Fuzzy Sliding Mode Controller for Slip Control of Antilock Brake Systems

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ABSTRACT:
Anti-lock braking system is designed to optimize braking procedure while maintaining automobile steerability through controlling wheels slip. However, due to nonlinearity and uncertainty of ABS structure, designing the controller for wheel slip encounters so many problems which necessitate a robust control system. In this paper, a hybrid controller is proposed for ABS to address this issue. The designed controller is a combination of sliding mode control and fuzzy control. In fact, the fuzzy system determines to switch factor of sliding mode controller proportional to automobile speed employing fuzzy rules. In this way, it would be able to avoid braking command fluctuations in lower speeds. Simulations are performed in ¼ model of automobile in MATLAB environment. The simulation results revealed the capability of proposed system to maintain slip ratio in optimal value as well as avoiding braking fluctuations in low speeds.

KEYWORDS: Anti-lock Braking System (ABS), sliding mode control, Fuzzy control

1. INTRODUCTION

The different surface of roads has bad influences on vehicle stability and causes long brake. Vehicle stability and control are significant features that ABS has it. Because the driver has not precision control on oil pressure of tires and have not enough information about the road, he presses the brake pedal hard that leads to more pressure than the friction between tires and the road.

This event not only couldn't stop the vehicle but also leads to lock of tire and loss of the lateral stability and controllability of the vehicle [1]. On the other hand, designing an ideal tire sliding controller is not easy since the brake system is nonlinear and uncertain and causes many complications in designing. The performance of anti-lock brake system severely depends on road condition parameter which changes over a wide range [2], [6].

Therefore, a good controller is a good option for this issue. Sliding mode controllers have been widely reviewed because of its effect on nonlinear systems [11].

An ideal sliding mode controller inevitably includes a discrete switching function resulting severe fluctuations in control signal. These fluctuations are known as chattering phenomenon. To mitigate this phenomenon usually, a continuous approximation of discrete sliding mode controller is exploited. For this purpose, a thin layer is considered in the vicinity of switching surface [12].

Despite their simple implementation, classic controllers are not capable of maintaining desired sliding level.

Thus, they lead to high brake torque fluctuations. To improve the behavior of sliding mode controller, it is combined with the fuzzy controller to obtain a new controller called fuzzy sliding mode controller [3], [5], [7].

The main advantage of the FSMC is that it requires fewer fuzzy rules than fuzzy control does and also FSMC system has more robustness against parameter variation [7].

In this study, first off, a sliding mode controller is designed. Although it properly tracks the desired trajectory in presence of uncertainties, it does not achieve acceptable performance at low speeds and during the braking procedure.

This leads to torque fluctuations. Therefore, a fuzzy system is utilized to determine to switch gain of sliding mode controller which shows appropriate performance.

So far, different types of ABS have been presented including adaptive fuzzy control [4], neural fuzzy [2], [10], PID-fuzzy [5].
The structure of this paper is as follow:

The second section describes the mathematical vehicle model and tire-road force relations. In the third section, the presents the different sliding mode controller and the fuzzy controller. The simulation results are presented in section four and conclusion constitutes the last part of the paper.

2. SYSTEM DYNAMICS

2.1. Vehicle model

A mathematical model for controller designing has been created based on rotational dynamics of a tire and longitudinal dynamics of the vehicle. Thus, according to Newton's second law and [7], [8] references, it is given:

$$\dot{\omega}_\omega(t) = \frac{1}{J_\omega}[-T_b(t) - B_\omega \omega_\omega(t) + R_\omega F_t(t)] \qquad (1)$$

Where J_w is the rotation inertia of the wheel, ω_ω is the angular velocity of the wheel, T_b is the braking torque, R_ω is the radius of the wheel , F_t is friction between the wheel and the road surface, B_w is the viscous friction of the wheel.

The slip rate is defined as following:

$$\lambda(t) = \frac{\omega_v(t) - \omega_\omega(t)}{\omega_v(t)} \qquad (2)$$

Which λ is slip rate and usually is presented in percent and 100% slip rate means complete tire lock and 0% means no tire lock. Also $\omega_v(t) = \frac{V_v(t)}{R_\omega}$ and V_v is speed forward and the quotation on longitudinal direction is:

$$\dot{V}_v = \frac{-1}{M_v}[4F_t + B_v V_v(t) + F_\theta(\theta)] \qquad (3)$$

Where M_v is the mass of the vehicle; B_v is the vehicle viscous friction, F_θ and F_t is defined as follow:

$$F_\theta(\theta) = M_v\, g \sin(\theta) \qquad (4)$$

$$F_t(t) = \mu(\lambda) \frac{M_v g}{4} \cos(\theta) \qquad (5)$$

Where -g is the gravitational acceleration constant, θ is the angle of inclination of the road, and $\mu(\lambda)$ is a function of friction that represents viscosity coefficient between the road surface and tires.

2.2. Bruck Hard wheel friction model

The goal of ABS system is to maintain the operating spot of each tire near the peak of μ-λ curve. Maximum friction occurs in this spot and optimum slip ratio also has been limited. In this paper, the below formula had been used as tire friction model that had been presented by Bruck Hard which friction coefficient between tires and the road has been given based on a function of tires slip and vehicle velocity.

$$\mu_x(\lambda, v) = (C_1(1 - e^{-C_2\lambda}) - C_3\,\lambda)e^{-C_4\lambda v} \qquad (6)$$

The parameters of this equation are:
C1: the maximum value of friction curve, C2: friction shape, C3: friction curve difference between maximum value and the value at λ =1, C4: wetness characteristic value and is int range 0.02 - 0.04m/s.
Table 1 shows the parameter of friction parameter in a different condition of the road.

Table 1. Friction model parameters [9]

Road Condition	C_1	C_2	C_3
Dry asphalt	1.2801	23.99	0.52
Wet asphalt	0.857	33.822	0.347
Snowy	0.1946	94.129	0.0646

3. DESIGN STRATEGY

3.1. Sliding mode control

Sliding Mode control has been accepted as the best procedure of control. The objective of Sliding Mode design is adjusting λ sliding coefficient over λ_d **the** reference value.
Deriving equation 1 and 2, we have:

$$\dot{\lambda} = \frac{(1-\lambda)\dot{\omega}_v - \omega_{\dot{\omega}}}{\omega_v} \qquad (7)$$

$$\lambda = -\frac{\omega_v}{\omega_v}\lambda + \frac{\omega_v}{\omega_v} + \frac{T_b}{J_\omega \omega_v} + \frac{B_\omega \omega_\omega}{J_\omega \omega_v} - \frac{T_t}{J_\omega \omega_v} \qquad (8)$$

Now for designing sling mode control we have to obtain the equation. The equation of sliding surface for this system is as follow:

$$s = \lambda - \lambda_d \qquad (9)$$

The control law could be presented in general case as follow:

$$u = u_{eq} - k sgn(s) \qquad (10)$$

u_{eq} is the input of control to the system, K Is slip use coefficient and $sgn(s)$ Is the mark function.

In ABS system, brake torque is T_b which is formed from two parts: equivalent torque control $t_{b,eq}$ and switching torque control $t_{b,rb}$ which the first part make $(\lambda, \dot{\lambda})$ States of the system to move along the sliding surface. It is determined from tires dynamics and sliding coefficient. Part two of the control is the assurance of attaining state route system to the optimum sliding surface which its value is determined by and stability condition analytically.

So in the following we calculate the value of $t_{b,eq}$ and $t_{b,rb}$.

Control equivalent is determined from $\dot{s} = 0$. In the most study, λ_d is assumed constant. So $\dot{\lambda}_d$ Is zero but we should keep in mind that λ_d. Is changed by velocity and different condition of road surface so we have;

$$\dot{s} = \dot{\lambda} - \dot{\lambda}_d = 0 \tag{11}$$

Using equations (7) and (8) we have:

$$t_{b,eq} = \omega_v J_\omega(\lambda - 1) - B_\omega\dot{\omega}_\omega + T_t + \omega_v J_\omega \dot{\lambda}_d \tag{12}$$

For determining the control advantage, switching and Lyapunov function is selected then, the derivation is obtained less than zero or negative value of $-\eta|s|$ In order to have Stability condition.

$$V(X) = \frac{1}{2}s^2 \tag{13}$$

$$\dot{V}_x = s\dot{s} \leq -\eta|s| \tag{14}$$

Using equations (8), (11) and (14) we have:

$$s\dot{s} = s\dot{\lambda} - s\dot{\lambda}_d \leq -\eta|s|$$

$$\Rightarrow \mathrm{K}\ \omega_v J_\omega|s| \geq \eta|s| \tag{15}$$

$$K \geq \omega_v J_\omega \eta \tag{16}$$

As the result, substituting (12), (16), we got brake torque in (17)

$$t_b = t_{b,eq} - K\, sgn(s) \tag{17}$$

$$\boldsymbol{t_b = \omega_v J_\omega(\lambda - 1) - B_\omega\omega_\omega + T_t + \omega_v J_\omega\dot{\lambda}_d - \omega_v J_\omega\eta - \mathbf{sgn(s)}} \tag{18}$$

3.2. Fuzzy control

Despite acceptable tracking performance in presence of uncertainties, sliding mode control is not efficient during braking and low speeds. The undesired behavior represents itself in the form of torque fluctuations and it results from constant switching gain. To overcome this problem a fuzzy system is proposed through which switching gain is decreased during braking.

The input of the fuzzy system is vehicle speed and its output is switching gain of sliding mode controller.

The gain is changed such that it remains in the range determined by stability criterion of sliding mode. The membership functions are illustrated in fig. 1.

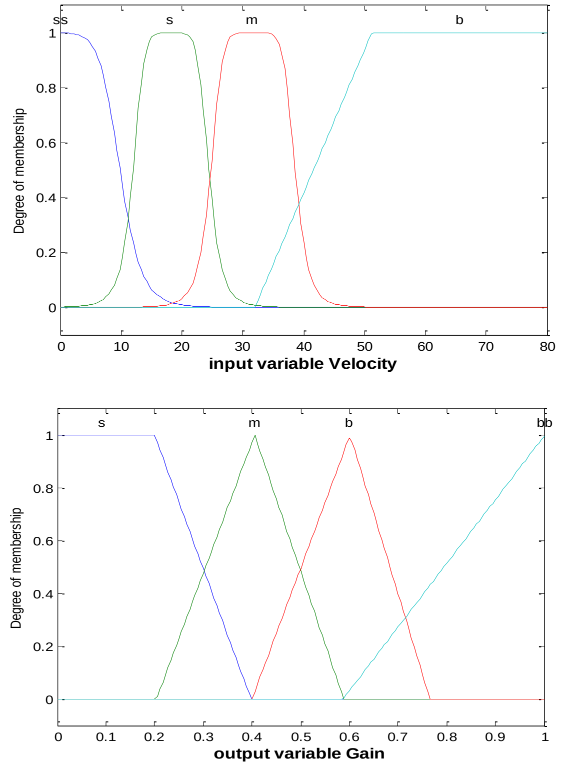


Fig. 1. Membership functions of the fuzzy controller.

4. SIMULATION RESULTS

For simulations, the parameters of the ABS used in this study are M_v= 4×342 kg, B_v = 6 Ns, J_w = 1.13 Nms^2, R_ω= 0.33 m, B_w = 4 Ns, and g = 9.8 m/s^2.

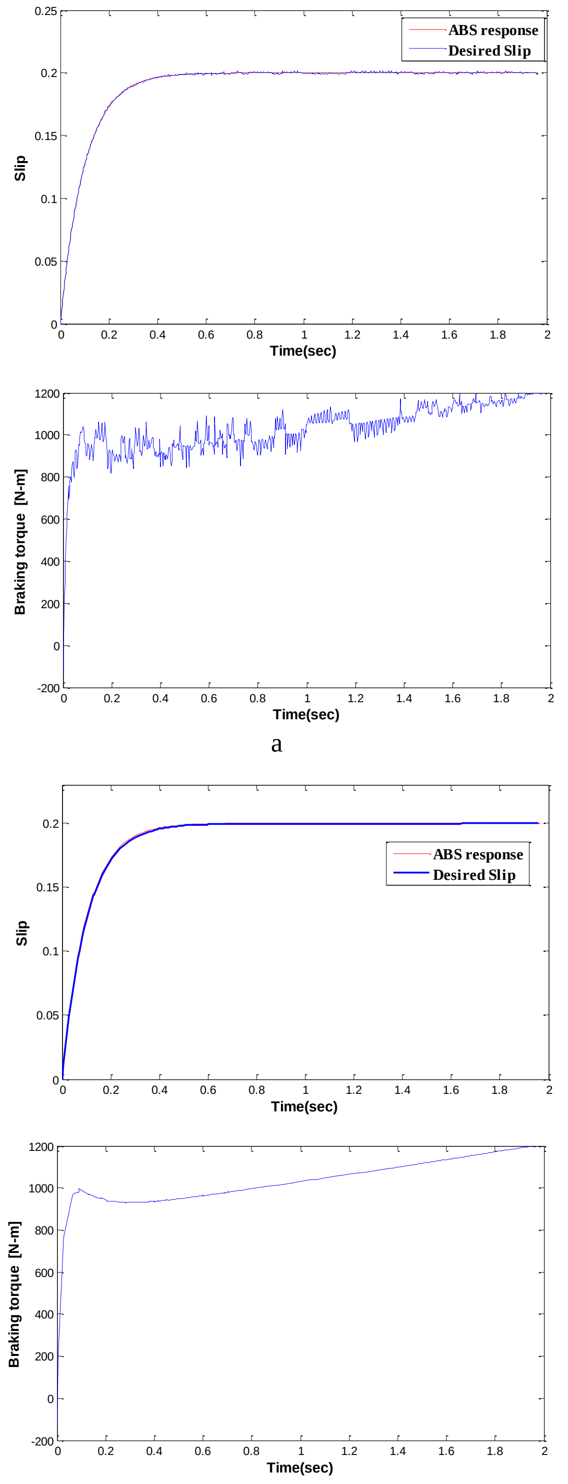
The results of stimulation sliding mode controller without identifying road surface are showed in Figure 2.

It is seen that the tractive forces for different road conditions are maximized near λ = 20%, so the slip command λ_c is chosen as 0.2. Moreover, a reference model is chosen as:

$$\dot{\lambda}_d(t) = -10\lambda_d(t) + 10\lambda_c(t) \tag{19}$$

And, the maximum braking torque is limited at 1200 N-m.

In figure 3, simulation results of SMC are demonstrated in three different roads; dry, wet and snow asphalt. Dry and wet asphalts constitute 1 second of simulation time (1 second for each) while the rest of simulation time is dedicated to snow road. Simulation results for hybrid FSMC controller are illustrated in figure4. The timing of simulation and share of different road types are the same as figure 3. It can be seen that braking torque fluctuations are significantly reduced.



a

b

Fig. 2. ABS response, Reference slip and brake torque , with
a) SMC and b) proposed hybrid controller

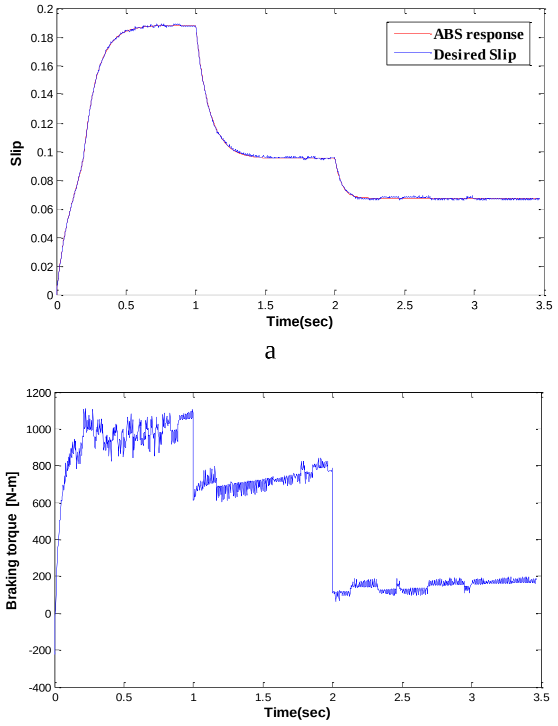


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Fig. 3. a) ABS response and Reference slip
b) brake torque
(sliding mode control)

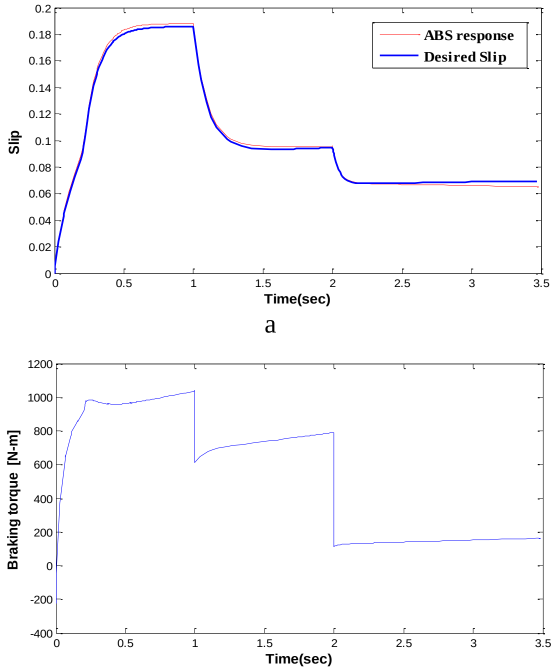

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Fig. 4. a) ABS response and Reference slip b) brake torque
(Fuzzy sliding mode control)

5. CONCLUSION

In this paper, an integral sliding mode controller was utilized. To track the desired slide in addition to avoiding severe fluctuations in the control activity, fuzzy logic was exploited. These fluctuations must be avoided as this undesired behavior in control signal (braking command) is translated to higher control activity which, in turn, damages braking system and its components. Furthermore, lateral stability is violated. As could be seen in simulation results, FSMC hybrid controller outperforms sliding mode controller and avoids torque fluctuations.

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