Recent Advancements in Intelligent Control Techniques of Active Suspension System

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(Manuscript Received 15th September, 2024; Revised 28th October, 2024; Accepted 30th October, 2024)

Abstract

Active suspension systems are designed to improve vehicle ride comfort and handling stability by adapting to changing road conditions, surpassing the capabilities of traditional passive and semi-active systems. The article explores intelligent control approaches in active suspension systems, focusing on three main strategies: FLC (Fuzzy Logic Control), Fuzzy PID Control, and MPC (Model Predictive Control). FLC is highlighted for its capacity to manage uncertainties and nonlinear vehicle dynamics using rule-based decision-making. Fuzzy PID Control builds upon traditional PID control by incorporating fuzzy logic, enabling real-time adjustments and improved adaptability to road conditions. This approach improves performance in complex systems by optimizing control gains, enhancing stability and comfort. MPC is noted for its predictive capability, which optimizes control actions based on future states, making it highly effective in multi-variable and constraint-heavy applications, despite its computational demands. While FLC and Fuzzy PID are simpler and responsive, MPC provides the advantage of precision in complex, high-dimensional scenarios. Reducing MPC's computational complexity for real-time use, enhancing adaptability through hybrid controls along with optimizing energy use alongside ride comfort and stability is the future in intelligent control of active suspension.

Keywords: Active suspension, Fuzzy Logic Control, Fuzzy PID, Model Predictive Control, Vehicle stability

1. Introduction

The suspension system in a vehicle is critical for ensuring ride comfort, handling stability, and overall performance. It plays a vital role in supporting the vehicle's weight, keeping the tires in contact with the road, and mitigating the effects of road irregularities on the vehicle's chassis. The primary function of a suspension system is to absorb vibrations caused by uneven surfaces, which directly affect passenger comfort and cargo safety (Yadav et. al, 2019). In essence, the suspension system acts as a mediator between the road and the vehicle, reducing vibrations by isolating the sprung mass (vehicle body and sub-assemblies above the suspension) from the un-sprung mass (components like wheels, tires, and axles in direct contact with the road)(Mohd Riduan et al., 2018). Broadly, there are three types of suspension systems: Passive suspension systems; Semi-active suspension systems and Active suspension systems.

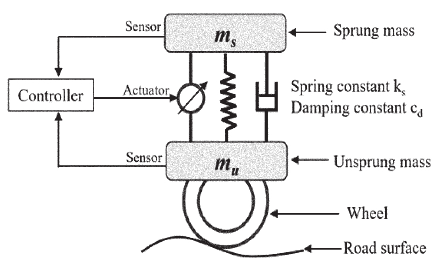

Fig. 1: Active suspension system

The passive suspension system, which is mechanical in nature, is the most traditional. It consists of springs and dampers that help regulate oscillations and vibrations but lacks the flexibility to adapt to changing road conditions(Kumar et al., 2021). The semi-active suspension system improves upon passive systems by using variable dampers that adjust damping stiffness in response to road conditions. While these advancements improved ride quality, they are still limited compared to the fully adaptive nature of active suspension systems (Soliman & Kaldas, 2021).

Unlike passive and semi-active systems, active suspensions utilize hydraulic actuators between the sprung and un-sprung masses to actively control the force exerted on the vehicle's suspension as shown in Fig. 1. By adjusting these forces in real-time, active suspension systems offer better vibration control, providing enhanced ride comfort and vehicle stability even on rough terrains. This ability to exert a control force on the suspension makes active suspensions particularly effective in mitigating vehicle vibrations caused by road irregularities.

If y_r is the road disturbance, y_u is the un-sprung mass displacement, y_s is the sprung mass displacement, f_a is the actuator force and k_w is the spring constant of wheel, the mathematical model for an active suspension system can be written as:

$$m_s = f_a - k_s(y_s\text{-}y_u) - c_d \qquad (1)$$

$$m_u = -f_a + k_s(y_s\text{-}y_u) - k_w(y_u - y_r) \qquad (2)$$

Active suspension systems are more advanced than passive and semi-active systems. They include several components such as actuators, sensors, and a controller. The actuators generate forces to control the suspension movement, while the sensors provide real-time data (e.g., road conditions, vehicle speed). The controller processes this data and adjusts the suspension accordingly to maintain optimal vehicle performance.

The control parameters in active suspension systems generally include:

i. Sprung mass displacement: The movement of the vehicle body relative to the tires.
ii. Tire deflection: The difference between the tire's actual position and the road surface.
iii. Suspension deflection: The amount by which the suspension components compress or expand.
iv. Actuator force: The force generated by the actuators to control the suspension movement.

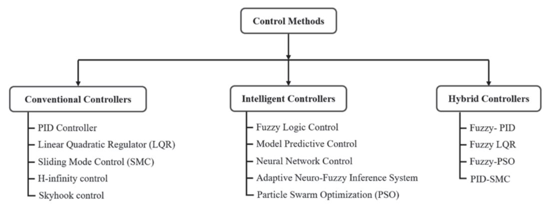

Fig. 2: Classification of control strategies for active suspension system

Control strategies are crucial for optimizing the performance of active suspension systems. These strategies aim to reduce body displacement, suspension deflection, and road-induced vibrations, while maintaining ride comfort and stability(Ayman & Salem, 2013). The control strategies can be broadly classified as conventional, intelligent and hybrid controller. Fig. 2 shows the classification of most applied control strategies for active suspension system. Conventional controllers such as PID (Proportional-Integral-Derivative), LQR (Linear Quadratic Regulator), and SMC (Sliding Mode Control) have been commonly employed in early active suspension systems. While these methods provide satisfactory results in linear control scenarios, they often fail to address non-linear dynamics, especially under highly dynamic and unpredictable conditions. This limitation in conventional control strategies has led to the emergence of intelligent controllers, which can adapt to complex, non-linear behaviors in real-time. Among the most promising intelligent control strategies are the FLC (Fuzzy Logic Controller), Fuzzy PID Controller, and MPC (Model Predictive Controller). Each of these controllers brings a unique approach to handling the non-linearities and uncertainties inherent in vehicle suspension systems.

The FLC (Fuzzy Logic Controller) is widely regarded for its ability to handle uncertainty and non-linear dynamics without needing a precise mathematical model of the system. FLC uses a set of rules based on human-like reasoning to adjust control forces, making it particularly suitable for managing the unpredictability of road conditions. Fuzzy-PID Controller builds upon the conventional PID approach by incorporating fuzzy logic to dynamically adjust the control parameters (k_P, K_I, and K_D) in real time. This allows for better performance in complex, multi-input, multi-output (MIMO) systems compared to the simpler PID approach, especially when dealing with non-linear behaviors of the suspension system.

MPC (Model Predictive Controller) stands out for its ability to predict future system states and optimize control inputs over a defined time horizon. MPC is highly effective in multi-variable control scenarios as it offers a predictive edge that allows for precise control of suspension system under varying conditions. While MPC requires higher computational resources, advancements in processing power are making it increasingly feasible for real-time applications in vehicle suspensions.

In recent years, intelligent controllers have gained attention for active suspension systems. Intelligent control techniques like Fuzzy Logic Control, Fuzzy PID control, and Model Predictive Control provide superior adaptability and performance in managing nonlinearities and disturbances. This section discusses these intelligent controllers, focusing on their methodologies and performance in active suspension systems.

2. Fuzzy Logic Controller

Fuzzy Logic Control has gained popularity due to its capacity to handle the complexities and non-linearities of vehicle dynamics without requiring an exact mathematical model. It relies on human-like reasoning and rule-based decision-making to manage the suspension system's response to road irregularities. This flexibility in dealing with uncertainties makes FLC particularly suitable for active suspension systems. the FL controller not only illustrates black and white like conventional digital logic, it also explains the immeasurable gray region in between black and white as well(Shah et al., 2020).

The control system itself consists of three stages as shown in Fig.3:

i. Fuzzification: It converts real-number input values into fuzzy values.
ii. Fuzzy inference machine: It processes the input data and computes the controller outputs based on rule base and the database.
iii. Defuzzification: The outputs, in fuzzy values, are converted into real numbers.

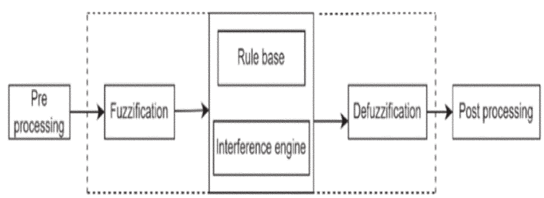

Fig. 3: Block diagram of fuzzy logic controller

The progression of research on active vehicle suspension systems highlights continuous advancements in improving ride comfort and handling through fuzzy logic control. Early studies aimed to address non-linearities in suspension systems by employing adaptive fuzzy inverse optimal control, which significantly improved ride comfort while maintaining state constraints, though it was limited to simpler vehicle models (Min et al., 2020). A study on a quarter-car model using FLC demonstrated substantial reductions in suspension deflection and improved sprung mass displacement, showing a 59.5% improvement in performance over passive systems (Hung et al., 2020). To balance the trade-off between ride comfort and road holding, hybrid Interval Type-2 FLCs further enhanced suspension dynamics by reducing ride index and dynamic tire loads, although optimization of the weighting coefficients remained an area for future work (Yatak & Şahin, 2021). Another approach integrated particle swarm optimization with an adaptive robust PID controller, achieving better results in minimizing body acceleration and relative displacement, highlighting the need for future exploration of more complex vehicle models (Mahmoodabadi & Nejadkourki, 2022a).

Subsequent research showed that fuzzy logic controllers could outperform PID control in handling road disturbances, particularly with impact signals, while also reducing actuator force by 59%—an indication of potential energy savings and reduced costs (Alp Arslan et al., 2022). A full-vehicle suspension model using advanced FLC showed an 81% reduction in vertical bounce, with substantial decreases in pitch and roll, underscoring improvements in both comfort and stability (Kumar et al., 2022). Moreover, the integration of a Fuzzy-LQR control method, optimized through particle swarm algorithms, resulted in significant improvements across body motion, suspension deflection, and tire deflection, though real-world testing was suggested to overcome simulation limitations (Abut & Salkim, 2023). Finally, the use of fuzzy control in an active suspension system incorporating hydraulic actuators demonstrated a 70.1% reduction in body displacement, although real-world dynamic factors still pose a challenge (Al-Ashtari, 2023). This body of work collectively indicates substantial progress in the control of active suspension systems, while future research aims to refine these models for practical applications.

However, the performance of FLC relies heavily on the design of the membership functions and rule base. When properly tuned, FLC delivers robust performance, but fine-tuning these parameters for varying driving conditions remains a challenge.

2.1 Fuzzy PID Controller

The Fuzzy PID Controller represents a hybrid approach that combines the advantages of traditional PID control with the adaptability of fuzzy logic. While conventional PID controllers struggle with the non-linear behavior of suspension systems, adding fuzzy logic to PID enables real-time adjustment of gains, allowing the system to respond more effectively to dynamic road conditions.

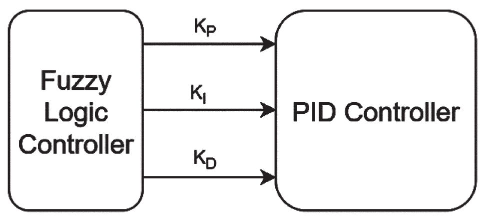

Fig. 4: Block representation of Fuzzy PID controller

The evolution of fuzzy-PID control strategies for active suspension systems has shown remarkable advancements in improving vehicle ride comfort and stability. Early studies introduced an Adaptive-Fuzzy Fractional Order PID (AFFOPID) controller, which significantly reduced Driver Body

Acceleration within a critical frequency range, demonstrating its effectiveness compared to traditional PID systems (Swethamarai & Lakshmi, 2022). Similarly, Ahmed et al. (2022) incorporated magnetorheological (MR) dampers with fuzzy-PID controllers optimized through a Differential Evaluation (DE) algorithm, yielding better performance metrics like Integral Absolute Error (IAE) than both traditional fuzzy-PID and passive systems(Ahmed et al., 2022). Both studies focused on enhancing vibration control, yet Ahmed et al. achieved more pronounced improvements by integrating MR dampers, targeting practical scenarios.

In the subsequent development, Li et al. (2022) refined fuzzy-PID control with a Particle Swarm Optimization (PSO) algorithm, reducing relative displacement and chassis acceleration, achieving an optimized value of 2.4625 compared to earlier models(Li et al., 2022). Mahmoodabadi and Nejadkourki (2022b) introduced a robust combination of fuzzy-PID and Whale Optimization Algorithm (WOA), further minimizing overshoot and oscillations with a superior objective function value of 1.7350 (Mahmoodabadi & Nejadkourki, 2022b). Comparative performance results highlighted by Yin et al. (2023) illustrated that fuzzy-PID control significantly reduces vertical acceleration by 40% and suspension workspace by 25% compared to passive systems, with Jin et al. (2023) advancing these techniques by integrating fuzzy neural networks and optimizing controllers using the grey wolf algorithm, marking a further leap in vehicle smoothness and stability (Jin et al., 2023). These developments reflect a clear trajectory toward more efficient, adaptive suspension systems.

2.2 Model Predictive Controller

Model Predictive Control is an advanced control technique that leverages a system model to predict future system behaviors and make real-time adjustments accordingly. By solving an optimization problem that considers constraints, MPC determines the optimal control actions to achieve desired outcomes, balancing tracking accuracy with operational limitations as shown in Fig. 5. The main advantage of MPC lies in its ability to handle multi-variable systems and constraints directly within the control formulation, providing flexibility and adaptability in complex applications (Schwenzer et al., 2021).

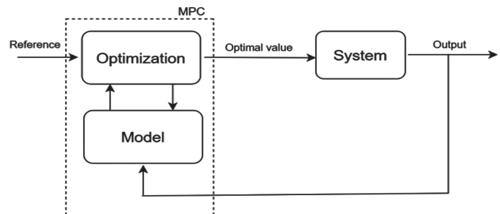

Fig 5: Block diagram of Model Predictive Control

The exploration of model predictive control (MPC) techniques for active suspension systems spans a range of applications, demonstrating consistent improvements in vehicle comfort and handling. Zhao et al. (2023) addressed the issue of excessive vibrations in tractor seat suspension systems using an optimized MPC with a dual-loop control strategy(Zhao et al., 2023). Their findings showed that the MPC-based system improved ride comfort while minimizing energy consumption, outperforming passive and PID systems. This research sets the foundation for optimizing agricultural machinery by improving operator health and efficiency. Similarly, Rodriguez-Guevara et al. (2023) applied MPC to nonlinear quarter-car systems to achieve a 60% reduction in chassis displacement and a 90% reduction in tire deflection, demonstrating significant improvements in passenger comfort and road holding with minimal impact on suspension acceleration (Rodriguez-Guevara et al., 2023). These results highlight MPC's capacity to handle nonlinearities and complex system behaviors.

Further advancements in MPC techniques are seen in Zhang et al. (2023), where a fast distributed MPC (DMPC) method was implemented for vehicle models with seven degrees of freedom(Zhang et al., 2023). The multi-agent system, enhanced with a radial basis function neural network, achieved notable reductions in vertical, pitch, and roll accelerations, showcasing improved computational efficiency and ride comfort. Pedro et al. (2020) also demonstrated the superiority of MPC when tuned with a particle swarm optimization algorithm, outperforming passive suspensions in terms of disturbance rejection and handling(Pedro et al., 2020). Enders et al. (2020) examined the impact of actuator limitations on MPC performance, showing that forces of 1000 to 2000 N are sufficient to handle road disturbances, emphasizing the need to account for actuator dynamics in future work (Enders et al., 2020). Across these studies, MPC consistently provides enhanced vehicle stability and comfort, with each paper contributing unique optimizations and applications

While MPC offers superior control in terms of predictive accuracy and constraint handling, it requires significant computational resources. Nevertheless, with the growing availability of high-speed processors and optimization algorithms, MPC is becoming more feasible for real-time applications, particularly in advanced automotive systems.

3. Discussion

The comparison of Fuzzy Logic Control (FLC), Fuzzy PID Control, and Model Predictive Control (MPC) reveals key strengths and trade-offs that are crucial when selecting an appropriate control strategy for active suspension systems. All three controllers improve ride comfort significantly compared to passive systems. While FLC and Fuzzy PID control schemes offer simplicity and faster real-time responses, they may not fully optimize the control actions across large, complex systems. Their performance depends heavily on fine-tuning fuzzy membership functions and PID gains, which can be a limitation in more dynamic environments. MPC, although computationally more intensive, excels in handling system constraints and optimizing control actions over a time horizon, making it ideal for applications where predictive behavior is crucial. Fuzzy PID and FLC controllers typically require fewer parameters to adjust compared to MPC. However, MPC's ability to incorporate optimization algorithms such as PSO (Pedro et al., 2020) or neural networks (Zhang et al., 2023) can mitigate this drawback, allowing it to adapt to complex real-world driving scenarios.

FLC, with its ability to handle non-linearities and uncertainties, excels in smoothing out vibrations under diverse road conditions, as seen in the work of Hung et al. (2020), where a 59.5% reduction in suspension deflection was achieved. Fuzzy PID controllers, like those developed by Yin et al. (2023), further enhance comfort by optimizing real-time adaptability through fuzzy logic and PID structures. MPC, on the other hand, has been particularly successful in high-dimensional systems, achieving notable performance improvements, with studies like Rodriguez-Guevara et al. (2023) showing up to a 60% improvement in ride comfort.

Fuzzy controllers, especially in hybrid configurations like Fuzzy-LQR (Abut & Salkim, 2023), strike a balance between ride comfort and vehicle handling, often outperforming traditional systems in reducing chassis displacement. Fuzzy PID systems offer improved stability by reducing relative displacement between vehicle components, as noted by Yin et al. (2023). MPC's advantage lies in its predictive nature, enabling optimal control actions over a future time horizon. This leads to precise control of both vertical and angular motions, as demonstrated by Zhang et al. (2023), making MPC particularly effective in scenarios requiring complex multi-variable control.

Active suspension systems exhibit significant non-linearities, which challenge traditional control methods. FLC is inherently robust to these non-linearities due to its rule-based structure that does not rely on an exact mathematical model of the system. The integration of Fuzzy Logic with PID controllers further enhances robustness, especially in non-linear multi-degree-of-freedom systems, as explored by Yin et al. (2023). MPC also effectively handles non-linearities, particularly in high-dimensional systems where constraints on control variables and physical limits must be accounted for.

4. Conclusion

This review has explored the application of intelligent control strategies—Fuzzy Logic Control (FLC), Fuzzy PID Control, and Model Predictive Control (MPC)—to active suspension systems. Each controller brings unique strengths to the table in terms of ride comfort, handling stability, response time, and robustness to system non-linearities.

FLC offers simplicity and robust performance in uncertain environments, making it ideal for lower-cost systems or vehicles where quick responses are necessary. Fuzzy PID controllers extend these benefits by optimizing traditional PID control structures, improving real-time adaptability and performance under varying conditions. MPC, though computationally demanding, excels in predictive control and constraint handling, positioning it as the optimal choice for more complex, high-dimensional systems or applications requiring precise multi-variable control.

Future advancements in computational power and optimization techniques, such as the integration of meta heuristic optimization or neural networks, will likely enable more widespread adoption of these intelligent controllers in real-time applications. The convergence of adaptive control, hybrid strategies, and multi-objective optimization represents the next frontier for active suspension system research. The areas that still require further exploration are:

i. Real-time Implementation: Efforts should be made to reduce the computational complexity of MPC for real-time applications. Distributed MPC (DMPC), as suggested by Zhang et al. (2023), offers a promising direction for future research.
ii. Adaptive and Hybrid Control Systems: Integrating adaptive mechanisms such as machine learning or neural networks can further enhance the adaptability of Fuzzy and MPC-based systems in handling unpredictable road conditions.
iii. Multi-objective Optimization: Future studies should investigate multi-objective optimization to balance ride comfort, handling stability, and energy consumption, particularly in hybrid vehicles where energy efficiency is critical.

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