Adaptive Integral Terminal Sliding Mode Control for the Nonlinear Active Vehicle Suspension System under External Disturbances and Uncertainties

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Abstract: Suspension system is one of the most effective vehicle components that play an essential role in the stability and comfort of the vehicle. The passive suspension can not fully meet a car's stability and comfort requirements. Instead, an active suspension system has been proposed to improve these challenges. Active suspension minimizes the vibrations entering the body using a closed-loop control system. To this end, in this research, an integral terminal sliding mode control (integral TSMC) for an active nonlinear car suspension system under external disturbances and uncertainties is designed. First, the integral TSMC is designed to deal with the uncertainties and the external disturbances in the system when the upper bound is known. Next, an adaptation law is recommended to estimate the upper bound of uncertainties and external disturbances. The results show that the proposed integral TSMC improves the convergence rate and tracking error of the closed-loop system. The stability of the nonlinear control system is investigated and proven using Lyapunov's stability theory. The numerical results indicate a good robust performance and stability for the proposed controller for the nonlinear suspension system with different road profiles in the presence of uncertainties and external disturbances. From the results, it can also be understood that important measures such as ride comfort, road holding, and mechanical structural limitations are met using the proposed approach.

Keywords: Suspension system, External disturbances, integral terminal sliding mode control, Adaptive law.

1. INTRODUCTION

Due to the recent governmental efforts to move towards the net-zero emisión by 2050, dynamic modeling and control of hybrid and lightweight vehicles have attracted more attention in recent years (Reeves et al., 2016; Reeves et al., 2016). This in turn will increase the level of noise and vibration inside the cabin and reduce driving comfort. The use of active noise and vibration control techniques has been proposed as a solution to address these problems. The suspension system is one of the most effective vehicle components in terms of stability and comfort (Montazeri, and Poshtan, 2009; Montazeri, and Poshtan, 2009). The most critical role of vehicle suspension systems is to maximize the friction between the road surface and the tires to create stable steering and proper handling (Abdelkareem et al., 2018). The three factors of road isolation, road handling, and cornering are the main factors that make stability and comfort in riding. Vehicle stability is closely related to the car's maneuverability (Ning et al., 2018). With the advancement of various sciences and technologies, automakers build and use semi-active and active suspension systems to remove the limitations of passive suspension and provide a better product, provide more comfort for car occupants, and improve driving quality (Deshpande et al., 2013). Active suspension systems respond dynamically to road changes, adapt to broad road conditions, and work well in a wide frequency range. Due to the effectiveness of controlled suspension systems in the vehicle's ride comfort, this topic has received much attention from researchers. Researchers (Narayanan, and Senthil, 1998) indicate that passive suspension systems are not suitable for quality suspension system requirements. A more appropriate compromise between the contradictory behaviors mentioned must be considered to overcome such systems' limitations. To improve the suspension system performance a controlled suspension is proposed. The properties of flexible elements or energy distributors are controlled to optimize the performance target. In fact, to improve the suspension's effectiveness, an external force supplied by controlled actuators can be used (Li et al., 2018). In a controlled suspension, the main purpose of the control is to provide a solution for calculating the external energy required to generate the control force.

Various control methods have been suggested to expand the functioning of recent suspension systems, such as H∞ control (Erol, and Delibaşı, 2018), optimal control (Bai, and Wang, 2021), adaptive control (Kararsiz et al., 2021), sliding mode control (SMC) (Li et al., 2012; Liu, and Chen, 2020), and adaptive fuzzy logic control (Min et al., 2020). PID controllers are widely used in industry due to their simplicity and ease of implementation, however, if the vehicle suspension system parameters such as mechanical vibrations and road disturbances change, these controllers lead to unfavorable results. Nonlinear controllers can improve the worst road conditions further to the normal road conditions (Li, Yu, Hilton, and Liu, 2012). Also, it has been shown that focusing on some specific performance indicators will lead to a limited improvement in passive suspensions. SMC is one of the well-known nonlinear methods for control systems with uncertainty and external disturbances (Ghadiri, and Jahed-Motlagh, 2016; Rahmanipour, and Ghadiri, 2020). The SMC approach is a simple, robust control method that is the best option to maintain stability and consistent performance in the face of uncertainty in modeling. SMC's main idea is developed based on defining a sliding surface that converges the system to the surface using the proper control law and ensures system stability (Emamifard, and Ghadiri, 2021) . But the problem with SMC method is the chattering phenomenon. In this case, other methods are proposed to reject the chattering phenomenon, such as terminal sliding mode control (TSMC) (Wang et al., 2020), fast terminal sliding mode control (FTSMC) (Mustafa et al., 2020), and super-twisting sliding mode control (STSMC) (Qin et al., 2019). The system's robustness is enhanced by introducing an integral terminal sliding mode, while system accuracy and speed convergence are guaranteed (Liu, and Chen, 2020). Besides, by the analysis of the stability of Lyapunov function, reassured is the whole signals' boundless within a close loop system as well. This is while the vertical displacement and pitch remain within the specified performance limit. In (Min, Li, and Tong, 2020), the adaptive fuzzy output feedback control problem has been designed for the active suspension system of the quarter-car model.

This research focuses on an active suspension system stability problem by considering unknown road disturbances and model uncertainties. In this regard, a novel robust adaptive control method based on the concepts of sliding mode control is proposed. The contributions of the paper can be summarized as follows (1) Road disturbances and uncertainty of the model are taken into account in the system model. (2) Upper bounds for the external disturbances and model uncertainties are assumed to be unknown. (3) A rigorous stability analysis of the closed-loop system is provided using the Lyapunov theory. (4) The chattering problem is alleviated by introducing a continuous approximation of the control signal.

The paper is structured as follows: Section 2 contains problem formulations. In section 3, the control scheme based on integral TSMC has been introduced. The simulation results are explained in Section 4. Finally, the conclusions are presented in Section 5.

2. ACTIVE SUSPENSION CAR MODEL

The quarter-car active suspension model is demonstrated in Figure 1. In Figure 1, m_s and m_u are the sprung mass and unsprung mass. F_s and F_d are the forces produced by the spring and damper, respectively. F_t and F_b represent forces produced by the tire. The control input is introduced by u. z_s and z_u are vertical displacements of the sprung and unsprung masses. z_r represents bump road disturbance. Consider a quarter car system (Ovalle et al., 2021)

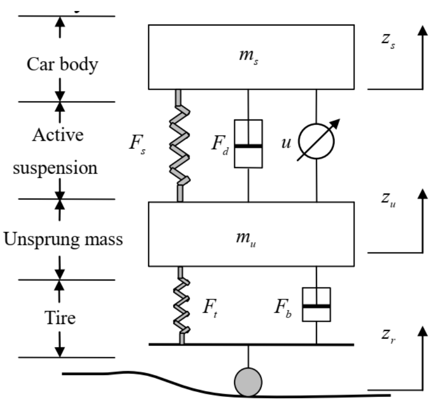

Figure 1. Quarter-car active suspension model.

$$\begin{aligned} m_s\ddot{z}_s &= -F_s(z_s, z_u) - F_d(\dot{z}_s, \dot{z}_u) + F_\Delta + u \\ m_u\ddot{z}_u &= F_s(z_s, z_u) + F_d(\dot{z}_s, \dot{z}_u) - F_t(z_u, z_r) \\ &\quad -F_b(\dot{z}_u, \dot{z}_r) - u \end{aligned} \quad (1)$$

which the F_Δ term is considered to show model uncertainty and external disturbance such as parameter uncertainties, external forces, and unmodeled dynamics, and

$$\begin{aligned} F_s &= k_{s_1}(z_s - z_u) + k_{s_2}(z_s - z_u)^3 \\ F_d &= c_1(\dot{z}_s - \dot{z}_u) + c_2(\dot{z}_s - \dot{z}_u)^2 \\ F_t &= k_t(z_u - z_r) \\ F_b &= c_t(\dot{z}_u - \dot{z}_r) \end{aligned} \quad (2)$$

The system state variables are selected as

$$x_1 = z_s,\ x_2 = \dot{z}_s,\ x_3 = z_u, x_4 = \dot{z}_u \quad (3)$$

Then, the state-space equation can be represented as

$$\dot{x}_1 = x_2 \quad (4)$$

$$\dot{x}_2 = \frac{1}{m_s}(-F_s - F_d + u + F_\Delta) \quad (5)$$

$$\dot{x}_3 = x_4 \quad (6)$$

$$\dot{x}_4 = \frac{1}{m_u}(F_s + F_d - F_t - F_b - u) \quad (7)$$

The performance requirements for the vehicle active suspension system are expressed with the following measures.

Ride comfort. The suspension's ride is closely related to the vertical motion of the spring-mass. Therefore, stabilizing the vertical movement to the desired trajectory in finite time is one of the important objectives to achieve ride comfort.

Road holding. The link between the tire and the road should be assured to enhance ride safety and ride handling quality. As a result, the dynamic tire load should be controlled in a reasonable range according to

$$\frac{F_t + F_b}{(m_s + m_u)g} < 1 \quad (8)$$

Mechanical structural limitation. The suspension deflection limitations must also be regarded to prevent structural damage on the suspension. This can be formulated as

$$|z_s - z_u| \le z_{max}\ , \quad (9)$$

where z_{max} specifies the maximum suspension deflection. The main control objective here is to design an integral TSMC for the nonlinear active vehicle suspension system to satisfy the above-mentioned constraints under the model uncertainties and external disturbances.

Assumption 1. The model uncertainty $\Delta = \frac{F_\Delta}{m_s}$ is bounded by a positive constant δ_1 ($|\Delta(t)| \leq \delta_1$).

3. DESIGN OF CONTROLLER

In this section, an integral TSMC will be formulated. First, the controller will be designed assuming that uncertainties and disturbances are known in the upper boundaries. Then, the adaptive integral TSMC technique is suggested for cases where the upper boundaries of disturbances and uncertainties are unknown.

3.1 Integral Terminal Sliding Mode Control

In this part, the integral terminal sliding mode control (integral TSMC) has been designed to stabilize the vertical movement of mass m_s. The objective is to stabilize the vertical movement of the mass m_s, i.e. x_1 and track the desired trajectory x_{1d}. By considering the tracking error

$$e = x_1 - x_{1d}, \tag{10}$$

$$\dot{e} = \dot{x}_1 - \dot{x}_{1d} = x_2 - \dot{x}_{1d}, \tag{11}$$

the integral terminal sliding surface can be written as

$$s = \dot{e}(t) + \alpha_1 e(t) + \alpha_2 \int_0^t e(\tau)^\gamma d\tau, \tag{12}$$

where $\alpha_i, i = 1, 2$ are two positive constants, and $0 < \gamma = \frac{p}{q} < 1$, with p and q are defined as two positive, odd, and integer constants satisfying the condition $p < q$. The sliding surface deviation is calculated as

$$\dot{s} = \ddot{e} + \alpha_1 \dot{e} + \alpha_2 e^\gamma \tag{13}$$

Substituting equations (4), (5), (10), and (11) in the above equations, yields:

$$\dot{s} = F_1 + b_1 u + \Delta(t) - \ddot{x}_{1d} + \alpha_1 \dot{e} + \alpha_2 e^\gamma \tag{14}$$

where $F_1 = \frac{1}{m_s}(-F_s - F_d)$, and $b_1 = \frac{1}{m_s}$.

Now, the equivalent controller u_{eq} can be calculated from equation $\dot{s} = 0$, as

$$u_{eq} = -b_1^{-1}[F_1 - \ddot{x}_{1d} + \alpha_1(x_2 - \dot{x}_{1d}) + \alpha_2 e^\gamma] \tag{15}$$

The total control input is defined as

$$u = u_{eq} + u_n \tag{16}$$

where

$$u_n = -b_1^{-1}[\rho|s|^\phi + \delta_1 + \theta(1 - \nu^{|s|})\text{sign}(s)] \tag{17}$$

with $\rho, \theta > 0$, $0 < \nu < 1$, and $\phi = \frac{a}{b}$, where a, b are two odd numbers satisfying $0 < a < b$.

To analyze the control stability, consider a Lyapunov candidate function as follows:

$$V = \frac{1}{2}s^2 \tag{18}$$

Differentiating (20) with respect to time and substituting (18) into (14) yields

$$\dot{V} = s\dot{s} = s[\Delta(t) - (\rho|s|^\phi + \delta_1 + \theta(1 - \nu^{|s|})\text{sign}(s))]. \tag{19}$$

After simplifications and applying Assumption 1 results:

$$\dot{V} \leq -\rho|s(t)|^{\phi+1} - \theta\left(1 - \nu^{|s|}\right)|s(t)| \tag{20}$$

Assuming that $\rho, \theta > 0$, $0 < \nu < 1$, and considering Lemma 1, it can be determined that $\dot{V} < 0$ and the system state tends to zero along the proposed sliding mode surface (12).

3.2. Adaptive Integral Terminal Sliding Mode Control

Usually, in practical systems determining the upper bound of the uncertainties and external disturbances is impossible. To deal with this problem, a method to estimate the upper bound of the uncertainty δ_1 is proposed. The estimation error can be defined as

$$\tilde{\delta}_1(t) = \hat{\delta}_1(t) - \delta_1 \tag{21}$$

Taking the time derivative of $\tilde{\delta}_1(t)$ yields

$$\dot{\tilde{\delta}}_1(t) = \dot{\hat{\delta}}_1(t) \tag{22}$$

Therefore, the adaptation law can be defined as

$$\dot{\hat{\delta}}_1(t) = \kappa^{-1}|s(t)| \tag{23}$$

where κ is a positive constant. Afterward, the adaptive integral TSMC is obtained as:

$$u_n = -b_1^{-1}[\rho|s|^\phi + \hat{\delta}_1(t) + \theta(1 - \nu^{|s|})\text{sign}(s)] \tag{24}$$

with $\rho, \theta > 0$, $0 < \nu < 1$, and $\phi = \frac{a}{b}$, where a, b are two odd numbers satisfying $0 < a < b$.

To investigate the stability of the closed-loop system, the Lyapunov candidate function below is considered

$$V = \frac{1}{2}s^2 + \frac{\kappa}{2}\tilde{\delta}_1^2(t). \tag{25}$$

By taking the time derivative of (25)

$$\dot{V} = s\dot{s} + \kappa\tilde{\delta}_1\dot{\tilde{\delta}}_1(t), \tag{26}$$

and replacing (14) and (23) into (26), we have

$$\dot{V} = s[F_1 + b_1 u + \Delta(t) - \dot{x}_{1d} + \alpha_1 \dot{e} + \alpha_2 e^\gamma] + \tilde{\delta}_1|s(t)| \tag{27}$$

Substituting the equivalent control (15) and adaptive integral terminal sliding mode controller (24), we will have

$$\dot{V} = s\left[\Delta(t) - \left(\rho|s|^\phi + \hat{\delta}_1(t) + \theta\left(1 - \nu^{|s|}\right)\text{sign}(s)\right)\right] + \tilde{\delta}_1|s(t)|. \tag{28}$$

After taking into account Assumption 1, equation (30) is rewritten as follows

$$\dot{V} \leq \delta_1|s(t)| - \rho|s(t)|^{\phi+1} - \hat{\delta}_1(t)|s(t)| - \theta\left(1 - \nu^{|s|}\right)|s(t)| + \tilde{\delta}_1|s(t)|. \tag{29}$$

After doing some mathematical manipulation the right-hand side of (29) can be simplified to

$$\dot{V} \leq -\rho|s(t)|^{\phi+1} - \theta\left(1 - \nu^{|s|}\right)|s(t)|. \tag{30}$$

Since ρ, $\theta > 0$, $0 < \nu < 1$, the Lyapunov function (30) decreases gradually, i.e., $\dot{V} < 0$ and the system states will quickly tend to zero.

5. NUMERICAL SIMULATIONS

In this section, numerical simulations are provided to analyze the performance of the active suspension with the proposed approach. The performance and robustness of the suggested approach are evaluated in the presence of various types of road profiles, uncertainty, and external disturbance. The value of the system parameters for the vehicle suspension system are provided in Table 1 (Ovalle, Ríos, and Ahmed, 2021). The continuous bump road disturbance is represented as:

$$z_r = 0.08\cos(2\pi t)\sin(0.6\pi t), \tag{31}$$

Figure (2) is represented the road disturbance profile. For robustness analysis, simulations will be considered in the following two cases:

Case1: Without external disturbance and uncertainty (Nominal system);
Case2: Considering disturbance (see Figure 3), and uncertainty: $m_s = (1-20\%) \times 290$, $c_1 = (1+20\%) \times 1385.4)$, $c_2 = (1+20\%) \times 524.28)$, $k_t = (1-30\%) \times 190)$, $k_{s_1} = (1+20\%) \times 14500$, $k_{s_2} = (1+20\%) \times 160000$, $c_t = (1-30\%) \times 170)$.
Considering the road profile (31), and the model uncertainty and external disturbances in case 2, the performance of the proposed controller is demonstrated in Figures (3)–(7).

Table 1. Parameters of active suspensions.

Parameter	Value	Parameter	Value
m_s	290 kg	m_u	59 kg
k_{s_1}	14.5 kN/m	k_{s_2}	160 kN/m
c_1	1385.4 Ns/m	c_2	524.28 Ns/m
k_t	190 kN/m	c_t	170 Ns/m
z_{max}	0.12 m	g	9.8 m/s^2

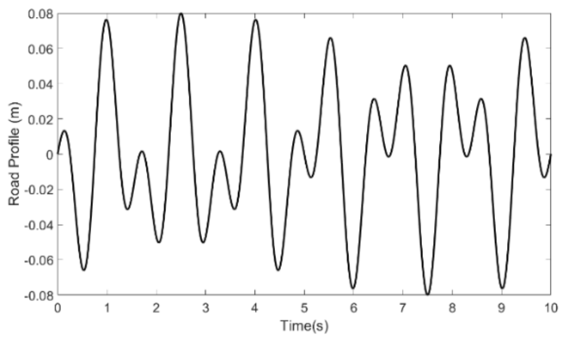

Figure 2. Road Profile (Bump Road disturbance).

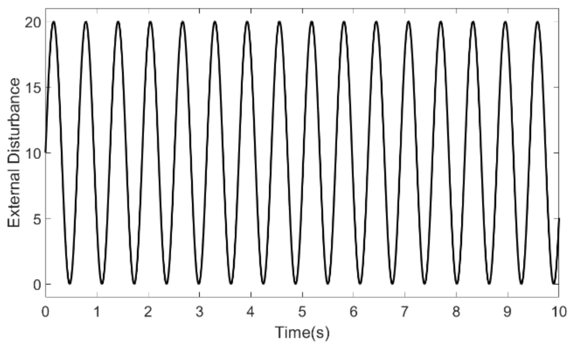

Figure 3. External disturbance signal in Case 2.

It should be noted that the suspension system must meet the requirements to reduce the vehicle vibrations and improve the suspension performance and driving comfort. The suspension performance and the driving comfort are closely related to the vertical displacement and acceleration of the body, respectively. As can be seen from Figures (3)–(4), the body's amplitude of vertical displacement and acceleration is significantly lower than the passive suspension system in front of the uncertainties and external disturbances, and the acceleration amplitude for the active suspension system is smooth without any significant changes.

Table 2. Parameters of Controller.

$p = 3$	$\phi = 3/5$	$\alpha_1 = 30$	$\rho = 0.1$	$\theta = 30$
$q = 7$	$\nu = 1/3$	$\alpha_2 = 0.1$	$\kappa = 5$	

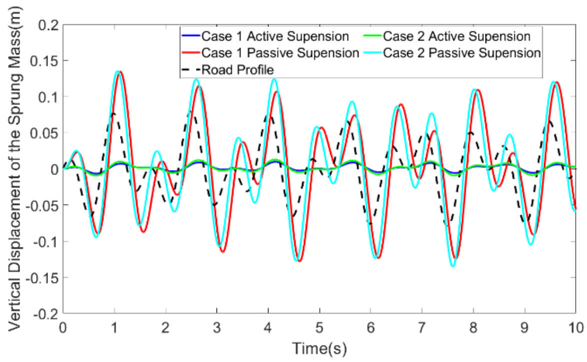

Figure 3. Displacement of the Sprung Mass.

In addition, it is also observed that despite the change of some system parameters, the displacements and accelerations have not been changed significantly, indicating the robustness of the proposed method. Also, Table 2 shows the controller parameters. Further to the vertical displacement, and acceleration, the results for the deflection of the suspension and the corresponding control signal, as well as the relative dynamic load of the tire, are shown in Figures (5)-(7). The results are plotted in comparison with the passive suspension system. As can be seen, Figures 6 and 7 satisfy the limits specified in equations (8) and (9). Finally, Figure 8 shows that the sliding surface has no chattering in case 1 (nominal system) and case 2 (with disturbance and uncertainty). Thus, the proposed controller can achieve satisfactory suspension performance regardless of parameter variation. This issue demonstrates the robustness of the suggested controller.

5.3 A Comparative analysis

In this section, to illustrate the capability of the recommended method, it will be compared with the results obtained in (Deshpande et al., 2014). The continuous bump road profile is given by (Deshpande, Mohan, Shendge, and Phadke, 2014).

$$z_r = \begin{cases} -at_1^3 + bt_1^2 + c(t); & 3.5 \le t < 5, \\ -at_1^3 + bt_1^2 + c(t); & 5 \le t < 6.5, \\ -at_1^3 + bt_1^2 + c(t); & 8.5 \le t < 10, \\ -at_1^3 + bt_1^2 + c(t); & 10 \le t < 11.5, \\ c(t); & otherwise, \end{cases} \tag{32}$$

where $t_1 = t - 3.5$, $t_2 = t - 6.5$, $t_3 = t - 8.5$, $t_4 = t - 11.5$, $c(t) = 0.002\sin(t) + 0.002\sin(7.5\pi t)$, $a = 0.0592$,

$b = 0.13332$. The performances of the proposed method compared with the control approach in Deshpande et al. are illustrated in Figures (9)-(10).

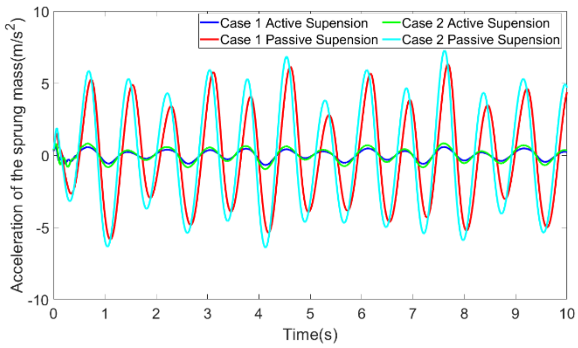

Figure 4. The acceleration signal of the sprung mass for the proposed method compared to the passive system.

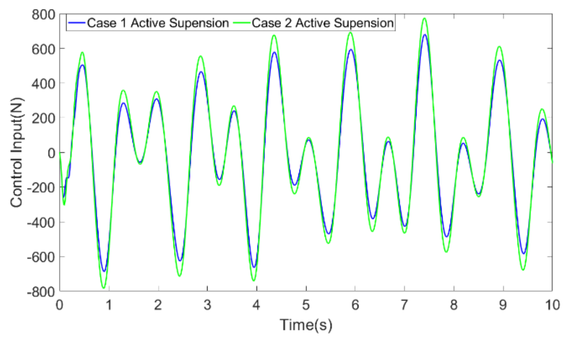

Figure 5. The control input signal of the proposed method.

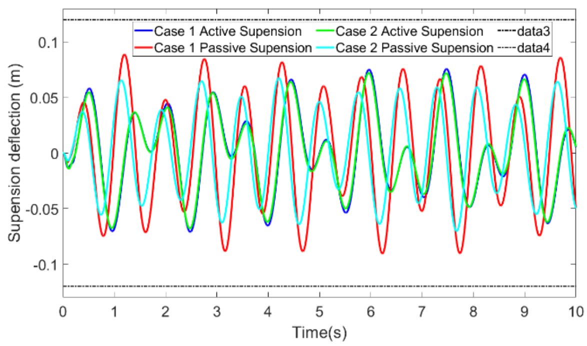

Figure 6. The suspension deflection signal of the sprung mass for the proposed method compared to the passive system.

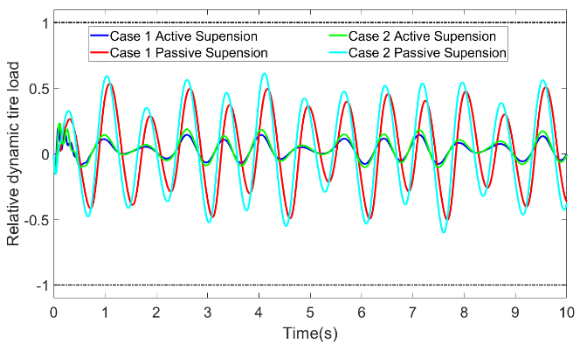

Figure 7. The relative dynamic tire load signal.

Figure 9 shows the performance of both the proposed method and the one in Deshpande et al. in reducing the vibrations created by the unevenness of the road surface. As can be seen from this figure, both methods are successful in providing a good comfort for the passengers. Furthermore, as can be seen from Figure 10, the sliding surface in the proposed method has no chattering. Finally, to evaluate the control system's performance and increase the comfort of movement, Table 3 compares the RMS values of sprung mass vertical displacement, acceleration, suspension deflection, control input, and the relative dynamic tire force.

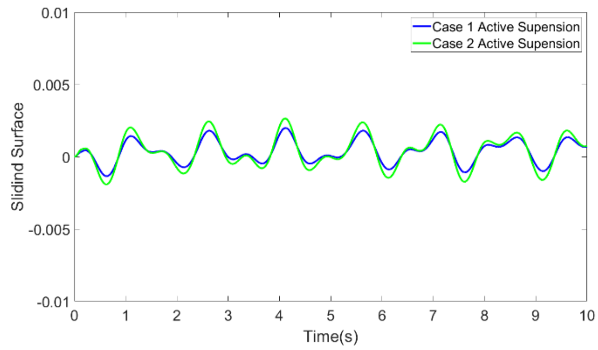

Figure 8. The sliding surface.

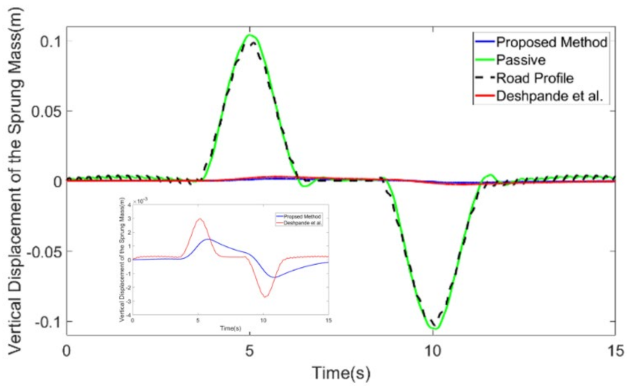

Figure 9. Displacement of the Sprung Mass.

It can be clearly seen from Table 3 that the proposed active suspension has a noteworthy improvement in ride comfort and decreases the RMS values compared to Deshpande et al.

Table 3. Numerical comparison of the suspension system performance in terms of RMS.

RMS	Deshpande et al.	Proposed Method
Acceleration	0.0086	0.0042
Displacement	2.4810×10^{-4}	2.0400×10^{-4}
Suspension Deflection	0.0383	0.0222
Control Input	1811	338.62
Relative Tire Force	3.4957	1.3916

5. CONCLUSIONS

The paper investigates an adaptive integral TSMC for a nonlinear active suspension system in the presence of uncertainties and external disturbances. As the first step, the proposed controller obtains an appropriate closed-loop performance in the presence of uncertainties and disturbances with a known uncertain bound. The stability of the nonlinear system is analysed using Lyapunov theory. Next, an adaptive integral TSMC was suggested for the nonlinear active suspension system considering uncertainties and disturbances with unknown bounds. The simulation results for different road profiles demonstrate that the recommended technique works better, and the system performance is improved using the proposed controller despite uncertainty and external disturbances. Furthermore, the results show that the performance requirements, namely the ride comfort, road holding, and mechanical structural limitation, have been satisfied.

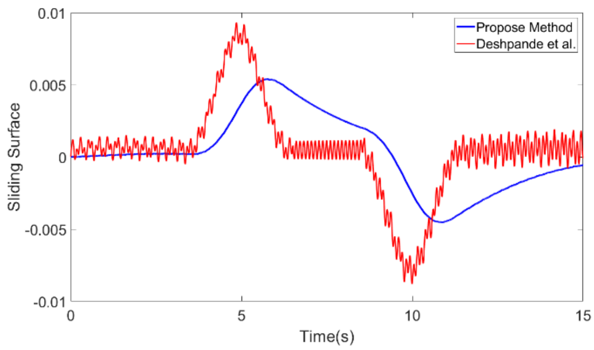

Figure 10. The sliding surface for both methods.

REFERENCES

M.A. Abdelkareem, et al. (2018) 'Vibration energy harvesting in automotive suspension system: A detailed review', *Applied energy*, Vol. 229, pp. 672-699.

R. Bai and H.-B. Wang (2021) 'Robust Optimal Control for the Vehicle Suspension System With Uncertainties', *IEEE transactions on cybernetics*.

V.S. Deshpande, et al. (2014) 'Disturbance observer based sliding mode control of active suspension systems', *Journal of Sound Vibration*, Vol. 333 No. 11, pp. 2281-2296.

V.S. Deshpande, et al. (2013) 'Active suspension systems for vehicles based on a sliding-mode controller in combination with inertial delay control', *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 227 No. 5, pp. 675-690.

A. Emamifard and H. Ghadiri (2021) 'Robust Control of Nonlinear Fractional-Order Systems with Unknown Upper Bound of Uncertainties and External Disturbance', *IETE Journal of Research*, pp. 1-12.

B. Erol and A.J.J.o.V. Delibaşı (2018) 'Proportional–integral–derivative type H∞ controller for quarter car active suspension system', *Journal of vibration control*, Vol. 24 No. 10, pp. 1951-1966.

H. Ghadiri and M.R. Jahed-Motlagh (2016) 'LMI-based criterion for the robust guaranteed cost control of uncertain switched neutral systems with time-varying mixed delays and nonlinear perturbations by dynamic output feedback', *Complexity*, Vol. 21 No. S2, pp. 555-578.

G. Kararsiz, et al. (2021) 'An adaptive control approach for semi-active suspension systems under unknown road disturbance input using hardware-in-the-loop simulation', *Transactions of the Institute of Measurement and Control*, Vol. 43 No. 5, pp. 995-1008.

H. Li, et al. (2012) 'Adaptive sliding-mode control for nonlinear active suspension vehicle systems using T–S fuzzy approach', *IEEE Transactions on Industrial Electronics*, Vol. 60 No. 8, pp. 3328-3338.

H. Li, et al. (2018) 'Adaptive event-triggered fuzzy control for uncertain active suspension systems', *IEEE transactions on cybernetics*, Vol. 49 No. 12, pp. 4388-4397.

Y.-J. Liu and H. Chen (2020) 'Adaptive sliding mode control for uncertain active suspension systems with prescribed performance', *IEEE Transactions on Systems, Man, Cybernetics: Systems*, (Access 2020

X. Min, et al. (2020) 'Adaptive fuzzy output feedback inverse optimal control for vehicle active suspension systems', *Neurocomputing*, Vol. 403, pp. 257-267.

A. Montazeri and J. Poshtan (2009) 'GA-based optimization of a MIMO ANC system considering coupling of secondary sources in a telephone kiosk', *Applied Acoustics*, Vol. 70 No. 7, pp. 945-953.

A. Montazeri and J. Poshtan (2009) 'Optimizing a multi-channel ANC system for broadband noise cancellation in a telephone kiosk using genetic algorithms', *Shock Vibration*, Vol. 16 No. 3, pp. 241-260.

G.I.Y. Mustafa, et al. (2020) 'Optimized fast terminal sliding mode control for a half-car active suspension systems', *International journal of automotive technology*, Vol. 21 No. 4, pp. 805-812 (Access 2020

D. Ning, et al. (2018) 'An energy saving variable damping seat suspension system with regeneration capability', *IEEE Transactions on Industrial Electronics*, Vol. 65 No. 10, pp. 8080-8091.

L. Ovalle, et al. (2021) 'Robust Control for an Active Suspension System via Continuous Sliding-Mode Controllers', *Engineering Science Technology, an International Journal (In Press)*.

Y. Qin, et al. (2019) 'Adaptive nonlinear active suspension control based on a robust road classifier with a modified super-twisting algorithm', *Nonlinear Dynamics*, Vol. 97 No. 4, pp. 2425-2442.

P. Rahmanipour and H. Ghadiri (2020) 'Stability analysis for a class of fractional-order nonlinear systems with time-varying delays', *Soft Computing*, Vol. 24 No. 22, pp. 17445-17453.

K. Reeves, et al. (2016) 'Model development and energy management control for hybrid electric race vehicles', *2016 UKACC 11th International Conference on Control (CONTROL)*, IEEE, pp. 1-6.

K. Reeves, et al. (2016) 'Validation of a Hybrid Electric Vehicle dynamics model for energy management and vehicle stability control', *2016 IEEE 25th International Symposium on Industrial Electronics (ISIE)*, IEEE, pp. 849-854.

G. Wang, et al. (2020) 'Practical terminal sliding mode control of nonlinear uncertain active suspension systems with adaptive disturbance observer', *IEEE/ASME Transactions on Mechatronics*, Vol. 26 No. 2, pp. 789-797.