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Design, Development and Enhancement of Suspension Systems Using Diverse Control Mechanisms for Performance Comparison

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Abstract

Advances in active suspension have now become important in the field of automotive engineering, mainly for electric and autonomous vehicles where improving ride comfort, stability and reducing energy use is essential. A complete evaluation of six control strategies, which are Proportional (P), Proportional-Integral (PI), Proportional-Derivative (PD), Proportional-Integral-Derivative (PID), Fuzzy Logic and hybrid Fuzzy-PID (FPID), is presented in this study as they are applied to an active suspension system. A quarter-car model was used in MATLAB/Simulink simulations to evaluate controller performance under various road conditions, focusing on body motion, wheel behavior, setting time, and deceleration. The results obtained suggest that FPID controller improves reliability, lifting the range of vertical body motion by 10.71% and speeding up settling time by as much as 20%. Importantly, FPID also reduces maximum speed of the vehicle's wheels on rough paths by 15%, making travel more comfortable for everyone. FPID enables electric vehicles to balance ride comfort and energy use by instantly adjusting damping forces, ensuring steady road contact for safer and smoother driving. The results show how useful FPID-based active suspension systems can be in future vehicles. Our findings on vibration control and response can help automotive engineers optimize comfort, stability, and fuel efficiency simultaneously. Future work should involve hardware simulation and connecting to cloud services for making predictive control adjustments with vehicles.

Keywords

controllers, ride comfort, Simulink, suspension system

1 Introduction

The driving comfort and the performance have much relation with the suspension systems because these devices regulate the forces induced between the vehicles and the surface of road. Conventional suspension systems have been extensively cast off in vehicle designs, although active suspension systems have grown as a sophisticated substitute for improved ride comfort owing to dynamic reactions. However, these active systems also have problems like power limitation and system complexity to be solved. In designing active suspension, the above features must be prudently managed to achieve the correct equilibrium between road surface and suspension, seat and other wheel loads, stability and low levels of vibration. This exposes the need to incorporate design elements to address existing constraints and improve general system performance simultaneously (Jiregna and Sirata, 2020).

The suspension system in a vehicle functions as a shock absorber, ensuring that shocks from bumpy roads do not impact the car's structure. It allows the vehicle to travel over obstacles without excessive bouncing. These are the system's linked shards, such as springs and shock absorbers. Its primary role is to absorb road vibrations so that passengers can travel comfortably while still supporting the car's weight adequately (Ayman et al., 2013). The suspension achieves a balance: it must be sturdy enough to support the vehicle's weight while remaining soft enough to absorb shocks and vivid impacts. First, only passive suspensions were used, which utilized mechanical components to dampen road waves and give stability. However, their downsides were quickly highlighted as engineers encountered numerous challenges, including decreased comfort and the capacity to respond to changing road

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conditions (Mohd Riduan et al., 2018). The car industry advanced with time, as did the research for superior systems of suspension. Suspension systems were classified as semi-active, active and passive. Every iteration was done with the objective of achieving even better performance and resolving issues connected to a specific level of comfort and handling qualities (Cao et al., 2011).

Against this context, active suspension systems provided a glimpse of hope, as they included in-built actuators that could modify the suspension setting at runtime. This breakthrough technology also improved vehicle handling by ensuring optimal tire-road contact while decreasing the vehicle body's tendency to roll (Patel, 2022). Driven by significant advances in control theory and increased computer capabilities, researchers investigated a wide range of control techniques, from simple PID control to complex fuzzy logic and different machine level algorithms. These controllers made suspension systems more adaptable; they could respond to changes in road surface as well as the driver's preferences (Li et al., 2022). In the field of suspension technology, daily advancements continue to seek out the finest. As vehicle engineers continue to strive for the ideal balance of ride quality, comfort and stability, active suspension systems are a true and amazing invention of human ingenuity in automobile innovation (Čorić et al., 2016).

In real world, this research is important as the automotive industry is demanding vehicles with more comfort, safety and intelligent adaptability. As the world is shifting towards more electric and autonomous vehicles, superior ride dynamics are not something optional but something required. Moreover, passengers expect smooth and controlled driving experience even in highly variable road conditions. Active suspension systems, especially those controlled by advanced control strategies like PID and fuzzy logic, is a tangible solution to this demand. By comparing the performance of these systems, this research contributes to the development of smarter and more efficient vehicles for future transportation (Huang et al., 2015).

Current literature lacks comprehensive studies on different controllers for active suspension systems; complexity of the systems and real-time capabilities need consideration. Some literature addresses PID and fuzzy logic controllers but very few articles address an adaptive control strategy as a way to improve power use and system efficacy. More research is required on the problems of controlling handling and stability along with a major focus on comfortable rides and through comparison of various control strategies with sufficient comparison between them for different dynamic vehicle states. Recent research showed that MATLAB/SIMULINK can model both passive and semi-active suspension systems in both simple linear and non-linear conditions, revealing that semi-active systems perform better. The data indicated that using a linear semi-active system lowered the displacement and improved the rate of settling, but adding non-linear components gave a more accurate response. They stress the importance of including control methods and considering that the system might not be linear in the design of suspensions (Yadav et al., 2019).

2 Controllers

The system's feedback controller controls a force actuator positioned between the automobile body and the wheels. When dealing with active suspension systems through the quarter-car modeling, there are specific control strategies involving PID control, such as PI control, P control, PD control, Fuzzy Logic Controller, and FPID control, which allow the engineer to consider working parameters related to ride comfort, handling, and stability (Changizi and Rouhani, 2011).

2.1 PID

One of the most popular feedback control systems in use today, particularly in the engineering and automation sectors, is the proportional-integral-derivative (PID) control. In essence, it modifies the control output according to the difference between the set point and the process variable. In order to improve ride comfort and avoid unsteadiness, PID control is utilized in both active and passive suspension systems inside the quarter-car model (Jiregna and Sirata, 2020).

The proportional (P) component of the controller responds directly to the error signal or, for instance, the difference between the set and real ride height. However, if the characteristic is configured via P control, it just produces oscillations and overshoots because it ignores previous system behavior. The integral (I) compartment adds the error values to cancel out steady-state errors while modifying the output. If carefully tweaked, this will improve accuracy but may cause instability in the process. The derivative (D) component looks for future faults and estimates how fast they change so that the system's response can be reduced, hence boosting stability. However, it can also produce increased noise within the system, as well as disturbances that interfere with the system's normal operation. As with the PI method, the latter is a combination of proportional and integral control; despite minor fluctuations, it allows the car's ride height to be maintained at the required level, and the control signal increases proportionally to the cumulative error, contributing to ride comfort. On the other hand, PD control, which combines proportional and derivative control functions, enhances how the steering responds to unexpected changes in road conditions, hence improving the car's handling and control (Gowda and Chakrasali, 2014).

2.2 Fuzzy

This logic controller utilizes fuzzy sets, and a rule basis for regulating the execution of nonlinear activities, making conclusions based on fuzzy reasoning and language factors (Avesh et al., 2019). The logic controller can control the degree of damping ratio to maintain ride comfort while also increasing vehicle controllability by reacting to factors such as road surface, vehicle speed, and driver preference in the quarter car model (Arslan et al., 2022).

2.3 FPID

FPID controller is the step wise arrangement of the fuzzy logic algorithm and PID algorithm that results in more flexibility and effective control technique for even more complex systems.

In quarter car model, FPID control is assigned for the active component of the suspension to provide online adaptive suspension parameters based on fuzzy rules and feedback control, addressing ride comfort, stability, and vehicle handling factors (Han et al., 2022).

3 System modeling

As part of the suspension system evaluation process, mathematical models to represent dynamic processes and interactions in suspension system components must be developed. It is critical for understanding and analyzing the way the system functions in various settings. It enables to fine-tune and create new suspensions that meet the necessary characteristics for comfort, behavior, stability, and isolation. As a result, when modeling suspension systems, numerous assumptions are made to make the model more analytically and computationally tractable. Linearizing system behavior even when springs and dampers are non-linear components, idealizing the actions of other components, and simplifying road contours are among the situations. In addition, insignificant influences such as rolling resistance and air drag of the tires and vehicle body are typically ignored, as are other forces that happen to be proportional to the product of the masses of the interacting parts of the car and in inverse proportion to square of distance between said parts. These considerations simplify the model while making it more manageable, allowing for a greater emphasis on the suspension system's most critical properties (Agharkakli et al., 2012).

3.1 Numerical modeling

In numerical modeling of suspension systems, computer simulations are used to represent suspension components and the way they perform and interact. These simulations are typically performed using software such as MATLAB or other specialized programs capable of predicting and determining suspension performance in the absence of real models. It determines the effects of altering designs on comfortableness, control, and steadiness of a car by adjusting parameters such as springiness stiffness or damping values. It helps one to learn more about suspensions and in the same time produce designs more effectively and cheaply. The free body diagrams for passive and active suspension systems are depicted in Fig. 1.

The mathematical model of a passive suspension system is:

$$ms\ddot{x}s + cd(\dot{x}s - \dot{x}u) + ks(xs - xu) = 0 \tag{1}$$

$$mu\ddot{x}u - cd(\dot{x}s - \dot{x}u) - ks(xs - xu) + kt(xu - xi) = 0 \tag{2}$$

The mathematical model of an active suspension system is:

$$ms\ddot{x}s + cd(\dot{x}s - \dot{x}u) + ks(xs - xu) = Fa - Ff \tag{3}$$

$$mu\ddot{x}u - cd(\dot{x}s - \dot{x}u) - ks(xs - xu) + kt(xu - xi) = Ff - Fa \tag{4}$$

The parameters that are used in the system while modeling them in simulation software are represented by Table 1, where M_s (sprung mass), M_u (unsprung mass), K_s (spring constant), C_d (damping constant), K_t (tire stiffness constant), K_p (proportional constant), K_i (integral constant), and K_d (derivative constant) are working parameters.

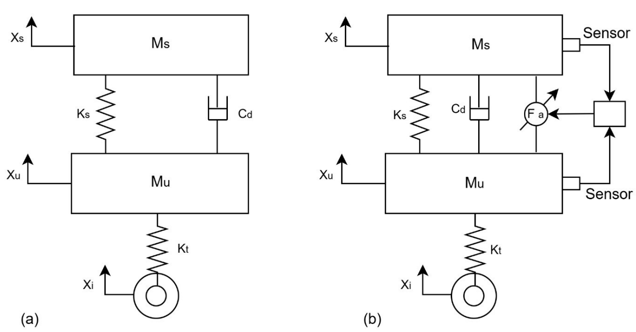

Fig. 1 Free body diagrams: (a) Passive suspension system, (b) Active suspension system

Table 1 Parametric values

S.N.	Parameters	Value
1.	M_b	250
2.	M_{us}	50
3.	K_t	16712
4.	C_a	1000
5.	K_t	190000
6.	K_p	12500
7.	K_i	50
8.	K_d	10

3.2 Simulink/MATLAB modeling

In Simulink/MATLAB modeling, detailed mathematical models of suspension systems can be created and analyzed. These models simulate the dynamic behavior of suspension components such as springs, dampers, and linkages under various driving conditions and road surfaces. By adjusting parameters and control strategies, users can evaluate performance of the suspension systems in terms of ride comfort, handling, and stability. This approach provides valuable insights into system behavior and allows for optimization of the design before physical prototypes are built. Moreover, different controllers can be simulated in parallel hence obtaining a comparative analysis of systems within the modelling.

In this work, the suspension system is simulated utilizing the following control units: P, P, PD, PID, fuzzy logic, and FPID controllers. The suspension systems' Simulink models are configured as shown in Figs. 2–5.

The value of proportional constant, integral constant and derivative constant are then calculated with PID controller using help of step response; however, fine-tuning is always necessary to achieve optimal performance. The Ziegler-Nichols approach, which is widely used, is one example of a fine-tuning technique. With this approach, the proportional component must be progressively increased until the system reaches a steady oscillation amplitude, while the integral and derivative terms must be turned off initially. The critical gain, the point at which oscillation begins, is recorded, and the integral and derivative gains are adjusted

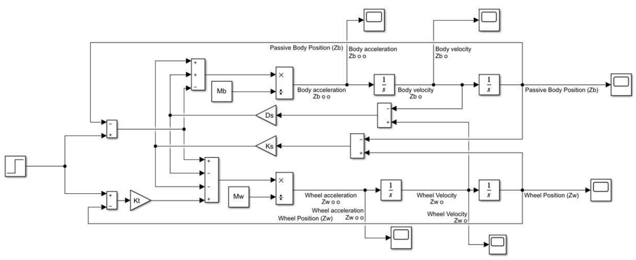

Fig. 2 Simulink model of a passive suspension system

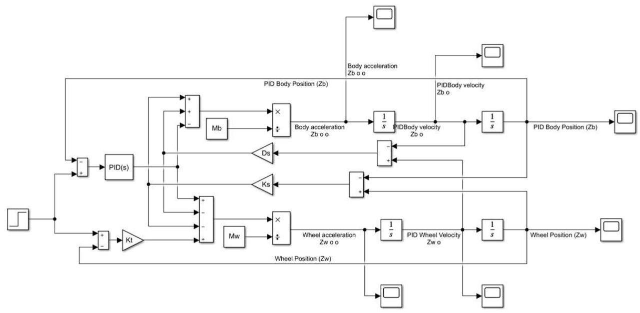

Fig. 3 Simulink model of an active suspension system with PID controller

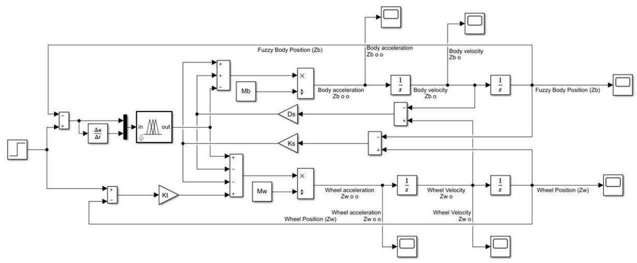

Fig. 4 Simulink model for active suspension system with Fuzzy Logic controller

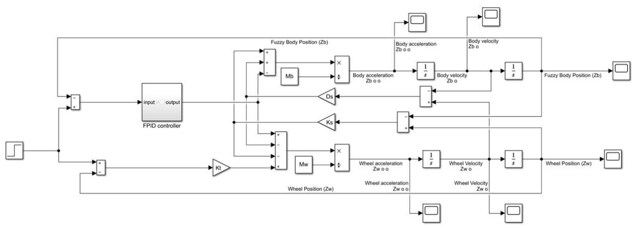

Fig. 5 Simulink model of an active suspension system with FPID controller

using fundamental tuning principles. Hence applying this methodology, as seen in Figs. 4 and 5, the PID controller suspension's optimal K_p, K_i, and K_d values were found to be 12.500, 50, and 10, respectively. In the FPID controller suspension system, the best K_p value is -1.85, K_i is -0.85, and K_d is -0.056 for the PID controller.

The fuzzy logic controller is operated after input parameters are fed and it decides the output based on the rule base that has been integrated into the system. The I/O parametric values that are considered in the system are presented in Tables 2 and 3 along with the range and types of membership functions used for simulation. Also, Table 4 shows the rule base that is used in the controller for operation.

The fine-tuning parameters used in both PID and FLC controllers are done by several hit and trial attempts to obtain better and optimized results.

4 Results

The simulation results have shown improved ride comfort with better vehicle handling active suspensions with different control parameters. The graphs obtained represent the

Table 2 Input parameters

Inputs	Range	Number of MF
For error	[−1 1]	5
For del error	[−500 500]	5

Table 3 Output parameters

Output	Range	Number of MF
Force	[−2.700 2.700]	5 [trapf]

Table 4 Rule base for FLC:

Del error / Error	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

maximum overshoot gained by the respective suspension systems when subjected to a step input rise of 0.2 units.

4.1 Displacement

The PID and FPID-controlled systems have significantly reduced the wheel displacement, which leads to better handling dynamics. The quicker stabilization shown in Fig. 6 ensures that the wheels follow the desired path more closely, improving the vehicle's responsiveness and control.

In Fig. 7, the body displacement data indicates more stable and comfortable ride for passengers. The graphical values of peak overshoot and the settling time for both displacements obtained by simulation are tabulated for better analysis in Table 5.

4.2 Velocity

The obtained results shown in Fig. 8 and Fig. 9 illustrate that there is a sharp spike in the wheel and body velocity but active control system shows faster damping of the oscillations as compared to passive system.

The quicker stabilization ensures that the wheels follow the desired path more closely and reduced body movement transfers fewer disturbances for passengers, enhancing overall comfort. The values obtained for both types of velocities are shown in Table 6.

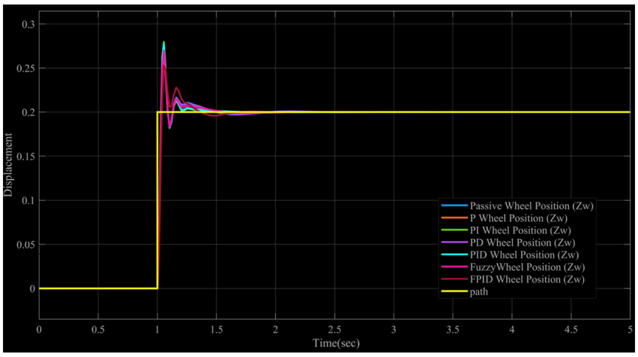

Fig. 6 Displacement vs Time graph for wheel displacement

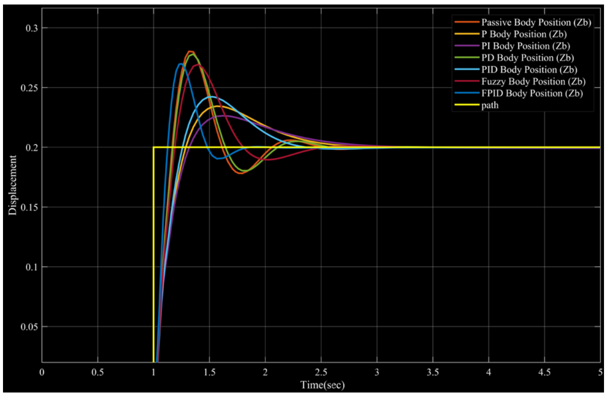

Fig. 7 Displacement vs Time graph for body displacement

Table 5 Displacement results

	Body displacement		Wheel displacement	
	Peak overshoot	Settling time	Peak overshoot	Settling time
Passive	0.28	3	0.28	2.5
P	0.23	2.8	0.26	2
PI	0.22	2.9	0.28	1.6
PD	0.275	2.6	0.27	1.7
PID	0.24	2.4	0.27	1.6
Fuzzy	0.27	2.5	0.27	1.7
FPID	0.27	1.8	0.25	1.4

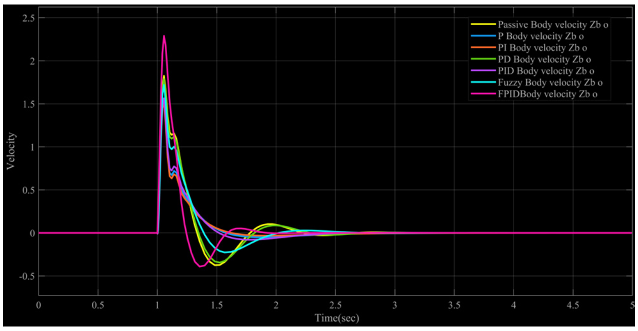

Fig. 8 Velocity vs Time graph for wheel velocity

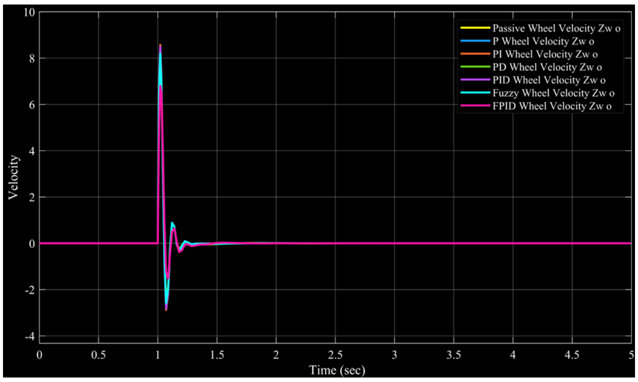

Fig. 9 Velocity vs Time graph for body velocity

4.3 Acceleration

Similarly, Fig. 10 and Fig. 11 shown below demonstrate the acceleration changes in the wheel and body with improved stabilization by active control systems leading to better vehicle responsiveness and minimizing the impact felt by passengers.

The values of acceleration obtained are mentioned as well in Table 7.

5 Conclusion

With a wide range of control strategies, the active suspension systems are qualitatively studied in this paper and illustrated how much better they are compared with the conventional passive systems. Simulations in Simulink/MATLAB showed substantial improvements in passenger comfort and vehicle dynamics. The application of PID and FPID controllers resulted in reduction of the vertical movement of the car's body by 10.71 %, and an increase in the speed of settling by 20 %. Furthermore, these controllers enabled the reduction of the settling time and the increase of the rate of change of upward velocity by 7 %, so making passenger comfort higher.

Table 6 Velocity results

	Body velocity		Wheel velocity	
	Peak overshoot	Settling time	Peak overshoot	Settling time
Passive	1.8	2.6	8.5	1.5
P	1.5	2.6	8.2	1.3
PI	1.5	2.4	8.3	1.3
PD	1.8	2.6	8.1	1.2
PID	1.6	2.5	8.2	1.2
Fuzzy	1.7	2.6	8.1	1.3
FPID	2.2	2	6.5	1.2

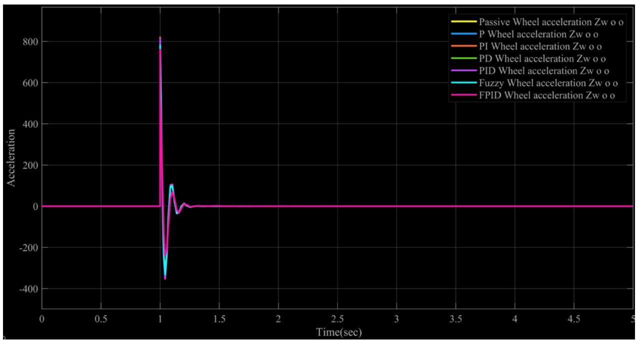

Fig. 10 Acceleration vs Time graph for wheel acceleration

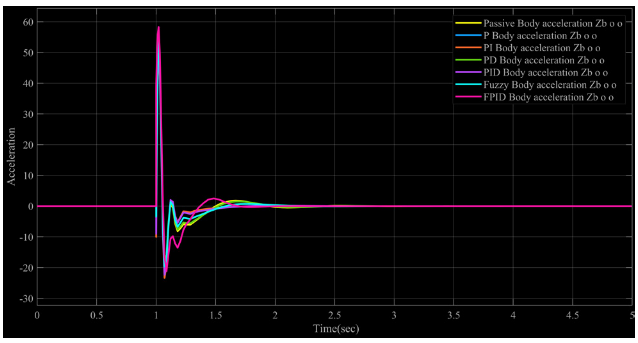

Fig. 11 Acceleration vs Time graph for body acceleration

Table 7 Acceleration results

	Body acceleration		Wheel acceleration	
	Peak overshoot	Settling time	Peak overshoot	Settling time
Passive	60	2.9	830	1.5
P	57	2.7	825	1.3
PI	58	2.8	827	1.2
PD	58	2.8	825	1.3
PID	53	2.6	816	1.2
Fuzzy	54	2.8	822	1.3
FPID	54	2.7	814	1.1

Comparing these control strategies such as P, PI, PD, PID, Fuzzy Logic, and FPID controllers, the outcomes showed that both PID and FPID controllers were significantly better in eliminating oscillations and enhancing ride comfort and vehicle stability. PID and FPID continuously outperformed other controllers in terms of settling time, ensuring fewer bouncing effects for passengers, even though PI and PD controllers demonstrated good performance in terms of vertical acceleration.

In summary, the research strongly supports the broader application of active suspension technologies, particularly those incorporating PID and FPID control strategies, within the modern automotive industry. These systems provide noticeable enhancements in dynamic response characteristics in addition to meeting theoretical expectations. Because they maintain better control and stability of the vehicle under dynamic driving conditions, they provide improved safety, a smoother ride, and less motion sickness.

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