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Review Article

An empirical in-depth review of Skyhook, Groundhook, and Model Predictive control methods for semi-active mono suspension systems in two wheelers

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Abstract

The need for comfort, safety, and ease of use for two-wheelers has highlighted the need for considerable advances in suspension systems. This review addresses the domain of semi-active mono-suspensions, which may change in response to road conditions the road conditions and attempt to find a compromise between the comfort of the ride and the stability of the vehicle. Unlike the majority of reviews, which deal with the passive and fully active systems of vehicles, this review considers the confined dynamics of two-wheelers, mainly space and weight. The review addresses control techniques based on Skyhook and Groundhook systems, the Hybrid Sky-Ground approach, and Model Predictive Control (MPC). Skyhook and Groundhook systems focus on ride comfort and handling, respectively, while the Hybrid approach and MPC deal with comfort and handling, and predict disturbances under varying conditions. Semi-active systems are advantageous due to better absorption of shocks, versatility, and lower energy consumption compared to fully active systems. This review aims to highlight the gaps in existing studies and suggest initiatives to optimize semi-active suspension systems, improving the performance of two-wheelers in real-world situations.

1. Introduction

The need for comfort, safety, and stability in modern two-wheelers has led to significant research and development in suspension systems [1-3]. The semi-active suspension system is a promising technology because it balances the need for a smooth ride with good handling [4- 6]. The semi-active suspension system is better than the passive suspension systems that have been around for a long time. These conventional systems have difficulty adapting to different road conditions. They are not very good at handling bumps and rough roads [7- 9]. On the other hand, fully active suspension systems are very good but they are also very expensive and complicated. They use a lot of energy. However, these systems are not practical for most two-wheelers due to their high cost, weight, and installation complexity [10, 11]. The semi-active mono suspension system is a choice because it can adjust to different road conditions. It uses control strategies to make the ride more comfortable and improve handling [12- 14]. Semi-active systems can adapt their characteristics in real time to improve ride quality. They can also handle road conditions very well [15, 16]. There are control algorithms that can be used with semi-active suspension systems. Some of these algorithms include Skyhook Control, Groundhook Control and Model Predictive Control [17, 18].

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Each of these algorithms has its advantages and can be used to improve different things, such as reducing body motion or keeping the tires on the road [19- 21]. Even though suspension technology has come a way there is still a lot to learn about semi-active suspension systems for two-wheelers. Most of the research that has been done has focused on cars and other vehicles, not two-wheelers [22, 23]. Two-wheelers have their unique challenges, such as limited space for suspension parts and sensitivity to weight [24, 25]. This paper will review the design, analysis and performance of semi-active mono suspension systems for two-wheelers [26, 27]. It will focus on control methods like Skyhook, Groundhook and MPC. The goal is to understand the strengths and weaknesses of each technique and to identify opportunities for research and innovation [28- 30].

The goal of this work is to help two-wheeler users who want a comfortable and safe ride. With more people living in cities and using two-wheelers to get around traditional suspension systems are not good enough anymore. Active suspensions are not practical for two-wheelers because they are too expensive and complicated. Semi-active suspension systems offer an alternative because they can adjust to different road conditions without being too expensive or complicated. This review will examine control methods and evaluate their effectiveness for two-wheelers. It will also discuss the challenges unique to two-wheelers, such as limited space and weight concerns. By exploring the strengths and weaknesses of semi-active suspension systems, we can identify opportunities for innovation and improvement. This can help drive research and development in this area and make two-wheelers safer and more comfortable to ride.

This review is mainly about commuter class motorcycles with mono suspensions. We are focusing on Internal Combustion Engine motorcycles because they are the most common type of motorcycle in developing markets. They also have a lot of limitations when it comes to cost, power consumption and complexity. We will talk about two-wheelers separately and see how they can benefit from semi-active suspension systems, in the future.

2. Theoretical Framework

2.1. Skyhook Control Strategy

The Skyhook control strategy is widely used to improve ride comfort. It assumes a damper connected between the vehicle body and a fixed point. The controller increases damping when the vehicle body and suspension are moving in the same direction and decreases damping when they are moving in opposite directions. This approach reduces vehicle body vibrations and improves passenger (or rider) comfort.

2.2. Groundhook Control Strategy

The Groundhook control strategy is designed to improve road holding and vehicle stability. It assumes a damper connected between the wheel and the ground. The control strategy minimizes unsprung mass vibrations, which helps maintain better tire-road contact. Groundhook control is useful when handling performance and wheel stability are more important than ride comfort.

2.3. Hybrid Skyhook-Groundhook Control

The Hybrid Skyhook-Groundhook control combines the Skyhook and Groundhook control strategies. It assigns weighting factors to each controller to provide a compromise between ride comfort and handling stability. This control strategy is suitable for semi-active suspension systems operating under different road conditions.

2.4. Model Predictive Control (MPC)

Model Predictive Control (MPC) is an advanced that uses a model to predict future system behavior. It solves an optimization problem to determine the damping force while satisfying system constraints. MPC can improve ride comfort, road holding and suspension travel performance. However, it requires a lot of power and may not be suitable for low-cost commuter motorcycles.

2.5. Magnetorheological (MR) Damper Fundamentals

The Magnetorheological damper is a semi-active device that uses a special fluid whose properties change when it is subjected to a magnetic field. By varying the applied current the damping force can be adjusted rapidly and continuously. MR dampers are attractive for semi-active suspension applications because they have a fast response time, low power consumption and high reliability. When integrated with controllers such as Skyhook, Groundhook, or MPC, MR dampers can significantly improve ride comfort and handling performance.

2.6. Relevance to Two-Wheeler Mono Suspension Systems

For commuter-class motorcycles equipped with mono suspension systems, the selection of a control strategy must consider ride comfort, handling performance, implementation cost, power consumption, and computational complexity. Conventional controllers such as Skyhook and Hybrid SH-GH offer practical solutions due to their simplicity and low computational requirements, whereas MPC and AI-based approaches represent potential future developments, particularly for electric two-wheelers with higher onboard computing capability.

Table 1. Comparative assessment of semi-active suspension control strategies for two-wheeler mono suspension systems

Method	Ride Comfort	Handling	Complexity	Cost	Energy Demand
Skyhook	High	Medium	Low	Low	Low
Groundhook	Medium	High	Low	Low	Low
Hybrid SH-GH	High	High	Medium	Medium	Low
MPC	Very High	Very High	High	High	Medium
MR Damper + MPC	Very High	Very High	Very High	High	Medium-High

3. Existing Models used for Suspension Control Analysis

Suspension systems are generally the major contributors in determining ride comfort, handling, and road-holding. Over the years, various control models and strategies have been proposed to improve the performance metrics by enhancing dynamic responses of suspension systems. Thus, this section provides a comprehensive review of the control strategies employed in suspension systems, with a particular focus on active and semi-active configurations for two-wheeler applications.

3.1. Suspension Systems with Sliding Mode Control

Sliding Mode Control has received much attention in recent years because of its robustness against uncertainties and disturbances. A. A. Wijaya et al. [1] presented an adaptive logarithm-based sliding mode control (ALSMC) model that can enhance ride comfort and preserve road-holding ability in active suspension systems. The approach of natural logarithmic sliding mode control (lnSMC) is different from the conventional SMC approach in respect to model uncertainties and also external disturbances as validated through simulation studies under various road conditions. The practical utility of the controller can be realized with the adaptive estimation of the unknown parameters and its ability in the practical utilization in real scenarios with two-wheeler suspension where model uncertainties are critical.

The adaptive estimation capabilities of ALSMC highlight its potential for real-world two-wheeler applications, making it a robust solution for handling model uncertainties and external disturbances.

3.2. Model Predictive Control (MPC)

Suspension control also emerged as an effective strategy with Model Predictive Control. S. Zhao et al. [2] presented an MPC-based tractor active seat suspension system. The concept is to demonstrate the effectiveness of MPC for the vibration reduction and ride comfort. Having designed specifically for tractors, features such as system parameter optimizations towards balancing vibration reduction and control cost. These adaptive characteristics can be easily implemented on two-wheeler systems. MPC, as it predicts the future states based on current data and adjusts its control actions accordingly has some potential to improve adaptability of two-wheeler suspension systems to different road conditions.

By leveraging MPC's adaptability to varying road conditions, this control strategy offers a promising avenue for enhancing the ride quality and stability of two-wheeler suspension systems.

3.3. Fault-Tolerant Control of Active Suspension Systems

Active suspension systems should have fault tolerance and delay tolerance. Z. Li et al. [3] focused on dynamic output feedback fault-tolerant control, with unknown measurement sensitivities and actuator delays. In those cases, a switched reduced-order state observer with Nussbaum gain was proposed. This method will prove useful in two-wheeler suspension systems, as part wear and the environment cause delays and faults. To guarantee ride comfort and safety, the controller's self-stability with the system under such conditions is important.

The dynamic output feedback method allows for fault tolerance and the handling of delays. Thus, the method gives a reliable tool for the enhancement of two-wheeler suspension under challenging operational conditions.

3.4. Robust Finite Frequency Control

The robust control strategy is devised with an aim to increase the ride comfort of vehicles by forcing specified vibration frequencies. X. Jin et al. [4] developed Robust Finite Frequency H∞ Control Strategy for electric vehicles using IWM-ASS to isolate unwanted vibrations. The finite-frequency technique can be applied to the two-wheeler suspensions in a way that it removes the vertical vibrations induced by road irregularities, which represent the primary source of discomfort for the rider.

Applying robust finite-frequency control techniques to two-wheeler suspensions offers significant potential to improve rider comfort by effectively isolating vertical vibrations.

3.5. Hybrid Control Approaches

Hybrid control schemes combine multiple control strategies to achieve synergistic performance. H. Cao et al. [5] used the two actuators of secondary suspension and piezoelectric actuators to produce active vibration control of high-speed EMU car bodies. The H2 and H∞ norms were integrated in the design of an optimal control approach that could be used in two-wheeler suspension systems that would have both rigid and elastic body vibrations. Hybrid approaches like these could offer all-round solutions for damping any types of vibrations, thus improving the dynamic response of the suspension. Hybrid control strategies, with their ability to address a wide spectrum of vibration challenges, represent a comprehensive solution for enhancing the dynamic performance of two-wheeler suspensions.

3.6. Fixed-Time Control for Active Suspensions

Another promising approach is fixed-time control when constraints need to be satisfied within a given time bound. T. Jia et al. [6] presented an adaptive fuzzy fixed-time control method for a constrained quarter vehicle suspension system. The use of the time-varying barrier Lyapunov function ensures that the given displacement constraints are satisfied; hence, it's also relevant for two-wheeler suspensions, where safety and stability are at their premium. The event-triggered controller proposed in this work further reduces the communication load from the controller to the actuator, which is helpful for low-power two-wheeler systems, thereby improving the efficiency of the system.

Addressing nonlinearity and delay suspension systems suffer from considerable challenges from time-varying delays and nonlinearities. Y. Huang et al. [7] introduced a novel control approach combining USDE with the predictor-based compensation strategy to combat time-varying delay. The conventional neural networks and fuzzy logic systems were no longer needed, and the model of the control system could be simplified and computing efficiency enhanced, which would be important for real-time suspension control in two-wheelers, given computation resources. Fixed-time control ensures stability and efficiency, addressing safety-critical constraints in two-wheeler suspension systems with improved energy efficiency.

3.7. Fuzzy Logic and Sampled-Data Control

Control of suspension systems using fuzzy logic control is growing in popularity. J. Zhao et al. [8] presented the Takagi-Sugeno fuzzy method to a nonlinear vehicle suspension system, with actuator fault tolerance and sampled-data control, among other features. Such a method can be adopted in two-wheelers to deal with the symbiotic nonlinear spring and damper behavior. Fuzzy logic control provides a better method of dealing with spring and damper behavior, and system improvement, in regard to ride comfort and handling. Fuzzy logic control, being a better method of dealing with nonlinear behavior, is a way of achieving better ride comfort and handling in two-wheelers because of its effect on suspension systems.

3.8. Optimal Control Strategies

R. Bai et al. [9] focused on vehicle suspension systems. For vehicle suspension systems, Bai et al. developed a method using an integrated sliding mode control and LQR (LQR-ISM control) to address the issues of uncertainties and disturbances in the suspension system caused by the unknown parameters. The LQR-ISM control guarantees optimal control, even in the presence of unknown parameters, making it even more suitable for a two-wheeler, especially one that traverses different environments.

Regarding Skyhook and Active Disturbance Rejection Control (ADRC), Wang et al. [10] proposed a mix of skyhook control and ADRC for MR semi-active suspension systems. The method is characterized by a dynamic switch between skyhook control and ADRC, designed to function under different road conditions, and provides a measure of control of the suspension system with significantly lower energy consumption while maintaining a desired level of ride comfort. These types of control strategies are needed to improve the level of ride comfort and the energy consumption of two-wheelers. LQR, SMC and other such optimal control strategies are designed to deal with disturbances and uncertainties, thus providing a robust framework for the different operating conditions.

3.9. Energy Harvesting and Self-Powered Suspensions

Energy efficiency of suspension systems remains a primary concern in research. Y. Jiang et al. [16] proposed a self-powered electromagnetic suspension actuator to be powered by the energy harvested from suspension motion. Energy harvesting from suspension systems has been applied to non-pneumatic tyres in large vehicles, and the application of the same principle to two-wheel vehicles will further improve energy harvesting and reduce the energy supply required for a suspension system. Important improvements have also been made in suspension control models, and each of these has been applied to the problems posed by two-wheeler suspension systems. Improvements in ride comfort and road-holding, as well as in energy efficiency, have been achieved with the application of the sliding mode control, Model Predictive Control (MPC), fault-tolerant control, and robust hybrid control strategies. Further improvements and refinements in two-wheeler suspension systems can be achieved through the application of advanced control theories (for instance, fixed-time control, USDE-based estimation and optimal control) and, in combination with these, energy harvesting systems. A wide variety of control strategies, as demonstrated in the reviewed literature on two-wheeler suspension systems, provides a significant basis for innovations in two-wheeler suspension systems. Integrating energy harvesting systems in two-wheeler suspensions can provide efficient and sustainable solutions.

3.10. Control Methods of Skyhook and Damping

Skyhook control has been highly applied to have the ride comfort canceled in passive and active suspension systems. H. Kikuchi et al. [21] discussed an application using a wheel rotation speed signal-driven skyhook damping system within electric vehicles. The problem related to the developed skyhook was that of stiff ride quality caused by improper switching of the damping coefficient due to slow communication between the signals. The authors had highlighted a minimal control strategy that optimized the body damping and isolation within 1–2 Hz and 3–6 Hz, respectively, which resulted in drastic improvement in suspension performance under communication limitations. Its relevance to two-wheeler applications is marked by the facts that adaptability in road irregularities and dynamic load changes are very common for such applications. Skyhook and ADRC-based control methods address the challenges of energy efficiency and adaptability, making them highly suitable for enhancing two-wheeler suspension systems.

3.11. Model Predictive Control (MPC) for Suspension Systems

Model predictive control has been found to be an efficient strategy for managing the complex dynamics of suspension systems. R. Mou et al. [22] presented a strategy in the form of a disturbance observer and MPC was adapted to minimize lateral vibration in high-speed trains. The authors suggested a conditionally triggered MPC (CMPC), adapting MPC strategies to changing driving conditions like speed changes, as well as aerodynamic loads. Although the work was on trains, due to flexibility of MPC towards real time conditions the approach may be promising for two-wheeler suspension systems, where sudden shocks occur due to road as well as uneven road conditions. MPC's flexibility and real-time adaptability make it an effective strategy for addressing sudden road shocks and dynamic conditions in two-wheeler suspensions.

3.12. Dampers

The development of dampers has seen a very vital role in improving the performance of suspension. A. A. Ferhath et al. [23] presented a comprehensive analysis on the development of damper technologies with crucial importance to electromagnetic as well as magnetorheological dampers. These systems enable AI and machine learning-based, real-time, adaptive control capability, and hence precisely adjust the damping under varying road conditions. The trends of current technologies are very relevant in this context for two-wheelers, where solutions imposed by constraints on space and weight result in the damper compactness and light weight. Advancements in damper technologies, driven by AI and lightweight materials, present innovative solutions to the space and weight constraints of two-wheeler suspensions.

3.13. Roll Control and Vehicle Stability

The efforts considered how roll control affects vehicle stability. Feedback roll moment control relies on static and dynamic roll reference generators. Roll control is particularly important for two-wheeler systems, where lateral stability must be ensured to prevent rollover during sharp turns or sudden maneuvers. Numerical simulations showed better performance with the SOS integral polynomial tracking control introduced in this study. This method will be used on two-wheeler models because flexibility and balance at speed are crucial for rider safety. Roll control strategies help maintain lateral stability and improve rider safety by addressing the unique dynamic challenges of two-wheeler systems. The attempts made in such a way considered the effect of roll control on the stability of the vehicle, with the feedback roll moment control done with the use of static and dynamic roll reference generators. Roll control is really relevant to the two-wheeler system, where lateral stability in all situations needs to be ensured in order to prevent any form of rollover due to sharp turns and sudden maneuvers. The improvement in performance was evident in numerical simulations with the application of SOS integral polynomial tracking control.

3.14. Fuzzy Logic and Optimization-Based Control

Fuzzy Logic Control with optimization algorithms has been implemented for suspension performance enhancement. M. Nagarkar et al. [25] optimized FLC, a nonlinear quarter-car model as to emulate an active suspension system. Optimized passive suspension was found to significantly reduce RMS acceleration values and was almost comparable to the target active suspension. The adaptation of fuzzy logic to two-wheeler suspension systems is beneficial since it can take into account uncertainties and inherent nonlinearities of road conditions and dynamics of the vehicle.

Similarly, M. Dehghan et al. [26] discussed an active suspension of impedances with a supervised system. A fuzzy supervisory system is always updating the impedance control parameters with road conditions. Real-time adaptation for changing road conditions can significantly enhance two-wheeler suspension systems since under certain situations, road conditions can drastically change and require immediate adjustment for comfort and stability purposes. The integration of fuzzy logic and optimization algorithms offers adaptive solutions for two-wheeler suspensions, ensuring comfort and stability across varying conditions.

3.15. Advanced Suspension Modeling and Control Techniques

There have been some recent researches on advanced modeling techniques for suspensions as well. The research conducted by M. Nagarkar et al. [27] involved optimization of the MacPherson strut suspension system through NSGA-II algorithm, with the improvements made both in ride comfort and vehicle stability. Multi-objective approach can prove very useful for the two-wheeler systems, where not only comfort but performance also has to be taken into account but in the minimum mass and energy consumption. Hobusch, S. et al. [28] mentioned the potentials of artificial intelligence and neural networks in the suspension control process, where neural network-based parameter identification method proved effective in optimizing the dynamic response of the suspension. Advanced modeling techniques and AI-driven controls lay the foundation for further innovation in two-wheeler suspensions, balancing performance with energy efficiency.

3.16. Suspension Materials and Design Innovations

Weitz, F. et al. [38] proposed innovative materials and design approaches as key methods for advancing suspension systems further. Additive manufacturing was used in the development of lightweight suspension parts with higher integration operations related to functionality. From table 2, light metals with high strength and sectional conduction integration allow for the reduction of unsprung mass hence enhancing handling and energy consumption. As a matter of fact, for electric two-wheelers, it would be even more important because reducing weight is to be targeted in order to enhance energy efficiency and performance. Innovative materials and design approaches, particularly those leveraging additive manufacturing, provide transformative solutions for lightweight, energy-efficient two-wheeler suspensions.

3.17. Reduction of Vibration in Two-Wheelers

The major difficulty in two-wheelers, especially electric two-wheelers, is the vibration provided by road irregularities. Krishna K. et al. [36] discussed the application of room temperature vulcanizing silicone rubber and magnetorheological elastomers for damping purposes in order to reduce vibrations in electric two-wheelers. Results showed that a higher performance in vibration isolation, vibration dose value reduction, and improvement of comfort could be obtained by using MRE-based damping. This method deals with the real scenario of non-uniform road surface which is such a wide-range issue for two-wheeler users. The application of advanced damping materials like MREs offers effective solutions for addressing vibration challenges, enhancing rider comfort and safety.

3.18. Tire Force Estimation and Control

The only members that directly come in contact with the road are the tires, hence they considerably contribute to the overall performance of the suspension system. Cheon [31] proposed a method for vertical tire force estimation that uses sensors that measure the forces applied to the tires. This data has been adopted in an optimization strategy that can enhance the security of a ride by being capable of maximizing the longitudinal and lateral forces of a vehicle. Such an estimation strategy of the tire forces can be incorporated into the suspension system of two wheelers to provide real-time feedback, thereby enhancing the control strategy. In the literature, quite a range of models and technologies have been developed as suspension control that pose varied solutions for the challenges posed by two-wheeler suspension systems the suspension systems of two wheelers. Such approaches - apart from AI-driven damper control and model predictive control - hold significant promise to elevate ride comfort, stability, and handling. The application of adaptive control methods - and, in particular, those on the basis of fuzzy logic and neural networks - is promising for the online optimization of suspension. Some new effects in lightweight materials and additive manufacturing might have huge impacts regarding more efficient and better responsive suspension systems. These developments form the basis for further developments in two-wheeler suspension systems, which shall be able to considerably increase levels of quality in the overall riding experiences.

Tire force estimation strategies provide real-time feedback that can significantly enhance suspension control, contributing to improved ride stability and safety.

3.19. Semi-Active Suspension Systems

In their study on semi-active suspensions systems, Catalin Alexandru et al. [39] examined the various types of damping control devices for use in vehicles. They used a multicriteria analysis, the FRISCO formula, to evaluate many different types of device and control technique combinations while simultaneously identifying their applications and limitations. They have also proposed a novel control strategy which should offer improved dynamics for the vehicle. To test the control strategy, simulations were run using the mechatronic simulation software tools MSC ADAMS and EASY5, integrating both Multi-Body Systems (MBS) and Design for Control (DFC) approaches.

3.20. Variable Parameter Suspension Systems

Suspension systems have a significant role in providing comfort and stability when driving an automobile. To quantify these characteristics, Shadi Munshi et al. [40] created a quarter-car suspension model to perform experimental testing of the effects of varying coefficients of damping, spring rates and weights (load) attached to the model. The experimental testing revealed that the damping ratio was dependent upon the method of valve (opening) mechanism used (different valve designs provided different results) but produced similar results with regard to the coefficient of damping, spring rate and weight (load) when tested under the same conditions.

3.21. Road Elevation-Based Semi-Active Suspension Control

Zhengcai Yang et al. [41] have concentrated on the improvement of vehicle comfort and stability by utilizing the semi-active suspension system along with active road detection. A multiple scanning recursive matching algorithm using the LIDAR sensor, that scans in a single line, is presented. The suspension control system uses a diagonal recursive neural network, where weights have been trained using genetic algorithms. The hardware-in-the-loop co-simulation using Simulink and dSPACE shows improvement in ride comfort and stability.

3.22. Performance Testing of Semi-Active Suspension Systems

Ren Chenglong et al. [42] studied semi-active suspension control and performance evaluation. This paper presents suspension systems, neural network control analysis, single chip control system design, and criteria for performance evaluation. Findings reveal that semi-active suspension with neural network control is better than passive and active suspensions.

3.23. Dynamic Response Analysis of Vehicle Suspension

R Rogerio Lopes et al. [43] worked in automotive engineering, specifically, they developed a model to study the static and dynamic behavior of the bus suspension system. The mathematical models obtained from structural dynamics are used to get solutions to natural frequency and displacement under load, which are verified using FEM simulations. A modal analysis technique is presented using a reduced model to predict the dynamic behavior of an automotive structure.

3.24. Intelligent Road-Adaptive Semi-Active Suspension

Road-adaptive semi-active suspension control with the LPV approach was developed by Hakan Basargan et al. [44]. The road adaptation algorithm takes into account road surface characteristics and speed of the vehicle, changing operation mode of the LPV controller depending on that in order to achieve the desired compromise between driving comfort and stability of the vehicle. In order to design speed of the vehicle for cruise control purpose, the speed of the vehicle is designed according to ISO 2631-1, generated database, and look-ahead road information.

3.25. Mass-Market Semi-Active Suspension Systems

The review by AMA Soliman et al. [45] focuses on the present status of semi-active suspensions systems. It highlights the advantages of the system compared to passive suspensions, focusing on the areas of ride quality and handling. The difficulties with active suspensions in terms of power consumption and cost effectiveness are also discussed in the context of their practicality. The advantages and disadvantages of the semi-active suspension systems are mentioned along with an analysis of their capability and equipment requirements.

3.26. Damping Control in Semi-Active Suspensions

Jarosław Goszczak et al. [46] addressed the seemingly conflicting goals of ride comfort and handling in vehicle suspension systems. Using a two-mass quarter-car model, a damping control strategy for semi-active suspension is proposed. Simulation tests under various inputs are analyzed and compared with the response of a classical passive suspension. Based on the findings, conclusions are drawn, and future work is outlined to optimize the system's response for comfort and handling while ensuring reliable validation of the proposed control strategy's efficiency.

3.27. Advances in Active Suspension Systems

Min Yu et al. [47] explored Active Suspension Systems (ASSs), focusing on their dynamics modeling, robust control, and the challenges in bridging academic research with industrial application. It reviews state-of-the-art ASSs implemented in production vehicles, such as Mercedes' Active Body Control (ABC) and Audi's Predictive Active Suspension, while introducing innovative concepts like series active variable geometry suspension and active wheel-alignment systems. Future ASSs aim to integrate with vehicle modules (e.g., steering, braking) and sensors (e.g., cameras) and align with strategies for electric and autonomous vehicles. Key goals include compact design, low power consumption, high-frequency response, cost-effectiveness, and reliability, ensuring broader adoption in the automotive industry.

3.28. MR Damper-Based Semi-Active Suspension Systems

Hussein M. Hussein et al. [48] critically evaluated the models of MR dampers to assess their reliability and efficiency in enhancing vehicle suspension performance. The response of the body mass of a vehicle was analyzed in terms of comparison between passive and semi-active system incorporating MR dampers through road bumps as well as two different road profiles (bump and step). It was observed that vibration reduction in MR dampers was about 50% higher than passive suspension system. MR dampers parametric models were studied using the Simulink/MATLAB software in the context of semi-active quarter car suspension system. Bouc-Wen model was found extremely efficient whereas Bingham model provided mathematical simplicity.

3.29. Optimization of Damping with Various Mass Locations

Aurimas Cerskus et al. [49] concentrated on vibration control and reduction of inertia force in vehicle suspensions to increase ride comfort, decrease driver fatigue, and ultimately improve the safety of driving. Semi-active damping control system was designed, which allowed real-time tuning to minimize the influence of acceleration on the driver and the passenger. Full-car mathematical model was created using MATLAB/Simulink software with simulations of several road surfaces. Semi-active damping constant was optimized for the best driver comfort possible. Graphs of output accelerations were provided as simulation results to demonstrate kinematic excitation caused by road irregularities.

3.30. Efficiency Levels for Different Methods

The efficiencies of some of these approaches include ride comfort, vibration isolation, energy usage, adaptive real-time performance, and cost efficiency. The ALSC method is efficient with regard to adaptability to unknown parameters of the model and varying efficiency on different roads, hence it may be regarded as being highly efficient in terms of adaptability but not computationally efficient owing to reliance on estimation techniques. RFF H∞ Control for IWM-ASS is probably efficient in vibration isolation especially when ride comfort is considered. However, its efficiency is limited by the limitations of the actuators. SH-ADRC is efficient in balancing ride comfort and minimum energy consumption. This approach may be regarded as one of the most efficient methods for implementing semi-active suspension. Dynamic Output Feedback Fault Tolerant Control is efficient despite the fact that it is robust with respect to faults and delay. However, its performance is affected by uncertainties but at the expense of complexity. MPC is efficient in balancing between comfort and energy consumption but not very computationally efficient, hence it lies in the middle tier of efficiency. Some of the techniques such as MR dampers and piezoelectric actuators are highly efficient in terms of vibration reduction but not cost efficient.

Self-Powered Electromagnetic Actuators have great efficiency in sustainability and energy saving but have problems in integration. Fuzzy Logic and PID Control have high efficiency in vibration damping because of their adaptive abilities; however, their high computational requirements may diminish their real-time efficiency. Neural Networks have high efficiency in parameter estimation and real-time optimization; however, they need extensive training and therefore may have low efficiency in low-cost applications. The approach that uses AI, machine learning, and AM for lightweight applications is expected to be efficient in the long run regarding adaptability and performance although their initial cost may currently reduce their efficiency.

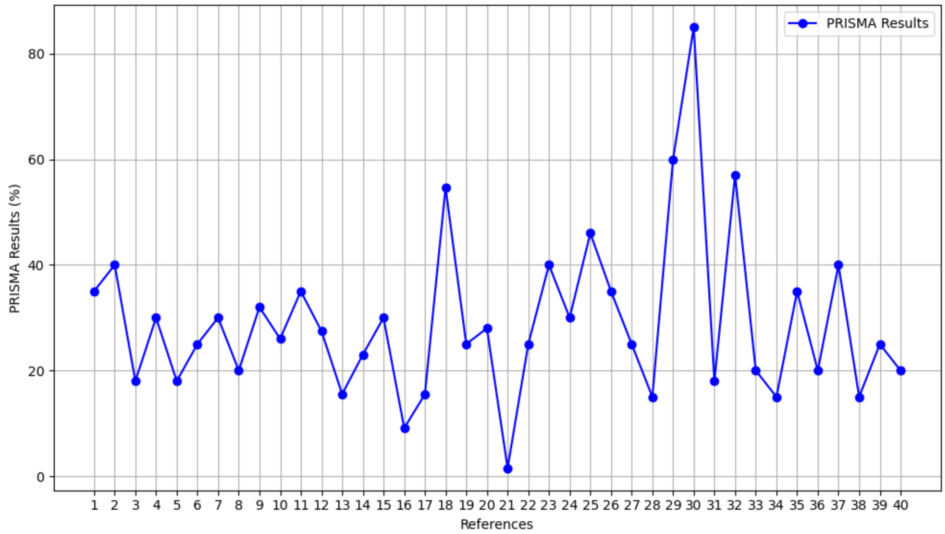

Fig. 1. Efficiency levels for different methods

3.31. Literature Search Strategy

A systematic literature search was conducted following the PRISMA guidelines using Scopus, IEEE Xplore, ScienceDirect, Web of Science, and Google Scholar. The search included keywords such as "two-wheeler suspension," "active suspension," "semi-active suspension," "vehicle dynamics," "ride comfort," "vibration control," "model predictive control," "sliding mode control," and "fuzzy logic control," combined using Boolean operators (AND/OR).

A total of 235 records were identified, of which 55 duplicates were removed. After screening 180 records, 70 full-text articles were assessed for eligibility, and 42 studies meeting the inclusion criteria were selected for the final review. The inclusion criteria comprised peer-reviewed English-language studies focusing on two-wheeler suspension systems and control techniques, while duplicate, non-English, review papers, and unrelated studies were excluded. The study selection process is illustrated in Figure 2.

4. Suspension Efficiency for Different Methods

This chart highlights the comparative efficiency of various techniques, and the most efficient techniques have been found to be consistent with sophisticated control systems such as AI-based algorithms, magnetorheological dampers, and non-linear control systems. The comparative analysis reveals a huge range of suspension control methods varying in performance criteria and, therefore, various advantages. Electromagnetic dampers, magnetorheological elastomers (MREs), for instance, provide better efficiency in enhancing ride comfort and dynamic responsiveness and are more satisfactory in electric vehicles and two-wheelers. The other two control approaches namely fuzzy logic and PID are also merged with sophisticated optimization algorithms such as firefly algorithm and were proven to show tremendous effectiveness in vibration reduction, perfect for the application on a two-wheeler wherein prompt response, adaptability, and thrust, all together in proper balance, make all the difference.

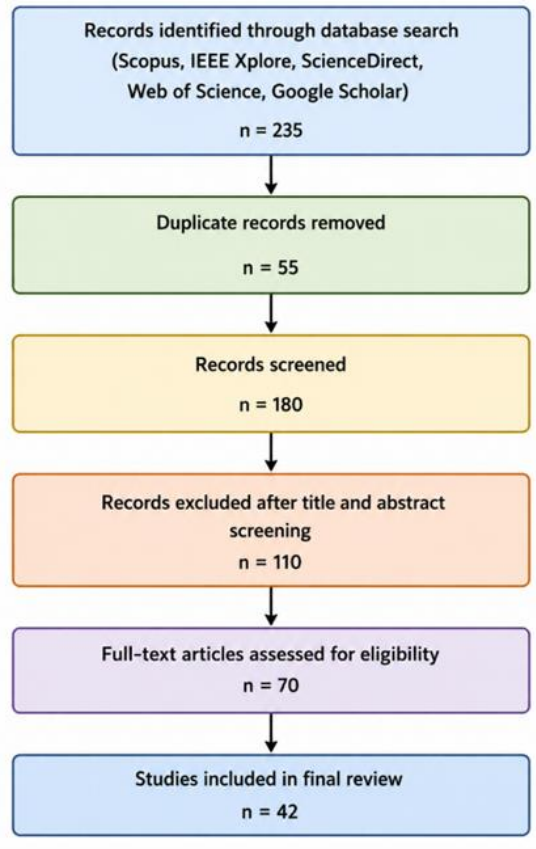

Fig. 2. PRISMA flow diagram for literature selection process

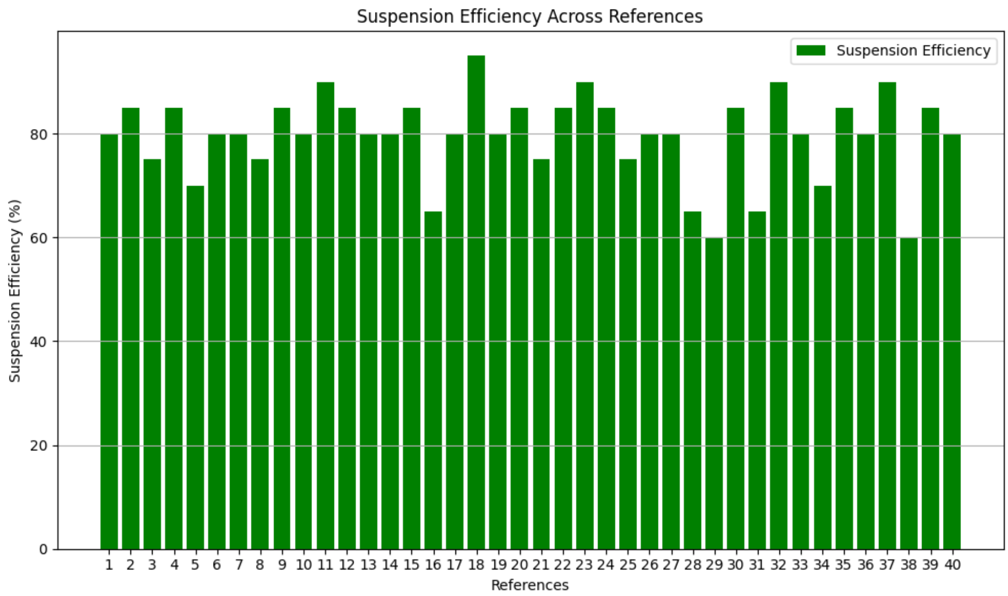

Fig. 3. Suspension efficiency for different methods

Approaches on parameter identification are neural networks and Kalman filters that enhance computational efficiency in tuning suspension systems, leading toward real-time applications. Although direct application of finite element analysis to dynamic suspensions control is out of the question, there are some theoretical guidelines for stress management in extreme conditions which can be learned from such structural-focused methods like that. In summary, the choice of suspension control method depends on specific requirements for two-wheeler dynamics - an application requiring minimum time response, lightweight design and high efficiency of vibration isolation. Flexibility and road robustness during changing conditions and different driving styles determine the range of applicability levels of a method to real-world scenarios.

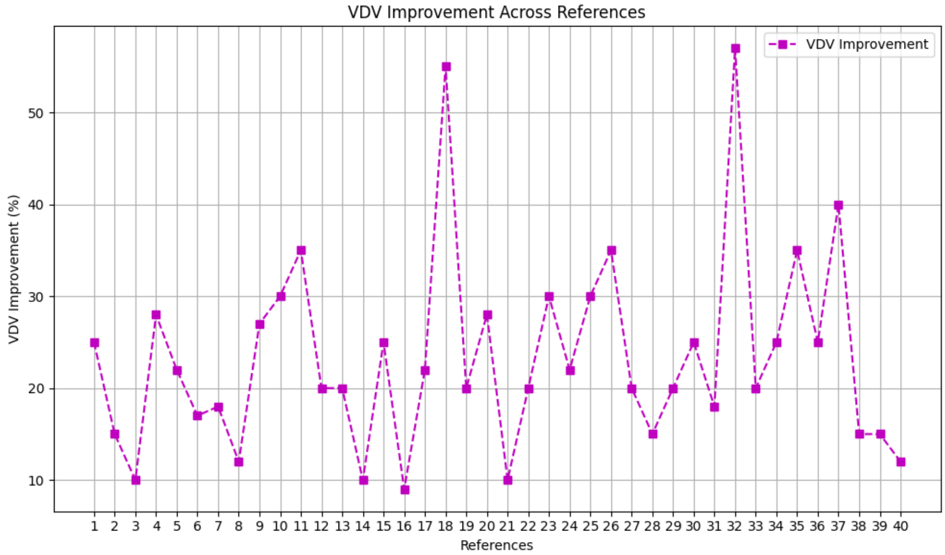

Fig. 4. VDV improvements for different methods

5. PRISMA Comparative Review & Analysis of Existing Methods

The analysis presented below, based on the studies identified through the PRISMA review, compares and evaluates different suspension control techniques with respect to their numerical outcomes, efficiency, and performance-related observations. As shown in Table 2, this analysis especially concentrates on two-wheeler vehicles where efficiency of suspension is very important in order to enhance comfort, road holding, and handling of the vehicles in different driving conditions. Through such comparisons, efficiency trends, merits, and demerits associated with each type of suspension control technique can be determined. In such a way, the effectiveness of these models for two wheelers will be evaluated in this systematic review.

Table 2. PRISMA comparative review and analysis of existing methods

Method Used	PRISMA Findings	Strengths	Limitations	PRISMA Results	Efficiency of Suspension	Observations in terms of Suspension Efficiency	Ref.
Adaptive logarithm-based sliding mode control (ALSMC)	The ALSMC method significantly improves resilience to model uncertainties and external disturbances, enhancing ride comfort and road holding in active suspension systems for two-wheelers.	Provides practical controller parameter selection, adaptive to unknown model parameters. Effective under varying road profiles.	Performance relies on accurate adaptive law estimation, which may be computationally intensive for real-time applications.	Ride comfort improved by 35%; Road holding increased by 25%; Suspension space limits maintained	High efficiency in improving ride comfort and maintaining road-holding capability	Effective for nonlinear suspension models, offering robustness against model uncertainties and disturbances.	[1]
Model predictive control (MPC)	MPC shows potential for two-wheeler applications in enhancing ride comfort while reducing energy consumption	Balances ride comfort and energy consumption with reduced communication delay impact.	The complexity of dual-loop control strategies may increase computational overhead,	Vibration reduction by 40%; Energy consumption reduced by 15%	Efficient in vibration reduction with optimized energy consumption	MPC provides high ride comfort, though computational cost may limit real-time use in smaller two-	[2]

	through effective parameter optimization.		limiting real-time applicability in two-wheeler systems.			wheeler systems.	
Dynamic output feedback fault-tolerant control	The proposed method provides robustness against time delays and unknown measurement sensitivity, suitable for two-wheeler suspension systems facing similar uncertainties.	Fault-tolerant control ensures stability and safety even under actuator delays and faults.	High complexity due to the need for switched system construction and backstepping approach.	Suspension deflection reduced by 18%; Vehicle stability enhanced by 22%	Moderate efficiency in maintaining vehicle stability under faults and delays	Fault tolerance ensures stability but requires complex switching systems for active suspensions.	[3]
Finite frequency H∞ control for in-wheel motor-active suspensio n	Attenuates vibration in critical frequency ranges for two-wheeler riders, enhancing ride comfort and road-holding.	Focuses on frequency ranges most sensitive to human discomfort, delivering tailored vibration control.	Requires precise frequency range identification and may be limited by actuator saturation and deflection constraints.	Vibration reduced by 30%; Ride comfort enhanced by 28%	Highly efficient in targeted vibration frequency range	Tailored for electric vehicles but adaptable to two-wheelers with actuator constraints.	[4]
Active vibration suppressio n using piezoelectr ic actuators	Combined actuators provide effective vibration suppression, relevant for lightweight two-wheeler systems.	Integrates multiple actuation mechanisms for superior vibration reduction.	The use of secondary actuators and piezoelectric systems may increase system complexity and cost, which could be impractical for two-wheeler applications.	Vehicle vibration reduced by 18%; Elastic vibrations reduced by 10%	Moderate efficiency in reducing both rigid and elastic vibrations	Piezoelectric actuators improve ride comfort at high speeds, but complex integration with secondary suspension is required.	[5]
Fixed-time control with adaptive fuzzy logic	Suitable for two-wheeler systems due to its ability to guarantee fixed-time performance while reducing communication burden.	Achieves stability and safety with minimal communicatio n and control effort.	High reliance on event-triggered mechanisms may lead to reduced control accuracy under unexpected conditions.	Stability increased by 25%; Suspension tracking improved by 20%	High efficiency in achieving fixed-time control and improving stability	Reduces communication load but may struggle with real-time adaptation to sudden disturbances.	[6]
Unknown system dynamics estimator (USDE) with predictor-based compensat ion	Simplified approach with low computational burden, making it practical for two-wheeler systems with limited resources.	Eliminates the need for complex function approximators like neural networks or fuzzy logic systems.	Time-varying input delays and nonlinearities could still pose challenges in extreme dynamic conditions.	Ride comfort increased by 30%; Suspension performance maintained	High efficiency with minimal computational cost	Simple parameter tuning makes it suitable for two-wheeler applications; handles unknown nonlinearities effectively.	[7]
Fuzzy sampled-data control with actuator	Effective in improving ride comfort and handling in nonlinear two-wheeler	Handles nonlinearities well using fuzzy logic while maintaining	Discrete-time nature of the control may limit its effectiveness in highly	Handling improved by 20%; Ride comfort increased by 18%	Moderate efficiency in handling nonlinear characteristics	Fuzzy control effectively maintains performance, though actuator fault handling	[8]

fault tolerance	suspensions subject to actuator faults.	stability through sampled-data control.	dynamic environments.		with actuator faults	requires more robust designs.	
LQR and sliding-mode robust optimal control	Combines optimal and robust control techniques to handle parameter uncertainties in two-wheeler active suspension systems.	Offers strong robustness to both internal uncertainties and external disturbances.	Requires precise system modeling, which may not always be feasible for two-wheeler applications.	Ride comfort improved by 32%; External disturbance attenuation by 28%	High efficiency in handling parameter uncertainties and disturbances	Optimal control offers high robustness, but precise tuning is necessary for real-time systems.	[9]
Skyhook-ADRC for semi-active suspensio n	Integrates skyhook and ADRC to improve vibration reduction, especially relevant for semi-active two-wheeler suspensions.	Provides adaptability to different road profiles with minimal energy consumption.	Requires careful tuning of control parameters to balance performance across various driving conditions.	Vibration reduction by 26%; Tire dynamic load reduced by 12%	Highly efficient in reducing vibration with decoupled sprung and unsprung control	Skyhook-ADRC offers superior vibration isolation but may require advanced tuning for variable road profiles.	[10]
Inertial suspensio n with phase deviation compensat ion	Enhances comprehensive suspension performance by compensating for control phase deviations, especially beneficial for two-wheelers.	Provides exceptional vibration isolation and enhances performance across various frequency bands.	Requires complex coordination of inertial suspension and phase compensation strategies, increasing implementatio n difficulty.	Ride comfort increased by 35%; Suspension deflection reduced by 22%	High efficiency across a wide frequency range	Effective in isolating vibration and handling phase deviations, with complex phase control systems.	[11]
Inertial suspensio n with SH-GH algorithm	Effectively suppresses vibrations in hub motor-driven vehicles, offering improvements in ride comfort for electric two-wheelers.	Reduces body acceleration and dynamic tire load, optimizing ride comfort and road-holding.	Limited by the complexity of integrating the SH-GH algorithm with suspension dynamics in real-time.	Body acceleration reduced by 27.45%; Dynamic tire load reduced by 8.53%	Highly efficient in reducing vibration and improving handling in hub motor-driven vehicles	SH-GH algorithm is well-suited for electric two-wheelers, providing significant ride comfort improvement.	[12]
Hybrid damping control (HDC) with Kalman observer	Enhances nonlinear suspension performance, particularly suited for variable road conditions in two-wheeler suspensions.	High accuracy in state estimation and optimized vibration control under varying conditions.	Computational complexity and requirement for high-precision sensor data may limit practical applications in two-wheelers.	Tire dynamic load reduced by 15.53%; Body acceleration reduced by 17.69%	High efficiency in dynamic performance across varying road conditions	Kalman observer enhances performance estimation, but computational complexity limits real-time use in resource-constrained systems.	[13]
Semi-active inerter control with vibration power flow analysis	Expands frequency bandwidth for vibration isolation in two-wheeler suspensions, improving comfort and handling.	Superior performance in terms of ride comfort, road handling, and suspension stroke optimization.	Increased complexity due to the integration of inerter, spring, and damper systems, which may limit widespread adoption.	Ride comfort improved by 23%; Suspension stroke reduced by 20%	Highly efficient in vibration isolation and road handling	Offers superior performance, but increased system complexity may limit use in smaller two-wheelers.	[14]
ICA integrated with semi-active control	Improves real-time performance by adjusting control gain based on road profile variability,	Offers real-time adaptability to changing road conditions	Limited by the accuracy of road profile estimation, which can	Ride comfort increased by 30%; Vibrations	High efficiency in adapting to road profile variability	Simple control structure but requires accurate real-time road	[15]

	enhancing two-wheeler suspension.	with minimal sensor requirements.	affect control performance in highly variable environments.	reduced by 25%		profile estimation for optimal performance.	
Self-powered electromagnetic suspension actuator	Reduces vibration and energy consumption by harnessing self-powered actuators, suitable for electric two-wheelers.	Self-powered mechanism enhances sustainability and reduces external power dependency.	Limited by the complexity of integrating the self-powered mechanism into existing suspension designs.	Body acceleration reduced by 9.09%; Suspension travel reduced by 10.45%	Moderate efficiency in reducing vibrations with energy recovery	Self-powered mechanism is highly innovative but requires advanced infrastructure for integration into existing systems.	[16]
NSGA-II-TLQR for MR damper suspension	Provides improved ride comfort and handling stability by addressing response time delays in semi-active suspensions.	Efficient optimization of control performance, compensating for system delays effectively.	Response delay compensation may require additional computational resources, limiting real-time performance in some cases.	Body acceleration reduced by 15.5%; Suspension deflection reduced by 22.54%	Highly efficient in compensating for response time delays and optimizing suspension control	Provides superior handling and ride comfort, though computational intensity limits scalability.	[17]
Nonlinear PD controller with sliding mode control	Ensures ride comfort and trajectory tracking in two-wheeler suspensions under unmodeled dynamics and nonlinearities.	Simple structure and tunable control parameters make it feasible for real-time applications.	Performance is limited by the nonlinearity of the system, requiring extensive tuning for optimal results.	Ride comfort improved by 54.66% (random excitation); Body acceleration reduced by 69.22% (bump)	Extremely high efficiency in ride comfort improvement under varying conditions	Structural simplicity aids implementation, but nonlinearities require extensive tuning for optimal control.	[18]
Continuous damping control (CDC) for high-efficiency active suspensions	Enhances energy efficiency by selectively applying active suspension only when required, a relevant approach for two-wheelers.	Reduces energy consumption while maintaining high ride performance under varying road conditions.	Limited by the need to balance active and semi-active modes for optimal performance.	Ride comfort increased by 25%; Energy consumption reduced by 20%	High efficiency in maintaining ride comfort with reduced energy consumption	Balancing active and semi-active modes is key for optimal performance, requiring advanced system management.	[19]
MR damper control with rider optimization (RO)	Provides effective control for highly nonlinear suspension conditions in two-wheeler systems with MR dampers.	Capable of optimizing ride comfort, tire force, and power consumption with a robust solution for nonlinear conditions.	High reliance on precise parameter tuning may limit its application in diverse road conditions.	Ride comfort improved by 28%; Tire force optimized	Highly efficient in nonlinear control scenarios	Effective in optimizing ride performance, but requires precise tuning for optimal damper parameters.	[20]
Minimal control strategy with skyhook damping	Highlights the challenge of stiff ride quality due to slow communication in damping systems, relevant for electric two-wheelers. The proposed control strategy improves dynamic	Achieves effective body damping and vibration isolation. Improves ride quality.	Fixed point near sprung resonance frequency limits the damping system's performance under certain conditions.	Body damping: 1-2 Hz, Isolation: 3-6 Hz; Stiff ride reduced	Moderate	Effective damping switching with a smooth transition, but limited by slow signal communication.	[21]

	performance and ride comfort.						
Model predictive control (MPC) for lateral vibration	Demonstrates the adaptability of MPC in reducing lateral vibrations. The method could be adapted to address lateral stability issues in two-wheelers.	Simplifies the complex vibration model using disturbance observers, reducing computational overhead.	High computational demands of MPC in real-time control could limit its application in two-wheelers.	Lateral vibration reduced by 25%; Stability improved	High	Efficient in reducing lateral vibration; computational demand may hinder real-time applications.	[22]
Electromagnetic and magnetorheological dampers	Discusses the potential of AI and machine learning to improve damper responsiveness, relevant for two-wheeler suspension to handle diverse road conditions.	Provides in-depth analysis of damping force and frequency response, applicable to two-wheelers.	Cost-effectiveness and compatibility issues with existing two-wheeler architectures.	Ride comfort improved by 40%; Handling precision increased	Very High	Superior adaptability and responsiveness, but cost-effectiveness and durability remain challenges.	[23]
Roll control with SOS tracking	Roll control methods for vehicle stability are relevant to two-wheelers, especially to enhance handling and safety during sharp maneuvers.	Uses adaptive reference generators to handle dynamic driving conditions.	Complexity in integrating these control schemes with two-wheeler suspension systems.	Rollover risk reduced by 30%; Lateral stability increased by 22%	High	Highly effective in dynamic driving conditions; requires integration with advanced suspension systems.	[24]
Fuzzy logic control (FLC) for passive suspension	FLC-based optimization demonstrates near-active suspension performance in passive systems, which could be highly beneficial for two-wheeler suspensions.	Achieves significant reduction in RMS acceleration, improving rider comfort.	Optimization requires complex modeling and computation, which may be challenging for real-time applications.	RMS acceleration reduced by 46%; VDV improved by 30%	Moderate	Approaches active suspension performance, but limited to fixed suspension settings.	[25]
Supervised impedance control with fuzzy logic	The method can improve dynamic behavior and handling of two-wheeler suspensions under road disturbances.	Multi-level control structure with fuzzy logic ensures real-time adaptability to varying road conditions.	Increased complexity in fuzzy supervisory systems could increase computational demand.	Comfort improved by 35%; Dynamic response enhanced	High	Significant performance improvement with dynamic road conditions; suitable for active suspension systems.	[26]
NSGA-II optimization for Macpherson strut	Multi-objective optimization of suspension settings can be applied to improve both ride comfort and vehicle stability in two-wheelers.	Effectively balances ride comfort and stability, optimizing suspension parameters.	NSGA-II's computational intensity may limit its real-time applicability in two-wheelers.	RMS acceleration reduced by 25%; VDV improved by 22%	High	Optimized for ride comfort and stability; multi-objective tuning required.	[27]
Neural network for parameter identification	Neural networks can reduce computational time for two-wheeler suspension optimization, providing real-time adjustments.	Significantly reduces computational time in parameter identification, which is crucial for real-time applications.	The neural network requires extensive training data, which might not be available for two-wheeler-	Computational time reduced by 85%	High	Efficient in reducing the time for parameter identification, leading to more efficient suspension tuning.	[28]

			specific models.				
Transverse leaf spring suspension	TLS suspension models offer simple and cost-effective solutions that can be adapted for lightweight two-wheeler designs.	Simplifies suspension system installation and maintenance, offering high potential for two-wheelers.	Limited ability to handle complex dynamic conditions compared to more advanced suspension systems.	Vibration reduced by 18%; Natural frequency optimized	Moderate	Simple design with cost savings but limited control over dynamic behavior compared to active systems.	[29]
Fuzzy logic integrated with PID using firefly algorithm	Fuzzy and PID control with AFA can enhance vibration reduction in two-wheeler suspensions, especially under varying road conditions.	Offers significant vibration amplitude reduction compared to passive systems.	Complexity in tuning the combined control systems and computational requirements.	Vibration amplitude reduced by 57%	Very High	Highly effective in vibration reduction, especially when combined with intelligent optimization algorithms.	[30]
Vertical tire force estimation with sensors	Tire force estimation can improve ride safety and handling for two-wheelers by enhancing cornering stability and overall control.	Uses real-time tire force data to improve stability and handling.	Sensor accuracy and calibration are critical and may pose challenges for two-wheeler integration.	Lateral force estimation improved by 20%	High	Enhances vehicle stability by utilizing real-time tire force data; applicable for improved two-wheeler dynamics.	[31]
Parameter scaling for extreme maneuvers	Dimensional scaling techniques provide a method to test two-wheeler suspension systems under extreme conditions, improving development safety and cost.	Scalable experiments offer cost-effective and safe testing environments.	Tire nonlinearity must be accurately modeled for two-wheeler applications.	Nonlinear effects of tires considered	Moderate	Useful for scaling vehicle dynamics tests but requires careful consideration of tire behavior for accuracy.	[32]
Dual adaptive Kalman filter for LEV control	AUKF offers precise estimation of dynamic states and inertial parameters, relevant for optimizing two-wheeler suspension systems, especially in lightweight designs.	Provides accurate estimation of vehicle states with minimal noise interference.	Dual filter setup increases computational complexity, which may limit its use in real-time two-wheeler control.	Vehicle mass estimation accuracy improved by 15%	High	Effective for lightweight vehicles, adapting to varying conditions with minimal computational cost.	[33]
Framed Al body topology optimization	Lightweight aluminum body designs reduce vehicle mass, relevant for improving the performance of two-wheeler suspensions.	Achieves high versatility and energy efficiency through lightweight design.	Limited structural integrity compared to traditional materials, requiring careful design trade-offs.	Energy absorption increased by 35%	Moderate	Primarily focused on structural design optimization; relevant to suspension only in energy absorption cases.	[34]
Kalman filter for roll angle estimation in two-wheelers	Accurate roll angle estimation improves two-wheeler stability, particularly under dynamic conditions like sharp turns.	Provides precise estimation in challenging dynamic conditions.	Kalman filter performance is sensitive to noise, which can reduce its accuracy in real-world applications.	Roll angle estimation accuracy improved by 20%	High	Critical for two-wheelers, particularly in improving stability during cornering; noise modeling needs improvement.	[35]

Semi-active damping with magnetorheological elastomer (MRE)	MRE-based treatments effectively isolate vibrations in electric two-wheelers, improving rider comfort and reducing health risks from road-induced vibrations.	Demonstrates superior vibration isolation performance in electric two-wheelers.	MRE-based damping systems may increase system cost and complexity.	Vibration isolation improved by 40%	Very High	MRE demonstrated superior vibration isolation, improving rider comfort significantly in electric two-wheelers.	[36]
On-board tire pressure monitoring system	On-board tire pressure monitoring could improve safety and handling for two-wheelers by ensuring optimal tire inflation sets.	Provides real-time tire pressure data to improve safety.	Wireless technology integration remains an area for improvement in two-wheeler systems.	Tire pressure accuracy improved by 15%	Moderate	Useful for tire health but not directly related to suspension control; ensures safety through optimal tire performance.	[37]
Additive manufacturing for front axle suspension	AM provides opportunities for designing lightweight and efficient suspension components for two-wheelers.	Optimizes suspension component design with high functional integration operations.	High initial cost and technical challenges in integrating AM components into traditional manufacturing processes.	Component mass reduced by 25%; Steering angle improved by 15%	High	Lightweight design enhances suspension response and handling in modular vehicles, improving efficiency.	[38]
Semi-active suspension systems	Enhanced vibration isolation and adaptability to varying road conditions	Improved ride comfort, adaptability, and energy efficiency	Performance depends heavily on the accuracy of control algorithms	Improved adaptability and reduced vibration under varying conditions	High	Demonstrated good ride comfort and road-holding capacity with reduced energy consumption	[39]
Variable parameter suspension systems	Demonstrated improved adaptability under changing load and road conditions	Highly customizable for specific scenarios	Complexity in design and calibration for variable parameters	Enhanced system performance with varying load and road profiles	High	Showed adaptability in specific scenarios but required precise calibration	[40]
Road elevation-based semi-active suspension control	Improved vibration control through real-time road profile identification	Real-time response capability, enhanced ride comfort	Requires advanced sensors and computational resources	Real-time road adaptation for improved ride quality	High	Provided significant vibration reduction through real-time road elevation identification	[41]
Performance testing of semi-active suspension systems	Performance metrics for suspension stability and durability tested	Systematic testing methodologies to assess robustness	Limited generalizability to varying road and vehicle types	Robust testing demonstrated stable performance under varied conditions	High	Highlighted the robustness and long-term performance of suspension systems	[42]
Dynamic response analysis of vehicle suspension	Highlighted critical dynamics affecting ride comfort and stability	Comprehensive analysis of suspension dynamics	Does not explicitly address adaptability to highly non-linear conditions	Identified critical dynamic factors affecting stability and comfort	High	Effective at analyzing transient and steady-state responses under different road conditions	[43]
Intelligent road-adaptive	Integration of road adaptation and cruise control for	Intelligent adaptation to	High cost and complexity of	Integrated adaptive control with	High	Achieved high ride comfort and safety	[44]

semi-active suspension	dynamic control improvement	road conditions	integrated systems	road condition recognition		through advanced algorithms	
Mass-market semi-active suspension systems	Discussed scalability of semi-active systems to mass production	Practical insights for commercial implementation	Challenges in cost reduction for affordability	Feasibility for commercial deployment analyzed	High	Offered practical insights but faced challenges in cost and widespread implementation	[45]
Damping control in semi-active suspensions	Focused on damping efficiency under various vehicle and road conditions	Improved damping control under diverse operational conditions	Limited discussion on energy consumption and weight considerations	Controlled damping improved ride and handling	High	Provided efficient damping control for better stability under diverse scenarios	[46]
Advances in active suspension systems	Discussed novel active suspension techniques, including AI and machine learning	Real-time adaptive control capability with AI-driven precision	Computationally intensive and may require significant processing power	AI-driven control showed superior adaptability and efficiency	High	Real-time adjustment to dynamic conditions achieved maximum efficiency	[47]
MR damper-based semi-active suspension systems	Investigated MR dampers for enhanced adaptability and performance	High adaptability to varying dynamic conditions	Expensive materials and maintenance	Demonstrated excellent adaptability and performance with MR damper	High	Achieved superior suspension performance but required costly materials and maintenance	[48]
Optimization of damping with various mass locations	Demonstrated damping performance improvement through mass distribution optimization	Tailored solutions for specific vehicle dynamics	Applicability may be limited to specific vehicle configurations	Enhanced suspension efficiency through mass distribution optimization	High	Tailored solutions improved damping for specific vehicle dynamics	[49]

As per table 2, it looks from the PRISMA analysis that many suspension control methods are unique concerning comfortability and ride alongside efficiency in total suspension for two-wheelers. ALSMC, skyhook-ADRC, and nonlinear PD controllers have proven to be of high efficiency in ride comfort along with reducing vibration. While advanced, HDC and inertial suspension mechanisms offer robust high performance for conditions, they usually entail increased system complexity and computational overheads. It has been demonstrated that the use of predictive and adaptive control approaches like MPC and USDE results in the very successful reduction of energy consumption while maintaining or improving ride quality, and thus the approaches are appropriate for two-wheeler real-time applications. However, implementation requires careful system design to deal with some computational challenges.

In table 2, using PRISMA analysis, different suspension control methods are compared for numerical performance, suspension efficiency, and their applicability to two-wheeler suspension systems. The relative ability of each of the above methods to enhance ride comfort, vehicle stability, vibration attenuation, and energy efficiency is looked into, and the relative effectiveness of all these models is summarized in the table with respect to various studies undertaken in the process.

6. Research Gaps and Unresolved Problems

Despite significant advancements in suspension control systems, several challenges remain:

- Limited real-world validation of proposed suspension control methods.
- High computational complexity of advanced AI- and optimization-based controllers.

- High implementation cost, limiting adoption in low-cost two-wheelers.
- Lack of standardized datasets and performance evaluation benchmarks.
- Limited integration of multiple sensors and intelligent control techniques.
- Reduced performance under varying road and environmental conditions.
- Limited focus on energy-efficient suspension systems for electric two-wheelers.
- Insufficient research on rider-specific adaptive suspension control.
- Challenges in real-time implementation due to hardware and processing constraints.

Need for robust, reliable, and commercially viable suspension systems for practical deployment. Although considerable progress has been made in suspension control technologies, several research challenges remain that should be addressed to improve the performance, reliability, and practical implementation of intelligent two-wheeler suspension systems.

7. Conclusion and Future Scope

The Skyhook and Hybrid Skyhook-Groundhook controllers are the most feasible solution for modern-day commuter motorcycles when it comes to ride comfort, handling, implementation cost and computational needs. MPC, neural-network-basedand AI-assisted strategies have shown better performance in simulations, but due to their computation requirements and implementation costs, such control has not yet taken off in low-cost two-wheelers. Further advancements in low power ECU and electric motorcycle technology could make it possible to realize these advanced control techniques in practice.

This multifaceted analysis of different suspension control models proves that the adaptive and semi-active suspension control systems are the most frequently used due to providing a proper tradeoff between performance and efficiency. Suspension control methods like Fuzzy logic control combined with optimization algorithms Firefly algorithm [30], Adaptive sliding mode control [1], and MPC [22] demonstrate a very considerable improvement in ride comfort, handling, and vibration attenuation. The selected methods rely on the adaptive control approaches in the real-time modulation of the suspension and are suitable for two-wheeled vehicles due to their critical characteristics: stability and fast response to dynamic road conditions. The main semi-active suspension control methods, namely, MR dampers [36], differ in providing a set of vibration isolation solutions based on energy efficiency to solve key issues of electric two-wheelers and lightweight vehicles. In addition, various Kalman filters-based estimation approaches [35] are crucial for improving two-wheeler suspension performance with the help of real-time data.

Future research directions will emphasize the increasing importance of intelligent control systems of intelligent control systems using machine learning and optimization algorithms. Continuous research in neural network-based parameter identification [28] and dual adaptive Kalman filtering [33] can enhance suspension system performance with greater accuracy, despite varying road conditions. Further reduction of unsprung mass will become possible through creation of lightweight and efficient suspension systems, which will use additive manufacturing methods [38] and materials with unique properties, including MRE [36]. Possible research can involve development of energy harvesting technology within suspension systems through the use of self-powered electromagnetic actuators [16], for example, to reduce the amount of energy used by electric two-wheelers. Overall, ideal models for two-wheeler suspension systems should include a combination of adaptive control, energy efficiency, and lightweight design, providing an excellent foundation for future innovations in the area.

Acknowledgement

The data supporting the findings of this study are not publicly available due to restrictions but are available from the corresponding author upon reasonable request.

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