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Adaptive Backstepping Sliding Mode Control for ABS with Nonlinear Disturbance Observer

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ABSTRACT

This study presents a nonlinear observer that estimates structured and unstructured uncertainties based on a control methodology that is an adaptive backstepping sliding mode controller to aim wheel slip tracking of a car-like robot. In the vehicle system, the scaling factor for the lengthwise force between tire and road contact is considered as unknown, then adaptation law with Lyapunov-based analysis is derived for the unknown parameter. The lump uncertainties estimated values that are estimated by the nonlinear disturbance observer and the scaling factor estimated values are directly applied in the control input. The closed-loop system stability under the proposed controller is proven using Lyapunov's stability analysis. Then, the adaptive backstepping sliding mode controller's performance with the nonlinear disturbance observer is verified through simulations by comparing to the neural network (radial basis function) observer, which is estimated as the lump uncertainties on quarter-vehicle dynamics.

Keywords: Sliding mode control, adaptive-backstepping control, nonlinear observer, wheel slip-tracking

Introduction

In today's vehicles, during emergency braking, an anti-lock braking system (ABS) that is constituted of the foundation of automatic braking control systems has been used to keep individual discs from locking. This braking control system has become more significant with technological developments. In addition, the attention of researchers on automatic control brake systems has increased, as well as the number. The main aim of the ABS system is to stabilize the vehicle, which is achieved by controlling brake torque or optimal wheel slip that tracks the vehicle wheel slip. This braking control system helps avoid wheel locking, and synchronically prevents accidents and decreases casualties using the mentioned flexible control properties.

Several control methods have been performed on automatic braking control systems in the literature, and these control strategies are classified into two classes, traditional rule-based methodology on ABS systems and model-based methodology on ABS systems. The first methodology controllers [1-3] focus on the deceleration of the thresholds of each car-wheel and tire slip. The second methodology controllers [4-8] are used in designing from the point of the nominal model of vehicle dynamics.

Backstepping control, which is one of the nonlinear control approaches, has generally been preferred due to its simple design steps and applied to many nonlinear systems that can be considered in the upper triangular form via state definition. Although these properties are useful to control a nonlinear complex system, the method is not robust to matched and unmatched uncertainties. Therefore, nonlinear backstepping control is combined with adaptive control approaches or sliding mode control method. Moreover, the method is extended to several combined methods such as adaptive backstepping control [9], backstepping sliding mode control [10, 11], and adaptive sliding mode control [12]. Additionally, the combined methods are robustly supported by different types of nonlinear observers against uncertainties, external disturbances, and input constraints [13-18].

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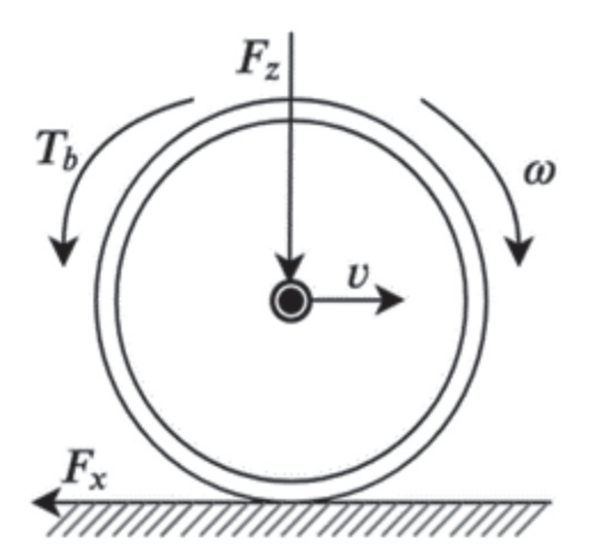

Figure 1. The 2-DOF quarter-vehicle model

In this article, the objective of the adaptive backstepping sliding mode controller for ABS is that the wheel slip is tracked to the desired wheel slip by designing the control signal under the matched and unmatched uncertainties. Although the adaptive backstepping sliding mode controller is robust for matched uncertainties and nonlinearities, the unmodeling dynamics and external disturbances are not considered. Using this motivation, to strengthen the proposed controller against to negative effects of the unmodeling dynamics and external disturbances, a nonlinear disturbance observer (NDO) is designed for nominal uncertain vehicle systems. An adaptive backstepping second-order sliding mode control method using nonlinear disturbance observer is presented to actualize the wheel slip control. The estimated value of the lump uncertainties is directly utilized in the control signal. The NDO reduces its undesired effects by estimating both matched and unmatched uncertainties in the model dynamics. In this way, the proposed nonlinear uncertainty observer assists in backstepping sliding mode control to overcome the unknown model dynamics and disturbances. Furthermore, the update rule of the other unknown scaling factor of the longitudinal tire–road contact force is derived from Lyapunov analysis, which proves system stability. Besides, the output success rate of nonlinear disturbance observer on the ABS is compared to the radial basis function neural network (RBFNN) considering as the nonlinear observer, which is adopted from the study [13]. Eventually, the viability and the designed controller efficiency including nonlinear observer for ABS control are confirmed through simulations for a quarter-vehicle dynamics Matlab/Simulink.

The remainder of the study is structured as follows. In Section 2, the quarter-vehicle mathematical equations having uncertainties in the system are introduced with defining lumped uncertainty. After the system deceleration differential equations are obtained, the state-space equations that belong to the wheel slip dynamics are derived. Subsequently, in Section 3, the continuous-time adaptive backstepping sliding controller is designed considering unknown parameters and lump uncertainties. The nonlinear disturbance observer is included in Section 3 as well. In Section 4, numerical simulations are carried out to examine the designed adaptive controller with NDO and the satisfactory results are presented with the RBFNN comparison, which is considered the uncertainty observer. Finally the conclusions are presented in Section 5.

Dynamic Model of Quarter-Vehicle

In this section, the quarter-vehicle model that has two degrees of freedom (2-DOF) is basically introduced for the ABS controller design. In this model, 2-DOF is given as the lengthwise speed and the tire angular speed, which are depicted in Figure 2.

The system dynamic model can be described as

$$J\dot{w} = R,F_x - T_b \tag{1}$$

$$mv = -F_x \tag{2}$$

where w and v denotes the wheel angular speed and longitudinal speed of the vehicle, T_b and F_x stand for the brake torque and the lengthwise force between tire and road contact, and J, m, and R_r denote the wheel inertia, the quarter-vehicle mass, and effective rolling wheel radius, consecutively. The wheel slip is given as follows

$$\lambda = 1 - \frac{wR_r}{v} \tag{3}$$

where wheel slip is satisfied. In this study, the friction coefficient between tire and road is calculated as slip ratio function using the nonlinear Burckhardt model. The Burckhardt formulations can be written as

$$\mu(\lambda) = c_1\,(1\text{-}e^{-\lambda c_2}) - \lambda c_3 \tag{4}$$

where c_1 , c_2 and c_3 indicate the tire–road friction coefficient maximum value, the friction shape, the friction curve difference between the maximum value and the value at $\lambda = 1$. Although the formulation gives the approximate accurate relationship between the tire–road friction coefficient and the wheel slip, the formulation is not accurate since the formulation is affected by changing the wheel sideslip angle and camber angle. Therefore, the longitudinal force between road and tire during braking is reformulated in the following form,

$$F_x = F_Z \mu\ (\lambda)\ \theta \tag{5}$$

where F_Z denotes the vertical force at the surface-contact region of the tire and the road and θ stands for the unknown scaling factor considering tire–road friction coefficient calculation. Substituting Equation (5) into (1) and (2) can be obtained as,

$$J\dot{w} = R_r F_Z \mu\ (\lambda)\ \theta - T_b \tag{6}$$

$$mv = -F_Z \mu\ (\lambda)\ \theta. \tag{7}$$

Taking Equation (3) second derivative with respect to time can be obtained as,

$$\ddot{\lambda} = \frac{1}{v}\left(-2\dot{v}\dot{\lambda} + \ddot{v}\left(1-\lambda\right) - \ddot{w}R_r\right) \tag{8}$$

and substituting the derivative of the uncertain dynamical model of the quarter-vehicle model (6)–(7) into (8) can be reformed as

$$\ddot{\lambda} = \frac{\theta}{v}\left(\frac{2F_z\mu(\lambda)\dot{\lambda}}{m} - \left(\frac{1-\lambda}{m} - \frac{R_r^2}{J}\right)F_z\dot{\mu}(\lambda)\right) + \frac{R_r}{Jv}\dot{T}_b. \tag{9}$$

In order to design the backstepping controller, Equation (9) must be converted into the strict feedback form. The state-space equations of (9) can be written by defining $x_1 = \lambda$, $x_2 = \dot{x}_1$ and $u = \dot{T}_b$

$$\dot{x}_1 = x_2 \tag{10}$$

$$\dot{x}_1 = F\theta + Gu \tag{11}$$

where

$$F = \frac{2F_z\mu x_2}{mv} - \left(\frac{1-x_1}{mv} - \frac{R_r^2}{Jv}\right)F_z\dot{\mu} \tag{12}$$

$$G = \frac{R_r}{Jv} \tag{13}$$

Here, the arguments of the functions have been omitted for simplicity.

In the quarter-vehicle model, the longitudinal tire–road contact force is unknown and has matched and unmatched uncertainties such as perturbation and external disturbance. The quarter-vehicle model with uncertainties can be written as

$$\dot{x}_1 = x_2 \tag{14}$$

$$\dot{x}_1 = (F + \Delta F)\theta + (G + \Delta G)u + d \tag{15}$$

where ΔF and ΔG indicate uncertainties in the dynamical model, and d stands for the disturbance. In this respect, the model considering the lumped uncertainty can be rearranged as

$$\dot{x}_1 = x_2 \tag{16}$$

$$\dot{x}_1 = (F\theta + Gu + D \tag{17}$$

where $\Delta F\theta + \Delta Gu + d$ is the lumped uncertainty.

In the next section, an adaptive backstepping sliding mode controller utilizing a nonlinear observer is designed with an estimation of the lumped uncertainty. Note that, dynamics of the wheel slip are much faster than longitudinal speed dynamics of the vehicle, so the design of the nonlinear observer for the lumped uncertainty is possible when the change of the lumped uncertainty is slow as to the nonlinear observer dynamics.

Controller Design

Nonlinear Disturbance Observer Design

In this article, the NDO of [19] has been adopted to estimate the lump uncertainties. Subsequently, the dynamics of NDO can be introduced as

$$z = -L\ (F\theta + Gu + z + \beta) \tag{18}$$

where L is NDO design gain and β is the nonlinear function depending on state variables. The nonlinear function $\beta = \kappa x_2$ can be selected and $\kappa > 0$ is the constant parameter. Considering the observer error $\widetilde{D} = D - \hat{D}$ and then the derivative respect to time of observer error dynamics of NDO can be obtained. Here, substituting Equation (18) into the observer error derivative, the derivative observation error can be obtained as

$$\dot{\tilde{D}} = \dot{D} - \dot{\hat{D}} = \dot{D} - \dot{z} - \dot{\beta} \tag{19}$$

in Equation (19). Using NDO dynamics (18) and choosing observer gain $L = \kappa$, Equation (19) can be arranged as follows:

$$\dot{\tilde{D}} = \dot{D} + L\left(F\theta + Gu + z + \beta\right) - \dot{\beta} = \dot{D} + L\hat{D} - LD$$
$$= \dot{D} - \kappa\tilde{D}. \tag{20}$$

Note that, (20) system is described as the perturbation system and $\dot{D}$ is taken into consideration as the perturbed term. In this case, the stability of the NDO can be proven uniformly asymptotically, if the perturbed system is totally stable, (for details see [19]).

Adaptive Backstepping Sliding Mode Control Design

In order to carry out the standard recursive backstepping controller, the state variables can be defined as follows

$$e_1 = x_1 - \lambda_d \tag{21}$$

$$e_2 = x_2 - \varphi - \dot{\lambda}_d \tag{22}$$

where φ is considered as the virtual control signal and λ_d denotes the trajectory slip of a tire. Selecting the Lyapunov function $V_1 = e_1^2 / 2$, the derivative of the V_1 becomes

$$\dot{V} = e_1\dot{e}_1 = e_1\ (e_2 + \varphi) \tag{23}$$

using

$$\dot{e}_1 = \dot{x}_1 - \dot{\lambda}_d = x_2\ \ \dot{\lambda}_d = e_2 + \varphi. \tag{24}$$

The virtual control signal can be designed as

$$\varphi = k_1 e_1 \tag{25}$$

where $k_1 > 0$ is the controller gain. (23) becomes

$$\dot{V} = -k_1 e_1^2 + e_1 e_2. \tag{26}$$

To realize the adaptive backstepping sliding mode controller, the sliding mode surface is defined as $s = k_2 e_1 + e_2$, where $k_2 > 0$ is the controller gain. The derivative of Equation (23) is obtained as

$$\begin{aligned} \dot{e}_1 &= \dot{e}_2 - \varphi - \dot{\lambda}_d \\ &= F\theta + Gu + D - \dot{\varphi} - \ddot{\lambda}_d \end{aligned} \tag{27}$$

where $\dot{\varphi} = -k_1 (\dot{x}_1 - \dot{\lambda}_d)$. Defining $\tilde{\theta} = \theta - \hat{\theta}$ the parameter error, the candidate Lyapunov function can be selected as

$$V_2 = V_1 + \frac{1}{2}s^2 + \frac{1}{2\gamma_1}\tilde{\theta}^2 + \frac{1}{2\gamma_2}\tilde{\delta}^2 + \frac{1}{2}\tilde{D}^2 \tag{28}$$

where $\hat{\theta}$ is the estimate value of θ, γ_1 and γ_2 are the positive design parameters, $|\dot{D}| \leq \delta \leq \infty$. Additionally, $\hat{\delta}$ is the estimate value of δ with defining $\tilde{\delta} = \delta - \hat{\delta}$. Note that,

$$\dot{s} = k_2 \left(e_2 + \varphi\right) + F\theta + Gu + D - \dot{\varphi} - \ddot{\lambda}_d. \tag{29}$$

The derivative of the Lyapunov function can be calculated as

$$\begin{aligned} \dot{V}_2 = &-k_1 e_1^2 + e_1 e_2 + s(k_2 e_2 + k_2 \varphi + F\theta + Gu + D - \dot{\varphi} - \ddot{\lambda}_d) \\ &- \frac{1}{\gamma_1}\tilde{\theta}\dot{\hat{\theta}} - \frac{1}{\gamma_2}\tilde{\delta}\dot{\hat{\delta}} - \tilde{D}\dot{\hat{D}} \end{aligned} \tag{30}$$

The control signal is designed as follows

$$u = -\frac{1}{G}\left(k_2 e_2 + k_2 \varphi + F\hat{\theta} + \hat{D} - \dot{\varphi} - \ddot{\lambda}_d - \rho_1 s - \rho_2 J(s)\right) \tag{31}$$

where ρ_1 and ρ_2 are the positive design parameters and

$$\vartheta(s) = \frac{s}{|s| + \eta}, \quad \eta > 0. \tag{32}$$

Equation (32) indicates the continuous function in order to eliminate the chattering phenomenon. Substituting the control signal (31) into form (30) yields

$$\begin{aligned} \dot{V}_2 = &-k_1 e_1^2 + e_1 e_2 - \rho_1 s^2 - \rho_2 s \vartheta(s) + sF\tilde{\theta} + s\tilde{D} - \frac{1}{\gamma_1}\tilde{\theta}\dot{\hat{\theta}} \\ &- \frac{1}{\gamma_2}\tilde{\delta}\dot{\hat{\delta}} - \tilde{D}\dot{\hat{D}}. \end{aligned} \tag{33}$$

Here, we can write $\dot{\hat{D}} = \kappa\tilde{D}$ using (20). Therefore, Equation (33) can be rewritten as

$$\begin{aligned} \dot{V}_2 &= -k_1 e_1^2 + e_1 e_2 - \rho_1 s^2 - \rho_2 s \vartheta(s) + sF\tilde{\theta} + s\tilde{D} - \frac{1}{\gamma_1}\tilde{\theta}\dot{\hat{\theta}} \\ &\quad - \frac{1}{\gamma_2}\tilde{\delta}\dot{\hat{\delta}} - \tilde{D}\dot{\hat{D}} \\ &= -k_1 e_1^2 + e_1 e_2 - \rho_1 s^2 - \rho_2 s \vartheta(s) + sF\tilde{\theta} - \frac{1}{\gamma_1}\tilde{\theta}\dot{\hat{\theta}} - \frac{1}{\gamma_2}\tilde{\delta}\dot{\hat{\delta}} \\ &\quad + \frac{1}{\kappa}\dot{\hat{D}}s - \frac{\dot{\hat{D}}^2}{\kappa} \\ &\leq -k_1 e_1^2 + e_1 e_2 - \rho_1 s^2 - \rho_2 s \vartheta(s) + sF\tilde{\theta} - \frac{1}{\gamma_1}\tilde{\theta}\dot{\hat{\theta}} - \frac{1}{\gamma_2}\tilde{\delta}\dot{\hat{\delta}} \\ &\quad + \tilde{\delta}s - \frac{\dot{\hat{D}}^2}{\kappa} \end{aligned}$$

Designing the adaptation laws as

$$\dot{\hat{\theta}} = \gamma_1 s F \tag{34}$$

$$\dot{\hat{\delta}} = \gamma_2 s \tag{35}$$

utilizing adaptation, the derivative of the candidate Lyapunov function, which is eventually a negative semi-definite function can be obtained as

$$\begin{aligned} \dot{V}_2 &= -k_1 e_1^2 + e_1 e_2 - \rho_1 s^2 - \rho_2 s \vartheta(s) - \frac{\dot{\hat{D}}^2}{\kappa} \\ &= -E^T S E - \rho_2 \frac{s^2}{|s| + \eta} - \frac{\dot{\hat{D}}^2}{\kappa} \end{aligned} \tag{36}$$

where $E = [e_1 e_2]^T$ and S is a symmetric matrix defining as

$$S = \begin{bmatrix} k_1 + \rho_1 k_2^2 & \rho_1 k_2 + 0.5 \\ \rho_1 k_2 + 0.5 & \rho_1 \end{bmatrix} \tag{37}$$

To satisfy the $|S| > 0$, k_1, k_2, and ρ_1 must be chosen so that it substantiates the condition $4\rho_1(k_1 - k_2) - 1 > 0$. Note that, ρ_2 can be selected as a positive constant value. Hence, it is concluded with Equations (28) and (36) that the uncertainty dynamical system given in the Equations (16)–(17) with the control signal in (31), and the nonlinear disturbance observer in (18) and the adaptation rules in (34)–(35) are stable according to the LaSalle–Yoshizawa theorem [20].

Table 1. System parameters

	Value	Unit
Mass of the vehicle (m)	342	kg
Moment of Inertia (J)	0.65	kgm^2
Radius of the wheel (R_r)	0.33	m
Gravitational Constant (g)	9.8	m/s^2
Maximum Braking Torque (T_b)	3000	Nm
Desired slip (λ_d)	0.1	
Moment of Inertia (J)	0.65	kgm^2
Radius of the wheel (R_r)	0.33	m

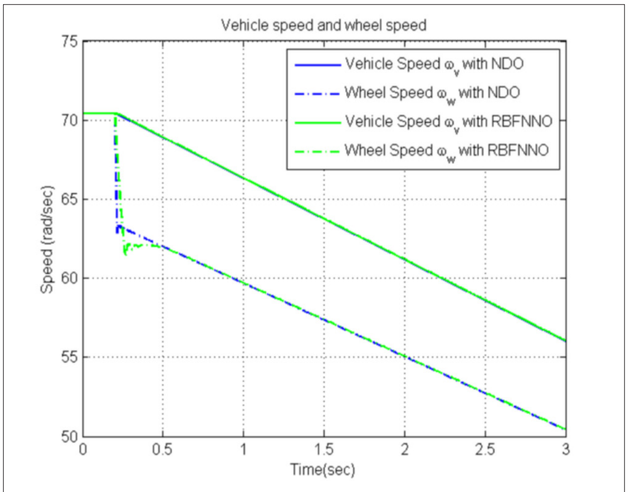

Figure 2. Vehicle Speed ω_v and Wheel Speed ω_w with NDO and RBFNNO

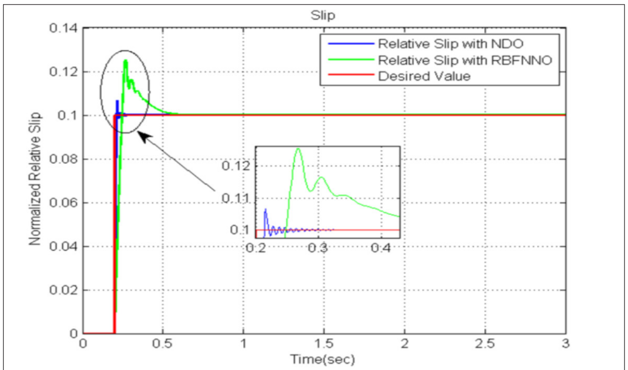

Figure 3. Relative Slip with NDO and RBFNNO

Simulation Results

To test the performance of the designed adaptive sliding mode backstepping controller, strengthened with NDO for ABS of the quarter-vehicle system, numerical simulations are carried out.

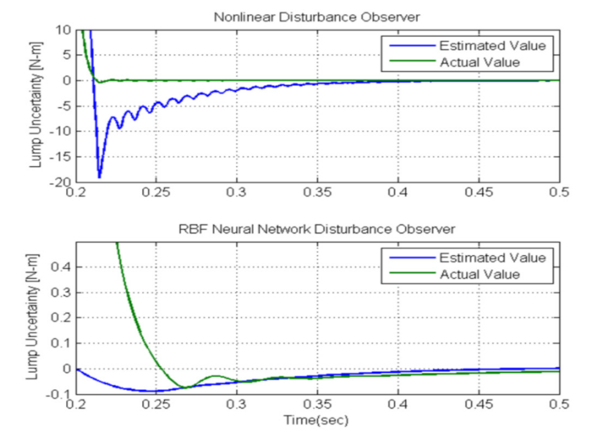

Figure 4. Estimated value and actual value with NDO and RBFNNO

The performance of the designed NDO for lump uncertainties is compared with an estimator of the RBFNN, which is one of the modern control approaches. The numerical simulation is carried out through MATLAB/Simulink. The system model parameters are presented in Table 1.

The adaptive backstepping sliding mode controller is performed on a dry asphalt road. The desired wheel slip is considered a step function at 0.1 value. The controller gain for the virtual control signal is set to $k_1 = 11000$. The design parameter of the sliding mode surface is set to $k_2 = 5000$. The controller design parameter values are set to $\rho_1 = 35$. The designing adaptation gain γ_1 of $\tilde{\theta}$, which is estimated as the unknown scaling factor considering tire–road friction coefficient calculation θ is used $\gamma_1 = 0.01$ in the numerical simulations. The designing adaptation gain of $\hat{\delta}$ which is estimated as the unknown bounded value δ of the $|\dot{D}|$ is assigned as $\gamma_2 = 10$. Besides, the disturbance observer gain is set to $\kappa = 20$ in the simulation works.

The results for vehicle speed and wheel speed using two lump uncertainty observers which are separately applied to the quarter vehicle, are depicted in Figure 2. The proposed adaptive sliding mode backstepping controller that is patched with NDO or radial basis function neural network observer (RBFNNO) for the control of ABS in a vehicle system guarantees the tracking of the desired wheel slip. Figure 3 presents the performance to follow the desired slip value of the relative slip for both NDO method and RBFNNO method. The aim of the control with a nonlinear disturbance observer is to reach the desired relative slip value, which was more effective. It is also shown that the neural-network-based relative slip search algorithm remains weaker as for that deterministic search algorithm. Namely, the relative slip with NDO is more successful than RBFNNO considering the percentage overshoot and steady-state error. The uncertainty observers can effectively estimate the system lump uncertainty, the result of which is given in Figure 4. The applied brake torque values and the stopping distance for each simulation are shown in Figure 5 and Figure 6, respectively.

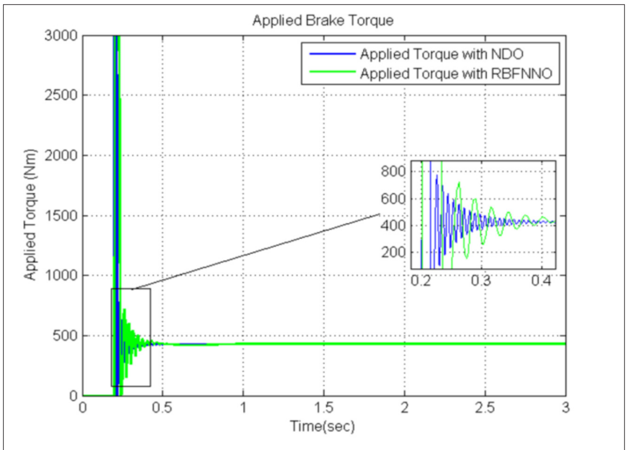

Figure 5. Applied brake torque with NDO and RBFNNO

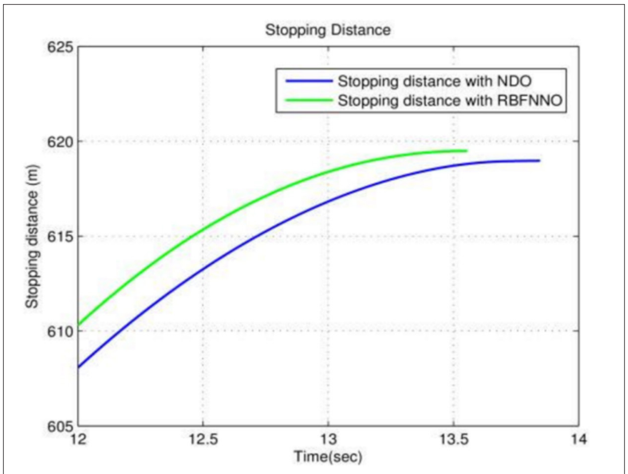

Figure 6. Stopping distance with with NDO and RBFNNO

According to the executed simulations on the proposed controller using NDO and RBFNNO, the adaptive backstepping sliding mode controller using NDO has reached the desired reference value of the wheel slip with more agile and faster performance. The proposed control approach based on the nonlinear estimation method was suppressed by better calculating of estimates values of the lump uncertainties, which include the unknown scaling factor, uncertainties in the dynamical model, and the disturbance. Consequently, numerical simulation results show the success of the proposed adaptive backstepping sliding mode controller using the NDO for ABS in the quarter-vehicle system model.

Conclusions

In this article, the adaptive backstepping second-order sliding mode controller is proposed for the ABS. Vehicle systems are negatively affected by the matched and unmatched uncertainties and undesired effects of the lump uncertainties also caused challenges to the control of the vehicle. Considering this phenomenon, a nonlinear disturbance observer is designed to attenuate the model uncertainties and disturbances. The stability of the proposed controller using the designed observer is shown in the sense of Lyapunov. Similarly, the effectiveness and viability of the adaptive backstepping sliding mode controller have been confirmed through numerical simulations. The performance of the nonlinear disturbance observer on the proposed controller is compared to the RBFNNO on the proposed controller, and the success of the designed observer has been presented.

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