in an electric vehicle with a hub motor [36]. Compared with classical control methods, MPC is more suitable for constrained optimization problems, but it requires more computational resources and accurate prediction models.

The development trend of electric vehicle suspension control is toward integration. In future electric vehicles, suspension control should be coordinated with braking control, torque vectoring, regenerative braking, and stability control. Since electric vehicles can control motor torque rapidly and independently, the integration of suspension and powertrain control may provide better ride comfort and handling stability than conventional separated control systems.

4. Optimization of Electric Vehicle Suspension Systems

Optimization is necessary because suspension design is a multi-objective problem by nature. A suspension parameter set that minimizes body acceleration may not minimize tire dynamic load. A controller that gives excellent comfort may require excessive actuator force or energy. Therefore, the aim of optimization should not be to find a mathematically impressive result for one index, but to obtain a balanced and physically feasible design.

Early optimization studies in suspension systems often focused on spring stiffness and damping coefficients. Quynh *et al.* [20], [21] optimized air suspension parameters for semi-trailer trucks and discussed the modeling procedure and resulting performance. Other studies examined the optimal design of drum isolation systems and the effects of suspension parameters on ride comfort and road friendliness [22], [23]. Although these works were not specifically about electric vehicles, they are relevant because they show how ride comfort and road friendliness can be treated together in a structured optimization framework.

For electric vehicles, the design space is broader. Suspension parameters, actuator parameters, control gains, vibration absorber properties, motor-side stiffness, and damping elements may all affect performance. Xu *et al.* [24] presented a model-based design of an active suspension for improving in-wheel-motor-drive electric vehicle performance. Long *et al.* [25] studied a regenerative active suspension system with residual energy for in-wheel-motor-driven electric vehicles. These studies show that electric vehicle suspension optimization should include both dynamic response and energy-related indices.

GA and PSO are among the most frequently used algorithms because they do not require gradient information and can handle nonlinear objective functions. Hybrid algorithms are also used to improve convergence and avoid local optima. Zhao *et al.* [26] combined PSO and GA to tune an LQR controller for an active suspension system. This type of method is attractive because the designer can use an established controller structure while allowing the algorithm to search for better parameters.

In addition to modeling, control and optimization strategies play a central role in improving the ride comfort and road-holding performance of electric vehicles. Table 2 summarizes the main control and optimization methods reported in recent studies, together with their typical targets, advantages, and remaining limitations.

Table 2: Main control and optimization methods for electric vehicle suspension

Method group	Typical methods	Main target	Strength	Remaining limitation	References
Classical semi-active control	Skyhook, modified skyhook, groundhook	Reduce body vibration	Simple and feasible	Performance depends on road and parameter tuning	[1], [14], [27]
Acceleration-based control	ADD and related damping logic	Improve ride comfort	Low computational cost	Needs careful switching and damping limits	[16], [28]
Classical active control	PID, dual-loop PID	Improve comfort and reduce suspension response	Easy to implement	Sensitive to gain selection	[11]
Robust and intelligent control	H∞, fuzzy control, sliding mode	Handle uncertainty and nonlinear behavior	Better robustness	More complex design and validation	[17]_[19], [29]
Optimal control	LQR, PSO–GA–LQR	Balance comfort, stroke, tire load, and control effort	Clear performance weighting	Weight selection is difficult	[26]
Predictive control	MPC and hybrid MPC	Handle constraints directly	Suitable for actuator and stroke limits	Requires accurate model and computing power	[36], [37]
Heuristic optimization	GA, PSO, IAFSA, FA	Tune suspension and controller parameters	Good for nonlinear problems	May depend on selected objective and search range	[15], [16], [20]_[23], [32]
Regenerative suspension optimization	Energy recovery and active/regenerative damping	Balance comfort and recovered energy	Supports EV energy management	Energy recovery may conflict with comfort	[25], [34], [35]
In-wheel-motor vibration reduction	Absorber, motor-side suspension, MR damper	Reduce unsprung-mass effect	Directly addresses EV-specific issue	Needs more experimental validation	[31], [33], [38], [40]

The comparison in Table 2 indicates that classical control methods are easy to implement but are sensitive to parameter variations and nonlinear operating conditions. Intelligent control and optimal control methods provide better adaptability, but they usually require more computational effort and careful validation. For electric vehicles future suspension control should be integrated with braking, traction, and energy-management systems rather than being treated as an isolated vibration-control problem.

Semi-active and magnetorheological suspension systems also benefit from optimization. The effectiveness of a semi-active controller depends on damping limits, switching rules, and control parameters. Experimental work on magnetorheological dampers [27] and optimal ISD suspension design [28] suggests that the physical realization of the damper or inerter network is as important as the control law. A mathematically optimal force is not useful if the actual device cannot generate it.

The optimization of vibration isolation systems for heavy vehicles and construction machinery also provides useful lessons. Tan *et al.* [29] improved the ride quality of a wheel loader using a semi-active cab isolation system with fuzzy self-tuning PID control. Long *et al.* [30] analyzed nonlinear characteristics of hydro-pneumatic suspension systems for mining dump trucks. These studies remind us that nonlinear stiffness, pressure variation, and real operating conditions should not be ignored when moving from simulation to application.

For in-wheel-motor electric vehicles, optimization often focuses on reducing the negative effect of increased unsprung mass. Li *et al.* [31] designed and optimized a vibration reduction system for an in-wheel-motor-drive electric vehicle. Hoang *et al.* [32] and Tan *et al.* [33] studied design parameters of in-wheel motor suspension systems and their effects on ride comfort. These works are useful because they address a specific weakness of in-wheel-motor architectures rather than treating the electric vehicle as only a heavier conventional vehicle.

Energy recovery is another important optimization target. Tuncer *et al.* [34] investigated the contribution of a regenerative suspension module to charge sustainability in fuel-cell electric vehicles. Swamy *et al.* [35] developed a regenerative shock absorber for electric vehicles. These studies show that suspension energy, which is normally dissipated as heat, can be partly recovered. However, energy recovery should be handled carefully. If the controller is tuned mainly to maximize recovered energy, it may increase transmitted vibration or tire dynamic load. Therefore, regenerative suspension should be optimized together with ride and road-holding constraints.

Recent studies show that optimization is becoming more application-oriented. Samaroo *et al.* [38] proposed a semi-active suspension design for an in-wheel-motor-driven electric vehicle using a dynamic vibration-absorbing structure and a PID-controlled magnetorheological damper. Aydoğan and Yildiz [39] modeled and optimized the active suspension system of a 6×6 electric vehicle. Liu *et al.* [40] optimized ride comfort for in-wheel-motor electric vehicles using in-wheel vibration absorbers. These works suggest that future optimization will not stop at tuning spring and damper values; it will increasingly include actuator limits, energy use, motor-side vibration, and vehicle-level constraints.

5. Conclusions

This review has shown that the suspension system of an electric vehicle should not be regarded as a simple extension of the conventional vehicle suspension. While ride comfort, road holding, and suspension travel are still the basic design requirements, the battery layout, in-wheel motor configuration, actuator dynamics, and energy demand introduce new constraints that must be considered together. This is especially important for in-wheel-motor electric vehicles, where the increase in unsprung mass can directly worsen wheel vibration and reduce ride performance.

The reviewed studies indicate that quarter-car and half-car models are still useful for basic analysis, controller comparison, and preliminary optimization. However, they are not sufficient when the objective is to describe the practical behavior of an electric vehicle under asymmetric road excitation, varying load conditions, pitch–roll coupling, actuator delay, and motor–wheel interaction. Therefore, more realistic full-vehicle and electromechanically coupled models are needed, particularly for suspension systems integrated with in-wheel motors or regenerative actuators.

In terms of control, passive suspension remains a necessary reference case, but it has limited adaptability. Semi-active suspension provides a more practical compromise because it can improve ride comfort with relatively low energy consumption. Active suspension offers greater control authority, but its benefits should be evaluated together with actuator bandwidth, power demand, delay, and reliability. Methods such as skyhook control, acceleration-driven damping, PID, LQR, H∞, fuzzy control, sliding mode control, and model predictive control have all shown potential, but their performance depends strongly on model accuracy and implementation feasibility.

Suspension optimization for electric vehicles should also move beyond single-objective tuning. A meaningful design should consider ride comfort, tire dynamic load, suspension working space, actuator force, energy consumption, and energy recovery at the same time. Algorithms such as GA, PSO, IAFSA, FA, and hybrid optimization methods are useful, but the obtained parameters should be checked under different road classes, vehicle speeds, and loading conditions before being considered reliable.

Overall, future research should place more emphasis on full-vehicle modeling, electromechanical coupling, robust semi-active and active control, multi-objective optimization, and experimental validation. A well-designed electric vehicle suspension system should not only reduce vibration, but also maintain tire contact, respect actuator limitations, reduce energy demand, and support the integrated chassis control of future electric vehicles.

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