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Comparative Analysis of Performance of Passive and Semi-Active Suspension Systems

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Abstract

The suspension system is a boon to the automotive industry, playing a crucial role in providing ride comfort to passengers. With the advancement of technologies, several studies and innovations in suspension systems have been categorizing them into different types and purposes. This paper analyzes semi-active suspension systems' performance using different control techniques. The suspension system plays a critical role in enhancing the overall ride comfort and stability of vehicles. Employing semiactive suspension systems can adjust the damping characteristics in real-time, leading to improved vehicle dynamics. This investigation uses several control techniques, such as Fuzzy logic control, Proportional Integral Derivative (PID), and Fuzzy PID (FPID) controllers that utilize computer simulations to evaluate the effectiveness of various control techniques for semi-active suspension systems of quarter car models. The performance of the semi-active suspension with control techniques is compared with the passive suspension system in terms of peak overshoot and settling time. Simulation results after comparison show an improvement of 31.37%, 9.85%, and 26.05% using PID, Fuzzy, and FPID-controlled suspension systems.

Keywords: Fuzzy Logic Control, Passive suspension system, PID Control, Semi-active Suspension System

1. Introduction

In the dynamic field of automotive engineering, pursuing enhanced ride comfort, improved handling, and increased vehicle stability has always driven innovation. Suspension systems play a crucial role in achieving these objectives by mitigating the adverse effects of uneven road surfaces and providing optimal vehicle dynamics control.

Suspensions used in automobiles are mainly classified into three types i.e., passive, semi-active, and active suspension system (Soliman & Kaldas, 2021). Suspension systems play a crucial role in achieving enhanced ride comfort, improved handling, and increased vehicle stability by mitigating the adverse effects of uneven road surfaces and providing optimal control of vehicle dynamics.

Traditional passive suspension systems are limited in adapting to varying road profiles and driver preferences, as they are designed to provide a fixed level of damping (Sharma & Kumar, 2017). On the other hand, active suspension systems are more complex, and repairing them costs more. However, a new area of possibilities has emerged with the advent of semi-active suspension systems. These systems combine the advantages of both passive and active suspensions, offering real-time adjustment of damping characteristics based on feedback from sensors and control algorithms (Gandhi et al., 2017).

The semi-active suspension system with a model-free fuzzy logical controller significantly reduces vehicle body vibration for improved ride comfort and driving safety (Ding et al., 2017; Rao, 2014). Using a fuzzy controller with magneto-rheological semi-active suspension improves vehicle comfort, reduces body acceleration, minimizes deformation and suspension wear, extends suspension lifespan, and maintains robustness against parameter changes within a specific range. The semi-active suspension system using the PID controller significantly improved settling times for body acceleration, wheel deflection, wheel position, suspension deflection, and body position compared to the passive system (Rao, 2014).

This paper aims to perform comparative analysis of semi-active and passive suspension systems using PID, Fuzzy and Fuzzy PID controllers. Three controllers are introduced in the following section.

1.1 PID Controllers

Proportional-Integral-Derivative (PID) controllers, are frequently utilized in control systems for the purpose of stabilizing and regulating dynamic processes(Ab Talib et al., 2021; Gowda & Chakrasali, 2014). A combination of three control actions serves as their foundation: integral, proportional, and derivative. The following is a brief description of each PID controller component:

i. Proportional (P) Control: The controller output is proportional to the current error between the system's actual value and the desired set point. The proportional gain (K_p) determines the strength of the corrective action.
ii. Integral (I) Control: The controller output is adjusted based on the accumulation of past errors over time. The integral gain (K_i) controls the response to eliminate steady-state errors.
iii. Derivative (D) Control: The controller output is adjusted based on the rate of change of the error over time. The derivative gain (K_d) helps anticipate future behavior and dampen the system's response.

The PID controller calculates the controller output by adding up the contributions of these three control actions. The last result of the PID controller is given by:

$$\text{Output} = (K_p \times \text{Error}) + (K_i \times \text{Integral of Error}) + (K_d \times \text{Derivative of Error})$$

PID controller parameters (K_p, K_i, and K_d) must be tuned for desired performance, balancing response characteristics like speed, stability, and disturbance rejection (Wang & Song, 2013).

1.2 Fuzzy Controllers

Fuzzy Logic Controllers (FLC), introduced by Lotfi A. Zadeh in 1965 and elaborated in 1973 with the concept of "linguistic variables" have been extensively used to enhance the control performance of active suspension systems, particularly in improving the ride comfort of a quarter-car model without relying on system models (Çalışkan et al., 2016; Palanisamy & Karuppan, 2016). The control system itself consists of three stages, as shown in Figure 1:

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.

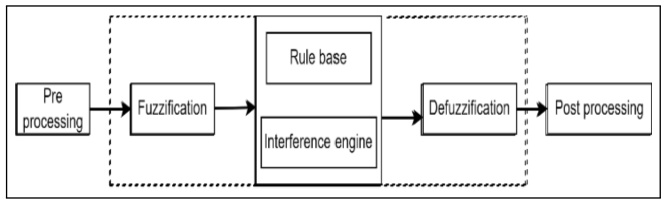

Figure 1 Block diagram of Fuzzy Logic Controller

1.3 Fuzzy PID controller

Fuzzy PID (Proportional-Integral-Derivative) control is a variant of traditional PID control that incorporates fuzzy logic principles. While conventional PID control uses precise mathematical algorithms to adjust control actions based on error signals, fuzzy PID control employs fuzzy logic to handle uncertain or imprecise information.

The benefits of fuzzy PID control include robustness to uncertainties, flexibility in handling complex systems with nonlinearities or varying dynamics, and the ability to incorporate human-like reasoning into control strategies. Fuzzy PID controllers are commonly used in applications where precise mathematical models are unavailable or difficult to derive, such as in industrial processes, automotive systems, and robotics[(Labh et al., 2024; Shah et al., 2020).

2. Methodology

A quarter car model for passive suspension system and semiactive system are as shown in the Figure 2.1. The quarter car model represents passive and semi active suspension system where m_s is sprung mass, m_u is unsprung mass, k_s is suspension spring stiffness, k_t is tire stiffness, c_d is damping coefficient, x_i is road disturbance vertical displacement, x_u is unsprung mass vertical displacement, x_s is sprung mass vertical displacement, and N is filter coefficient.

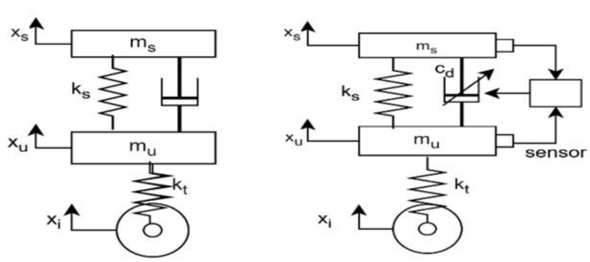

Figure 2 Schematic model of Passive suspension system and Semi-active suspension system

The mathematical model of passive suspension system is described as (Yadav et al., 2019):

$$m_s\ddot{x}_s + c_d(\dot{x}_s-\dot{x}_u) + k_s(x_s-x_u) = 0 \quad (1)$$

$$m_u\ddot{x}_u - c_d(\dot{x}_s-\dot{x}_u) - k_s(x_s-x_u) + k_t(x_u-x_i) = 0 \quad (2)$$

The mathematical model of semi active suspension system is described as:

$$m_s\ddot{x}_s + \bar{c}_d(\dot{x}_s-\dot{x}_u) + k_s(x_s-x_u) = 0 \quad (3)$$

$$m_u\ddot{x}_u - \bar{c}_d(\dot{x}_s-\dot{x}_u) - k_s(x_s-x_u) + k_t(x_u-x_i) = 0 \quad (4)$$

Simulink model of passive and semi-active suspension system with PID, Fuzzy and FPID control techniques for step and square bump input was developed and simulation was done. Two inputs; road profile and un-sprung mass displacement were given for simulation.

The PID and Fuzzy Logic Controllers were tuned by several hit and trials, changing the values of PID constants (K_p, K_i, K_d) and selecting the most suitable range for the membership functions of the Fuzzy Logic Controller. After several iteration of trials, the most suitable and appropriate values for optimizing the best results are illustrated in the tables with respective constant names and range parameters.

Figure 3 represents the Mamdani model for Fuzzy Logic Controller with two input and one output block. Table 1, 2, 3 and 4 shows the input output variables, controller rule base and parameters with their respective values that are used in mathematical model for simulation.

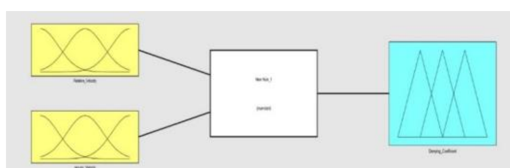

Figure 3: Fuzzy logic controller block

Table 1: Table for range of inputs of FLC

Inputs	Range	Number of MF
For relative velocity	[-5 5]	3 [trapf]
For sprung mass velocity	[-20 20]	3 [trapf]

Table 2: Table for range of outputs of FLC

Inputs	Range	Number of MF
Damping Coefficient	[0 2500]	3 [1 trif and 3 trapf]

Table 3: Fuzzy Control Rule Base

Descriptions	V relative (x)		
V relative (y)	Negative	Zero	Positive
Negative	Small	Medium	Large
Zero	Medium	None	Medium
Positive	Large	Medium	Small

Table 4: Parameters used in system simulation

S.N.	Parameters	Value
1	m_s	504.5 (kg)

2	m_u	62 (kg)
3	k_s	13100 (N/M)
4	k_t	252000 (N/M)
5	c_d	400 (Ns/m)
6	k_p	0.003558
7	k_d	0.006736
8	k_i	0.00457
9	N	16.36

3. Results and Discussion

The conventional passive suspension system and semi-active suspension system with PID controller, fuzzy logic controller and FPID controller were observed with two different inputs. Simulation result shows that the performance of the semi-active suspension system with PID controller is better than the passive suspension system. This performance improvement in turn will increase the passenger comfort level and ensure the stability of vehicle. It also showed that for random excitation of the body position, response of semi active suspension system is superior compared to passive suspension system. The results obtained after simulation sows the performance in a graph form where x-axis represents time and the y-axis represent displacement values.

3.1 Step Input

Figure 4 - 7 represents the performance graph of a respective system for step input as a road profile. The step input with a rise of 1 unit amplitude was given.

The peak overshoot of the vehicle body position (sprung mass displacement) differs across various suspension systems. In a passive suspension system, it is 1.785cm occurring at 1.6s (Figure 3.1); in PID-controlled semi-active suspension, it reduces to 1.225cm at 2.1s (figure 3.2); for fuzzy controlled suspension system, it is 1.609cm at 1.55s (figure 3.3) and for FPID controlled system it is 1.32cm at 1.49s as shown in (figure 3.4). The settling time for passive, PID, Fuzzy, and FPID-controlled suspension systems is 9.8s, 7.5s, 6.5s, and 2.8s, respectively.

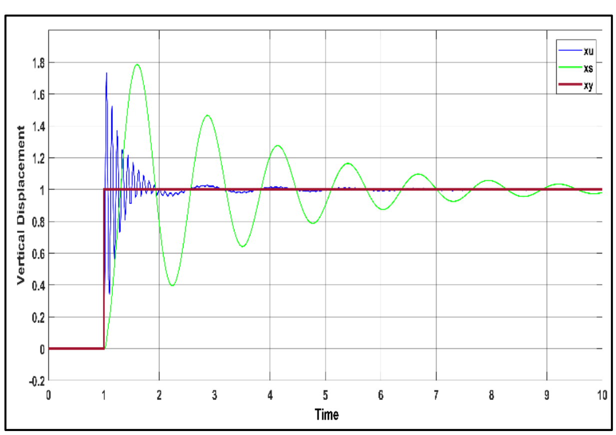

Figure 4: Time vs sprung and upsprung mass displacement having passive suspension

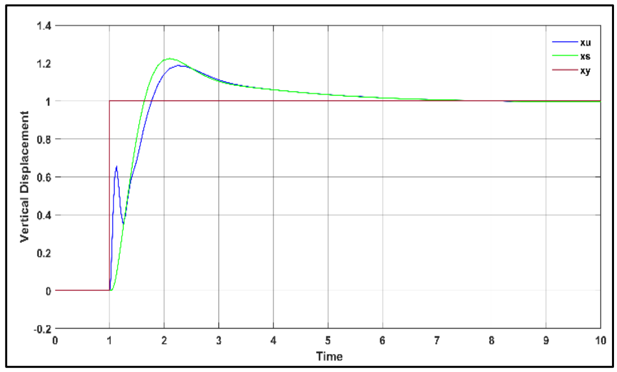

Figure 5: Time vs sprung and upsprung mass displacement having PID-controlled suspension system

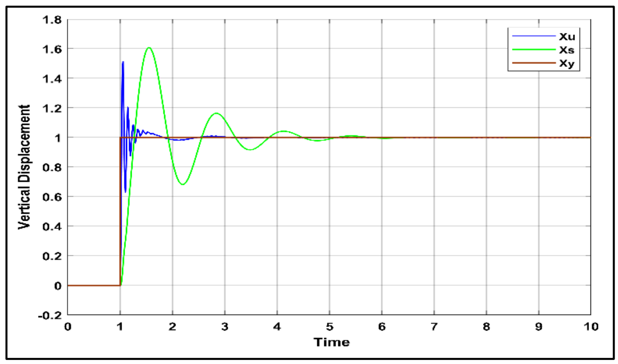

Figure 6: Time vs sprung and upsprung mass displacement having Fuzzy controlled suspension system

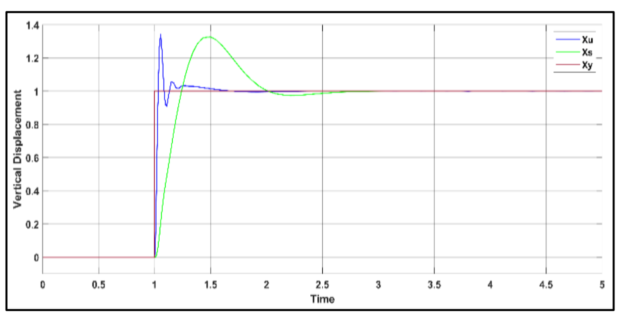

Figure 7: Time vs sprung and upsprung mass displacement having FPID controlled suspension system

3.2 Square Bump

The figure 8 - 11 represents the performance graph of respective system for square bump as a road profile. Here the square bump is generated by pulse generator. The amplitude of square bump is 1unit with period value of 5s and pulse width of 5% of period.

The peak overshoot of vehicle body position for passive suspension system is 1.058cm at 0.35s (figure 8), for PID controlled semi active suspension is 0.503 cm at 0.39 s (figure 9), for fuzzy controlled system is 1.0009 cm at 0.288 s (figure 10) and for FPID controlled system is 1.05 cm at 1.26 s as shown in (figure 11). The settling time for PID, fuzzy and FPID controlled system is 2.8s, 5.5s and 2.4s respectively.

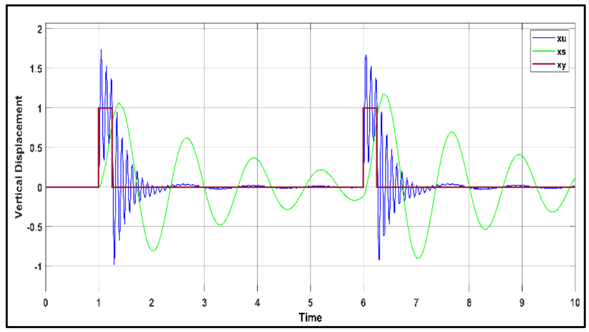

Figure 8: Time vs sprung and upsprung mass displacement having passive suspension

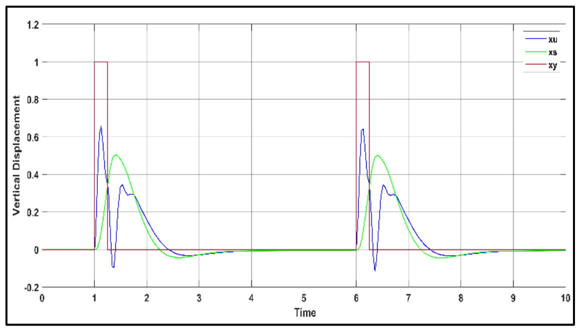

Figure 9: Time vs sprung and upsprung mass displacement having PID controlled suspension system

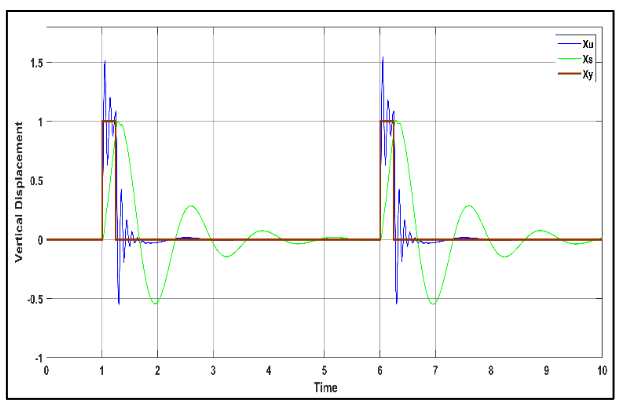

Figure 10: Time vs sprung and upsprung mass displacement having Fuzzy controlled suspension system

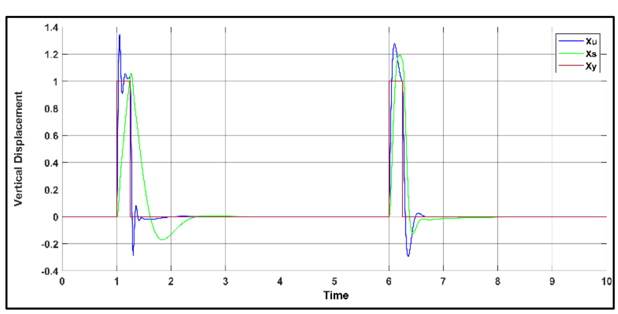

Figure 11: Time vs sprung and upsprung mass displacement having FPID-controlled suspension system

To compare and validate the response of the system we take data and response from the ISOR journal "Comparison of passive and semi-active suspension system by MATLAB SIMULINK for different road profiles" by Phalke & Mitra published in 2016 (Phalke, 2016). The simulated models produced results with an error percentage of about 11.56% and 23.43% in terms of peak overshoot for passive and semiactive suspension using PID controller with respect to Phalke and Mitra.

4. Conclusions

Based on the comparison of simulation results demonstrates the feasibility and potential of the control system used in the quarter-car suspension model. Applying these optimized gains in physical model control can improve real-world performance and precision. It lays a strong foundation for future developments in suspension systems, with potential scope for enhancing comfort levels through further research and implementation of advanced control techniques in semi-active suspension systems.

i. The mathematical models of passive suspension systems, PID controlled, Fuzzy controlled, and FPID controlled semi-active suspension systems were modeled in MATLAB/Simulink and simulated for analysis.
ii. Performance comparison between semi-active and passive suspension systems was conducted, revealing that the semi-active system offers better ride quality based on displacements of upsprung mass and sprung mass.
iii. The mathematical model was analyzed on two different road profiles; step input and square bump, demonstrating improved vibration control by adjusting parameters like damping coefficient and introducing PID parameters (K_p, K_i, K_d).
iv. Simulation results after comparison showed that the performance of semi-active suspension systems improved by 31.37%, 9.85%, and 26.05% using PID, Fuzzy, and FPID-controlled suspension systems in terms of peak overshoot.

Future studies should focus on digitizing and implementing controllers in real-world systems, conducting robustness analysis, and setting up suspension test benches for practical evaluation.

Further research in suspension control should explore comprehensive models, fuzzy systems, multi-objective optimization, Gaussian membership functions, and fractional-order controllers to improve vehicle suspension control for enhanced ride comfort and stability.

The gain values (K_p, K_i, K_d) can be optimized using a PID controller to enhance the active suspension system's performance, stability, ride comfort, and road handling.

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