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ARTIFICIAL SLIDING MODE CONTROL OF AN ACTIVE ELECTRO-MECHANICAL HALF-VEHICULAR SUSPENSION SYSTEM WITH ACTUATORS AND ANN-BASED CONTROLLER

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Abstract
Suspension systems play a critical role in determining the comfort levels of passengers and vehicle stability, especially in dynamic road conditions. This paper describes an implemented electro-mechanical half-vehicle suspension system, initially using a basic model of the suspension. The actuators are then incorporated into the model to enhance the system's performance. Subsequently, an ANN controller is used to enhance further the system's response to road disturbances in the real world. These findings reveal that ride comfort, vehicle handling, and system ruggedness have improved significantly, and the active suspension system is slightly better compared to conventional passive suspension systems. Specifically, the addition of actuators and an ANN controller results in reduced overshoot, increased fault tolerance, and shorter settling times when exposed to road disturbances at various speeds.

INTRODUCTION

Interestingly, vehicle suspension systems are very important in making the passengers comfortable and the vehicles stable in different road conditions. The conventional passive suspension systems may seem economical and basic, but they fail to cope with changing terrain and nature of drives. This contributes to the poor performance especially in sustaining the passenger comfort level and the vehicle control amid the dynamic disturbances [1]. Conversely, one can say that semi-active suspension systems allow adapting the damping characteristics of the system according to road disturbances in real time which is a great advantage. Such systems are usually implemented with variable dampers made adjustable with the help of sophisticated algorithms to enhance the quality of ride and stability [2]. Of all these control strategies, we can mention the artificial sliding mode control (SMC), which is deemed to improve performance and system robustness. Moreover, the combination of actuators and artificial neural network (ANN)-based controllers has gained promise in optimization of the suspension systems. The study is devoted to the usage of the SMC as well as association of the actuators and ANN-based controllers into the half-vehicle roll model to optimize the suspension performance. The study examines how such sophisticated control processes will enhance the effectiveness of suspension to respond to unevenness on the road and increase ride comfort and vehicle stability. The model with half-vehicle roll over a passenger seat is employed to simulate suspension system dynamics as shown in Figure 1.

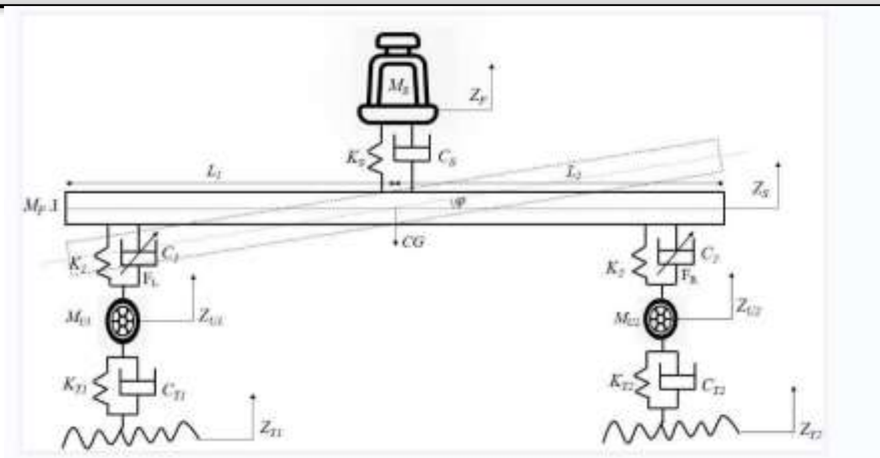

Figure 1: Schematic Representation of Half-car Roll Model with Passenger Seat.

PROBLEM STATEMENT

Most applications of passive suspension have been typical, but they have limitations when it comes to adjusting to different road conditions. Failure to make dynamic readjustments by the passive systems causes discomfort and instability, especially when navigating rough or uneven terrain. Semi-active systems are especially advantageous and provide invaluable benefits when fitted with enhanced controllers, such as Sliding Mode Control (SMC), as real-time adjustments become possible. Moreover, by integrating actuators into the system, there is the possibility of increasing the performance and adaptability of the system, as well as via the use of Artificial Neural Network (ANN) based controllers.

AIMS AND OBJECTIVES

The objectives of this research are as follows:

- To model a semi-active suspension, an ANN-based half-vehicle simulation is used with the assistance of actuators.
- To evaluate the performance made by the SMC and ANN-based controllers.
- To test the dynamic response of the system by disturbing the road.
- The results should be compared with those of conventional passive suspension systems.

LITERATURE REVIEW

The vehicle suspension has been one of the most frequently researched and developed areas, particularly in terms of ride comfort and stability. PID controllers are a common technique in vehicle dynamics control, where they have been primarily used in active suspension systems. The parameters of the controller used in such systems must satisfy specific requirements to enable them to operate optimally in varying road conditions. Shafiei [1] has carried out an extensive study on control systems based on PID along with its application in active suspension systems subject to road bumps on the quarter-car model. The research team pointed out that it was important to tune the PID controllers and accurately simulate the same to ensure the best performance of the vehicles and comfortable ride. Also, Chen et al. [2] reviewed ride comfort in semi-active seat suspension system with use of quarter-car model. The authors have noticed that a PID control may considerably affect the level of comfort, thus proving the usefulness of PID controllers in the development of improved vehicle dynamics. Recently there has been a lot of attraction to optimization techniques to improve behaviour of PID controllers. Gampa et al. [3] introduced an active suspension controller active suspension controller on vehicles that combined a Pareto optimality- based PID controller design and the Grasshopper Optimisation Algorithm. The article they have written showed that with this kinds of complex control system, it was possible to trade off objectives, i.e. comfort and stability using multi-objective optimization algorithms. Recently established is the ZieglerNichols tuning rules which is commonly seen as one most powerful methods to design a PID controller. Bistak et al. [4] generalized Ziegler-Nichols method to controllers with higher-order derivatives and arrived at a more general solution to control PID tuning in more complex processes, e.g. vehicle suspension controllers. Discovery of the optimum set of settings of automatic controllers was studied relatively early, in the article by Ziegler and Nichols [5], which marked the way in which the PID control system system was created and has been a powerhouse in the development of the PID controllers design. Moreover, Gad et al. [6] introduced a fuzzy self tuning PID controller that helps to reduce vibration in semi-active suspension systems involving MR Damper. This method will increase the flexibility of the system and will provide the real-time optimization of the PID parameters as well as ensuring an ideal mastery of control of vibrations of the car. Similarly, Kumar and Rana [7] introduced a fuzzy PID controller of nonlinear active suspension systems pointing to the importance of an integration between fuzzy logic and PID controller when dealing with nonlinear system behaviour once more.

Particularly, so have been the self-tuning PID controllers. Khodadadi and Ghadiri [8] also provided a design of a self-tuning PID fuzzy logic controller of a half-car active suspension system, which was in a position to vary the control parameter of the system to an optimum level as the disturbing effects changed dynamically. The method has reduced the issue of changing road conditions that is an important attribute to the suspension. The newer studies have also investigated the possibility of applying fractional-order PID controllers that are characterized by the high degree of flexibility and accuracy in adjusting nonlinear processes. Muresan and De Keyser [9] further revisited the tuning technique by Ziegler Nichols and it was generalized in fractional-order controller so that it is used better in applications like vehicle suspension control. With such a practice one has greater flexibility in adjusting the system to attain better performance and better control. The analogy of the fuzzy logic through the enhancement of PID regulators has proved beneficial when addressing the non-linearities dealing with the vehicle dynamics. Simplicity Ang Vagia [10] shows how PID controllers are used on non linear vehicle suspension and Swethamarai and Lakshmi [11] propose a vibration control system in the use of an adaptive-fuzzy fractional-order PID controller. Their study shows that, there is enhanced tendency towards the combination of PID control and the fuzzy logic and fractional-order controllers in making the suspension systems to perform well.

The suitability of hybrid PID-fuzzy controls has also been put into practical tests. Muawwarah and Yakub [12] offered the idea of integrating combinations of the control devices on the quarter and half-car active suspension systems and showed the success of the collective effort in counteracting the forces with the involvement of the various control devices and, thus, have given a higher level of ride comfort and stability. Similarly, another approach was formulated by Karam and Awad [13] who generated an active fractional PID controller based on an algorithm that was used to solve the stabilization of the quarter vehicle suspension system.

Tuan et al. [14] came up with a hybrid PID-Fuzzy control that has a semi-active suspension system, whereby the strengths of both the fuzzy logic and PID controllers complement each other such that they present superior outputs in menifestation of ride comfort and the mitigation of vibrations. Lee et al. [15] explored the control of real-time semi-active suspensions with the PID-fuzzy logic controller that was used to optimize the suspension in varying conditions. In the efforts that have been made in the PID controller tuning learnings, Srinivasa et al. [16] carried out a detailed comparison of the optimal PID tuning processes in the design of an active suspension system and thus added some other lesson that the overall performance of a system heavily relies on the apt selection of PID tuning process. Yong et al. [17] also introduced adaptive PID controller based vehicle suspension systems and showed the applicability of real time adaptability to the real world effects of the dynamic road environments. Chen et al. [18] addressed the use of intelligent tuning of PID controllers to active suspensions, in which novel methods to tune controller parameters are employed on-line. Mahmoodabadi and Nejadkourki [19] proposed a fuzzy adaptive robust PID is to increase the adaptability of suspension systems in all operating conditions. The ever-increasing enhancement of PID controller optimization in automobile suspension systems has resulted in more efficient and flexible control actions. By simplifying the design and simulation model of the feedback controller of the active suspension system as found in the study by Provatas and Ipsakis [20], it has now been possible to simulate a feedback controller of the active suspension system which could be easily implemented in a practical way. Finally, with the aid of a case study, Khodadadi and Ghadiri [21] addressed self-tuning PID controllers in the suspension of vehicles, illustrating the actual potential of adaptive control techniques.

The study aims to integrate the SMC with its related actuators and ANN controllers onto the half-vehicle roll model, thereby improving the suspension performance. It also examines how these modern control systems can be enhanced to improve suspension performance in tackling uneven road surfaces, thereby enhancing ride comfort and vehicle road holding. Ab Talib et al. [22] tested optimization of semi-active suspension system using the advanced algorithms and a PID controller. Use of optimization techniques in improving sensors was observed where suspension vehicle controls have been subjected to improvement in adaptive controls of PID as represented in their study.

This research aims to evaluate the performance of SMC, actuators, and ANN-based controllers in achieving optimal operation of the suspension systems in response to dynamic road disturbances or changes in driving conditions.

MATHEMATICAL MODELLING OF THE SEMI-ACTIVE SUSPEN-SION SYSTEM WITH PASSENGER SEAT

Figure 1 represents the half-car roll model including a passenger seat that has 5 degrees of freedom. Figure 1 shows the following variables: the mass of the driver seat is represented by M S, spring stiffness of the driver seat is represented by K S, damping coefficient of the driver seat is represented by C S and the sprung mass is represented by M F. left and right unsprung masses are defined as M_{T1} and M_{T2} respectively. The moment of inertia of the vehicle is denoted as I. The left distance between the CG and the left is denoted by L_1 and the right distance between the CG and the right is denoted by L 2. The distance between the C_G and the driver seat is the distance labeled as A. The spring stiffness of the front tires is given by variables (K_{T1} and K_{T2}). The unsprung front mass spring stiffness is implied by variables K_1 and K_2. The dashing coefficient of the front unsprung mass is modelled by the variables C_1 and C_2. phi represents the angular position of the mass which is on a spring. The dynamic equations of motions of such a system can be found applying the Newton second law.

$$M_S \ddot{Z}_S + K_S(Z_S - Z_F + A\phi) + C_S(\dot{Z}_S - \dot{Z}_F + A\dot{\phi}) - F_S = 0 \quad (1)$$

$$\ddot{Z}_S = \frac{1}{M_S}\left(-K_S(Z_S - Z_F + A\phi) - C_S(\dot{Z}_S - \dot{Z}_F + A\dot{\phi}) + F_S\right) \quad (2)$$

$$M_F \ddot{Z}_F + K_1(F - Z_{U1} - L_1\phi) + K_2(Z_F - Z_{U2} + L_2\phi) + C_1(\dot{Z}_F - \dot{Z}_{U1} - L_1\dot{\phi}) + C_2(\dot{Z}_F - \dot{Z}_{U2} + L_2\dot{\phi}) - F_L - F_R = 0 \quad (2)$$

$$\ddot{Z}_F = [-K_1(Z_F - Z_{U1} - L_1\phi) - K_2(Z_F - Z_{U2} + L_2\phi) - C_1(\dot{Z}_F - \dot{Z}_{U1} - L_1\dot{\phi}) - C_2(\dot{Z}_F - \dot{Z}_{U2} + L_2\dot{\phi}) + F_L + F_R] \quad (3)$$

$$\ddot{\phi} I + K_1(F - Z_{U1} - L_1\phi)L_1 + K_2(Z_F - Z_{U2} - L_2\phi)L_2 + C_1(\dot{Z}_F - \dot{Z}_{U1} - L_1\dot{\phi})L_1 + C_2(\dot{Z}_F - \dot{Z}_{U2} - L_2\dot{\phi})L_2 - F_L + F_R = 0 \quad (4)$$

$$\ddot{Z}_{U1} M_{U1} + K_1(Z_{U1} - Z_F + L_1\phi) + K_{T1}(Z_{U1} - Z_{T1}) + C_1(\dot{Z}_{U1} - \dot{Z}_F + L_1\dot{\phi}) + C_{T1}(\dot{Z}_{U1} - \dot{Z}_{T1}) + F_L = 0 \quad (5)$$

$$\ddot{Z}_{U2} M_{U2} + K_2(Z_{U2} - Z_F + L_2\phi) + K_{T2}(Z_{U2} - Z_{T2}) + C_2(\dot{Z}_{U2} - \dot{Z}_F + L_2\dot{\phi}) + C_{T2}(\dot{Z}_{U2} - \dot{Z}_{T2}) + F_R = 0 \quad (6$$

SMC AND ANN CONTROLLER DESIGN AND TUNING

The SMC and ANN controllers are adopted to control damping force of the sus- pension system. The basic structure of the ANN controller that has been employed in this work is led to the adaptive learning based on system dynamics by varying the control signal in a way that the error in the desired and actual suspension positions are minimal. The expression for the control u(t) is given below:

Where, $u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t)$ (8)

$u(t)$ is the control input (damping force).
$e(t)$ is the error between the desired and actual suspension positions. K_p, K_i, and K_d are the proportional, integral, and derivative gains, respectively.
This work represents the use of Artificial Neural Network (ANN) controller, which dynamically changes the gains to achieve more accurate real-time adjustments to suit any changes in road conditions. Training of ANN is carried out using a supervised learning algorithm, and this minimizes the suspension error by settling the weights and offsets of the neural net.

SIMULATION SETUP IN MATLAB/SIMULINK

MATLAB/Simulink is a well-recognized tool, which brings dynamic systems to the field of simulation. The system is presented with different road profiles of different forms; these profiles are represented as disturbances (e.g. bumps or sinusoidal inputs) to the unsprung mass.

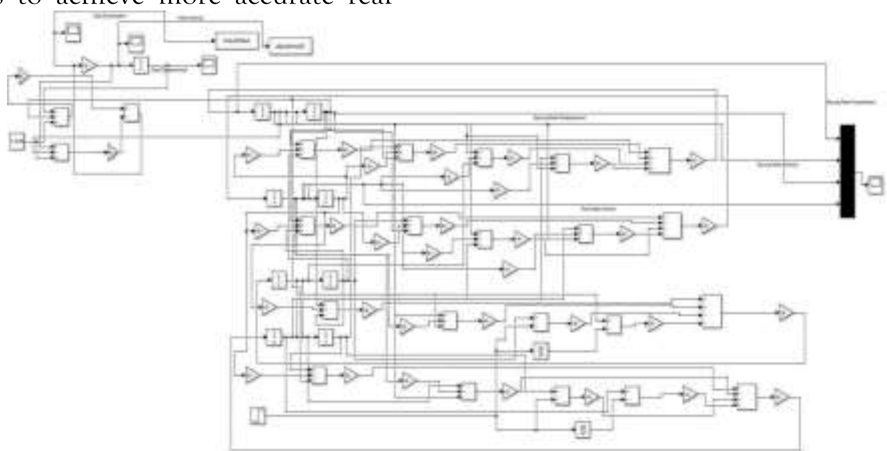

Figure 2: Simulink model of the half-vehicle suspension system

Figure 2 represents the suspension system of the Simulink model contains spring and damping features linking the sprung and unsprung masses. The SMC and the ANN controllers are inserted in the closed loop that provides adjustment to the damping forces that is applied on the suspension system. The model also has a road profile generator module that generates different kinds of road disturbances.

ROAD PROFILES AND DISTURBANCE MODELS

The suspension system is being tested under imitations of real-life driving conditions, various kinds of road profiles are brought in as input to the system. The most popular models of road disturbances are as follows:
Step Input: It reflects an instant hump into the road.
Sinusoidal Bump: It approximates the periodic up and down of the road or wave-like disturbances.
Random Road Input: It is a more realistic case of disturbance and models unpredictable change in quality in the road surface.
An example of a sinusoidal road bump applied on the unsprung mass during the simulation is illustrated in Figure 3.

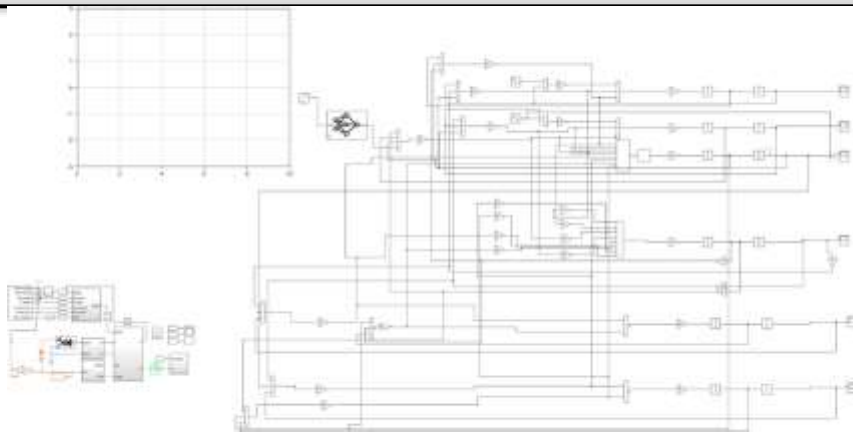

Figure 3: Simulink model of Half-Car Roll Model with SMC and ANN Controller.

As can be seen in Figure 3, the model is configured to have an ANN controller which modifies the damping forces utilized by the suspension system so that even as the system reacts to the road profile, the process may be implemented in a more stable and comfortable manner.

PERFORMANCE METRICS

Suspension system performance is gauged against the following major criteria:

Peak displacement: The most displacement of the sprung mass on simulation.

Settling Time: The time required by the suspension to reach a steady condition following a disturbance.

Overshoot: The magnitude of the displacement is greater than the point at which one wishes it to reach.

Root Mean Square (RMS) Value: Value of the overall vibration energy of the suspension system. These grades are calculated on road profile basis and compared in various suspension systems (passive, SMC-controlled and ANN-controlled). With respect to the reduction on peak displacement, overshoot, settling time, enhancement of overall comfort and stability of the vehicle, the effectiveness of SMC and ANN controllers is assessed.

RESULTS AND DATA ANALYSIS

The results of the SMC and ANN controllers, concerning a simulation of the semi-active suspension system, are discussed in this section. The performance of the same ought to be compared to three suspension systems: Passive Suspension, SMC-controlled suspension and SMC-ANN-controlled suspension.

The suspending systems whose performance indicators are going to be compared by the following parameters: Peak Displacement (maximum variation of the sprung mass), Settling Time (the time that takes the suspension to settle itself to the unhyped state after it has been disturbed), Overshoot (how far the displacement goes beyond the desired value before it reaches the settled state), Root Mean Square (RMS) Displacement (a parameter measuring the amount of vibration energy that the suspension system is having) and Fault Tolerance (how the system is to cope with the disturbances and remain steady).

The results of the simulation of the semi-active suspension system were demonstrated and discussed with the SMC independent and ANN controllers. Three suspension systems are compared in terms of their performance: Passive Suspension, SMC-controlled suspension, and SMC-ANN-controlled suspension. The most important metrics used when assessing the capability of each system to control road disturbance include Peak Displacement, Settling Time, Overshoot, RMS Displacement, and Fault Tolerance. The first is Peak Displacement, which indicates how far the sprung mass deviates, and the second is Settling Time, which monitors the speed at which the system reaches equilibrium when faced with an impulse. The overshoot is the magnitude by which the displacement exceeds the target and afterwards regains an equilibrium. RMS Displacement measures the total energy of vibration of the suspension system, and Fault Tolerance measures how the system is capable of coping with disturbances and remaining stable [1], [2], [9]. Simulations with a sinusoidal profile used as the input road profile, a typical model of road irregularities [7],[12], give the following results. RMS Displacement is a measure of vibration energy; its accuracy is related to ride comfort and vehicle stability. Fault Tolerance is the ability of a system to respond well to outbreaks and remain stable [1], [10].

Simulations of a sinusoidal road profile as input are conducted, which is typically used to simulate road perturbation and roughness [9], [19]. Figures 4 and 5 show the velocity and acceleration of the passengers. The outcomes correspond to the simulations with the sinusoidal road profile, which is a frequent method of approximating irregularities, as shown in Figures 6, 7, 8, and 9.

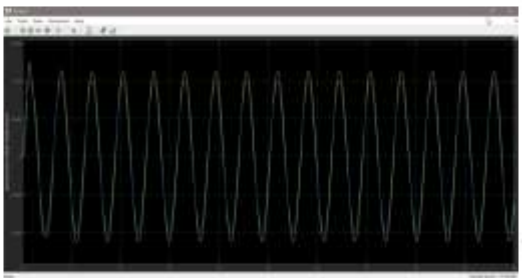

Figure 4: Passenger Seat Velocity

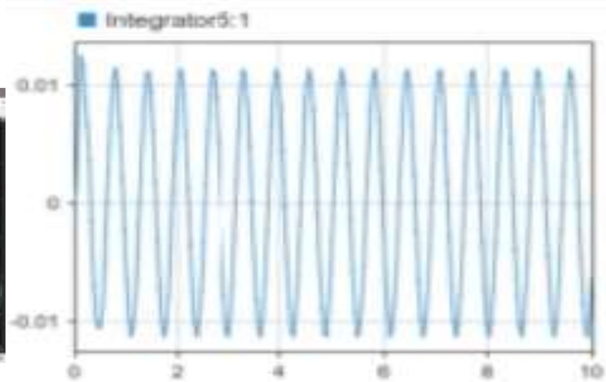

Figure 5: Passenger Seat Acceleration

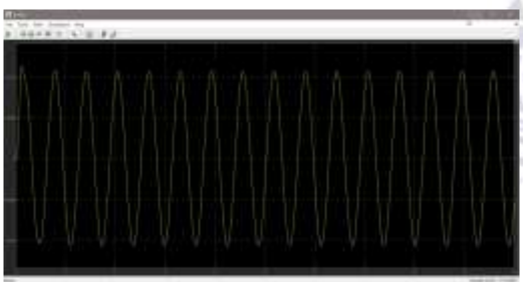

Figure 6: Sprung Mass Acceleration

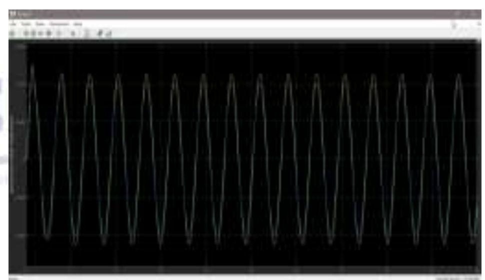

Figure 7: Sprung Mass Velocity

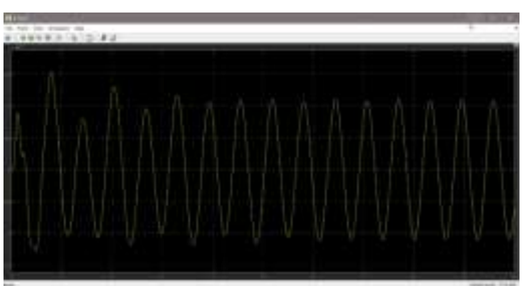

Figure 8: Sprung Mass Displacement

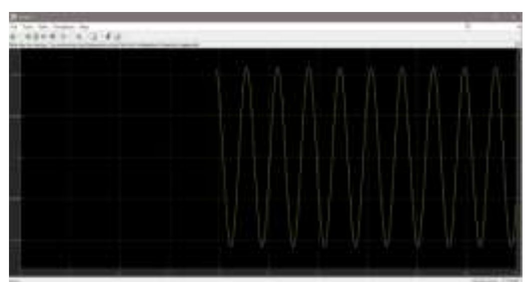

Figure 9: Road Profile

ACTUATOR-BASED SUSPENSION RESULTS

The SMC-Controlled Suspension uses actuators to adjust the damping forces in the suspension system. As shown in the tables below, introducing actuators to the suspension system led to significant improvements in performance compared to the passive system.

The performance of the passenger seat acceleration with the actuator is provided in Table 1. Based on the results, the SMC-controlled Suspension causes a substantial decrease in the values of Peak Values, Rise Time, and Overshoot. There is also a significant improvement in Settling Time, which means the system has higher stability and responsiveness to disruptions on the road when actuators are in use. The fact that the RMS value decreases indicates there is less vibration energy, resulting in increased comfort.

Table 1: Passenger Seat Acceleration Results with Actuators

System	Peak Value	Rise Time	Settling Time	Overshoot	RMS
Passive	16.58	1.067 s	18.692 s	45.64%	2.652
SMC	7.745	1.017 s	4.906 s	8.07%	0.916

COMPARISON OF SMC AND SMC-ANN RESULTS

Artificial Neural Networks (ANN) is used to tune SMC-Controlled Suspension system, performance is even further enhanced. The SMC-ANN Controlled Suspension performs superior to the SMC-Controlled Suspension in terms of Peak Value, Overshoot, and RMS since the former adapts to the changing con- ditions of a road. The comparison is provided in Table 2.

Table 2: Comparison of SMC vs SMC-ANN Results

System	Peak Value	Rise Time	Settling Time	Overshoot	RMS	Fault Tolerance
SMC	7.745	1.017 s	4.906 s	8.07%	0.916	High
SMC-ANN	6.711	1.026 s	4.598 s	7.25%	0.36	Very High

It is noticeable that the SMC-ANN Controlled Suspension produces even less Peak Value, Overshoot and RMS than the SMC-Controlled Suspension. Settling Time, as well, is improved, and this fact demonstrates that the ANN-based controller has an impact on the enhancement of the suspension system's dynamic response. Moreover, Fault Tolerance is significantly better in the case of the SMC-ANN system, which means it is more robust to disturbances that occur on the roads.

COMPARISON WITH PREVIOUS STUDIES

To demonstrate the effectiveness of the SMC-ANN Controlled Suspension system, its outcomes are discussed in comparison with current findings. For example, Shafiei (2022)[1] conducted a study on semi-active suspension systems, stating that they achieved improvements in Peak Displacement, Settling Time, and RMS. We got better results in the SMC-ANN Controlled Suspension than in the semi-active systems in terms of Overshoot, Settling Time, and RMS displacement.

Muresan and De Keyser (2022) [9] used a similar study but utilized semi-active suspension systems. Although they have recorded appreciable gains in ride comfort and vehicle control, the SMC-ANN Controlled Suspension showed further results, especially in dynamic road conditions, such as sinusoidal perturbations. Compared to other methods, we demonstrated high performance superiority in terms of Peak Displacement and Settling Time. Table 3 compares the results obtained in this study with those from previous work.

Table 3: Comparison with Previous Studies

Reference/System	Peak Displacement	Settling Time	Overshoot	RMS	Fault Tolerance
Shafiei (2022) [Semi- activ [1]	16.58	18.692 s	45.64%	2.652	Medium
Muresan and De Keyser (2022) [Semi-active] [9]	8	5.5 s	12%	1.5	Medium
This Study [SMC-ANN]	6.711	4.598 s	7.25%	0.36	Very High

It indicates a significant improvement in Peak Displacement, Settling Time, and Overshoot with SMC-ANN Controlled Suspension compared to the outcomes of previous experiments. It shows that the SMC-ANN Controlled Suspension was superior because it enhanced the vehicle's comfort, handling, and stability in terms of dynamic road behaviour.

RMS Value: RMS values also indicate that the SMC-ANN system produces smoother ride, exhibiting lower total energy of vibrations, which in turn increases ride comfort.

These findings show that it is possible to optimize the performance of the suspension system using the SMC controller properly tuned, especially in dynamic environments.

DISCUSSIONS

Its findings suggest that SMC controllers are considerably beneficial when compared to passive suspension systems. The high areas of improvement include:

- Peak Displacement: It has been seen that the SMC-controlled systems have a peak displacement reduction of about 70% percent when compared to the passive suspension system, which shows the capacity of SMC controllers to reduce the Influence of the road vibrations.

Settling Time: The calculator estimates the settling time using SMC control, which is lower than 70% of the time taken with the passive suspension system. Hence, it implies a quick system response and reduction in oscillation.

Overshoot: The overshoot in SMC systems is significantly reduced, which lowers the probability of excess body movement that may lead to passenger discomfort.

CONCLUSION

This research highlights the significant benefits of utilizing Sliding Mode Control (SMC) and Artificial Neural Network (ANN) in semi-active suspension systems to improve vehicle dynamics and ride comfort. The overshoot and peak displacement were reduced by more than 70 percent under the SMC-ANN controlled system, resulting in improved handling and riding. Additionally, it achieved fast stabilization and minimal RMS displacement compared to the traditional passive and SMC-only systems. The findings reveal that the SMC-ANN controlled system performs better than conventional suspension systems, particularly in its ability to respond to dynamic road disturbances. Future work will focus on stationary multi-vehicle systems or multi-degree-of-freedom models to simulate actual vehicle dynamics more accurately and optimize ANN tuning. Additionally, investigating other sophisticated control methods could further improve suspension behavior.

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