Robust Wheel Slip for Vehicle Anti-lock Braking System with Fuzzy Sliding Mode Controller (FSMC)

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***Abstract*-Anti-lock Braking System (ABS) is used in automobiles to prevent slipping and locking of wheels after the brakes are applied. Its control is a rather complicated problem due to its strongly nonlinear and uncertain characteristics. The aim of this paper is to investigate the wheel slip control of the ground vehicle, comprising two new strategies. The first strategy is the Sliding Mode Controller (SMC) and the second one is the Fuzzy Sliding Mode Controller (FSMC), which is a combination of fuzzy logic and sliding mode, to ensure the stability of the closed-loop system and remove the chattering phenomenon introduced by classical sliding mode control. The obtained simulation results reveal the efficiency of the proposed technique for various initial road conditions.**

Keywords-Anti-lock Braking System (ABS); sliding mode control; fuzzy logic control; fuzzy sliding mode control; wheel slip ratio

I. INTRODUCTION

Anti-lock brake system (ABS) is generally utilized in road vehicles. To diminish product cost, standard ABS utilizes wheel speed sensors to distinguish angular velocities, which isn't sufficient to directly obtain the wheel slip required by the control unit, yet can be utilized to compute the reference slip proportions with estimated wheel precise speeds and the evaluated vehicle speed. The friction coefficient of the road, which decides the vehicle deceleration amid extreme braking, is an essential parameter in assessing vehicle speed. ABS comprises of a hydraulic modulator (control valve), control electronics (central unit) and sensors on the wheels. Sensors continually get information on braking power, although there are no sensors which can precisely distinguish road surface, and make this information accessible to the ABS controller. The primary aim of ABS is to maintain the wheel slip in the required value and to ensure the steerability of the vehicle when the brakes are applied suddenly. ABS control is influenced by the nonlinear behavior of the dynamics of the brake and other factors such as the type of road surface, tire pressure, vehicle mass, etc. because the required wheel slip is continuously changing [1].

The target is the control of the wheel slip of each tire in order to continue running at its relating desired slip value. However, the wheel slip dynamics control is a difficult problem due to the nonlinear and complex behavior of the tire. In addition, the system is also suffering from parametric uncertainties, and is subjected to external disturbances from the environment leading to the emergence of many difficulties in the design of controllers for ABS. This leads to the requirement of a controller which will be capable of dealing with these uncertainties and nonlinearities. One of the controllers which can successfully deal with the parametric and modeling uncertainties of the ABS system is Sliding Mode Control (SMC). SMC systems are generally utilized for ABS control, since they are insensitive to parameter variations. The best advantages of this control approach are its fast convergence and good performance [2-3] and its robustness with respect to structural uncertainties and external disturbances [4].

Sliding mode controllers have been developed and studied in [5, 6]. However, the presence of the sign functions in the control law, also known as the Variable Structure Controller (VSC) causes a phenomenon of chatter that can excite high frequency and can damage the system [7-9]. To overcome this drawback, several solutions have been proposed, such as the introduction of a transition band around the sliding surface [10-11] or Fuzzy-Sliding Mode Control (FSMC) which is a combination of fuzzy control and sliding mode control. The main advantages of FSMC is that it requires fewer fuzzy rules than fuzzy control and it is more robust against parameter variations [12-13]. Fuzzy Logic (FL) control is one of the accepted strategies to deal with uncertain control systems. Control systems on FL have been developed for ABS [14]. FL is a knowledge-based system which is very useful in handling systems whose models are not fully or accurately developed or the information about the system is uncertain.

In this paper, a new robust FSMC for the ABS model is proposed. The performance of the proposed FSMC is assessed through digital simulations for varying road surface conditions.

II. DYNAMIC MODEL OF THE PNEUMATIC WHEEL

A quarter-car model is utilized to create the longitudinal braking dynamics. It comprises of a single wheel carrying a quarter of the mass of the vehicle. At any given time, the vehicle is moving with a longitudinal velocity $V_v(t)$. Before the

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brakes function, the wheel moves with an angular velocity $\omega_\omega(t)$ motivated by the mass in the direction of the longitudinal motion. Due to the friction between the tire and the road surface, a tractive force is generated $F_t(t)$. When the driver applies the braking torque, it will cause the wheel to decelerate until it comes to a stop. The two degree of freedom quarter-car model is shown in Figure 1.

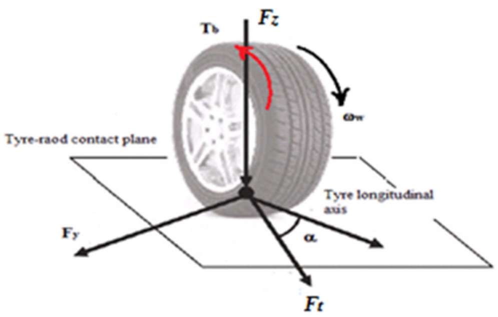

Fig. 1. The dynamics of the vehicle wheel single-corner model.

The dynamic equation of the ABS system is the consequence of Newton's law exerted to the wheels and the vehicle which is determined by the total sum of the forces applied to the vehicle during braking.

$$\sum_{i=1}^{n} F_i = V' \times m$$

$$V_v'(t) = \frac{-1}{m_v} F_t(t) \quad (1)$$

The wheel rotational dynamics equation is given by:

$$\omega_\omega'(t) = \frac{1}{J}[-T_b + T_t(t)] \quad (2)$$

where ω_ω is the wheel angular velocity (r/s), J is the wheel rotational inertia (Kg.m^2),T_b is the effective braking torque (N.m), and T_t is the torque generated by the sliding between the wheel and the road surface (N.m).

The expressions of various forces are given by:

$$F_z(\mathrm{t}) = m_v g \sin(\alpha) \quad (3)$$

$$F_t(t) = \mu(\lambda) \frac{m_v g}{4} \cos(\alpha) \quad (4)$$

$$T_t(t) = R_\omega F_t(t) \quad (5)$$

where F_t and F_z are the braking force of tire and the vertical force respectively, a is the tyre side slip angle (rad), and R_ω is the tire radius (m)

III. Wheel Slip Control and Friction Curve

The wheel slip is the conventional and main controlled variable, still utilized in certain ABS systems. The slip measurement is critical, since it requires the estimation of the speed of the vehicle. Wheel slip control is the most reasonable decision for the structure of braking controllers that are robust with respect to road surface variables. The control target of the ABS is to regulate wheel slip to maximize the coefficient of friction between the wheel and the road for any given road surface. In general, the coefficient of friction μ during a braking operation can be described as a function of the wheel slip ratio λ, which is characterized as:

$$\lambda(t) = \frac{\omega_v(t) - \omega_\omega(t)}{\omega_v(t)} = 1 - \frac{\omega_\omega(t)}{\omega_v(t)} \quad (6)$$

or:

$$V_v(t) = R_\omega \times \omega_v \quad (7)$$

with ω_v(t) being the angular velocity of the vehicle (r/s).

Note that, whatever the value of λ ($0 \le \lambda \le 1$), this control guarantees the uniqueness of the equilibrium point. The friction coefficient which characterizes the road and tire $\mu(\lambda)$ is a nonlinear parameter, with properties: $\mu(\lambda=0)=0$ and $\mu(\lambda>0)>0$. The expression of $\mu(\lambda)$ may change, according to different road conditions.

$$\mu(\lambda, V_v) = \left[\mathrm{C}_1(1 - e^{-C_2.\lambda}).C_3.\lambda\right].e^{-C_4.\lambda.V_v} \quad (8)$$

where C_1 is the maximum value of the curve of friction, C_2 is the shape of the curve of friction, C_3 is the difference of the curve of friction between the maximum value and the value at λ=1, and C_4 is the characteristic value of moisture. One $\mu(\lambda)$ curve for various road surfaces is shown in Figure 2.

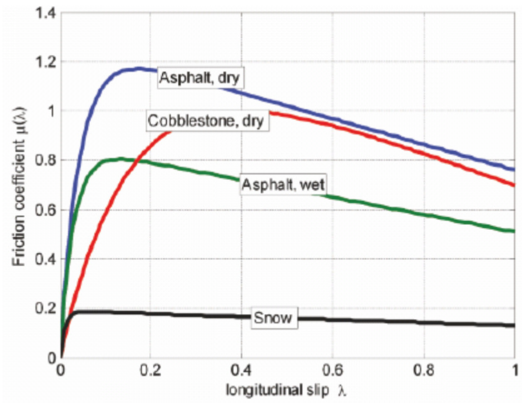

Fig. 2. Slip-friction $\mu(\lambda)$ curves for different road conditions.

The qualifying feature depends on the longitudinal:

$$\lambda'(t) = \frac{(1-\lambda)\omega_v' - \omega_w'}{\omega_v} \quad (9)$$

IV. Sliding Mode Controller Based ABS Control

SMC is an approach of robust control that is used to control nonlinear systems such as the ABS. The design of the SMC is simple and the system is robust against variations in process dynamics and external disturbances.

Let a nonlinear system be represented as:

$$\lambda'(t) = f_n(\lambda,t) + g_n u(t) \quad (10)$$

where:

$$f_n(\lambda,t) = \lambda.\underbrace{\frac{F_t(\mathrm{t})}{m_v\omega_v R_\omega}}_{a} \underbrace{- \frac{F_t}{R_\omega \omega_v m_v} - \frac{R_\omega F_t}{\omega_v J}}_{b},$$

$$g_n = \underbrace{\frac{1}{J\omega_v}}_{c} \quad \text{and} \quad u(t) = T_b(t)$$

where $f_n(\lambda, t)$ and g_n represent the nominal values of the system parameters.

If uncertainties occur, then the controlled system can be modified:

$$\begin{aligned} \lambda'(t) &= \left[f_n(\lambda,t) + \Delta f_n(\lambda,t) \right] + \left[g_n + \Delta_{ng} \right] \times u(t) \\ &= f_n(\lambda,t) + g_n u(t) + D \qquad (11) \\ D &= \Delta f_n(\lambda,t) + \Delta g_n(\lambda,t) u(t) \end{aligned}$$

where $\Delta f_n(\lambda,t)$ and$\Delta g_n(\lambda,t)$ are the uncertainties of the system and D is constant and positive.

The control aim in this paper is to drive the longitudinal slip ratio to the desired slip in finite time and find a control braking torque in order to have the system track the desired slip (λ_d) error defined by:

$$\lambda_e(t) = \lambda_d(t) - \lambda(t) \quad (12)$$

Tthe conventional sliding controller defines a scalar function of the sliding surface given by the equation:

$$s(\lambda,t) = (\frac{\partial}{\partial t} + k_i)^{n-1}.\lambda_e \quad (13)$$

In a system of the second order, the sliding surface is defined as:

$$s(\lambda,t) = \lambda_e{}'(t) + k_1\lambda_e(t) \quad (14)$$

where k_1 represents the surface parameters. The values of k_1 determine the slope of the sliding surface and one of the conditions for the existence of sliding surface is that k_1 is strictly positive real constant.

To ensure the stability of system, the function form of Lyapunov is given by the following relation:

$$V = \frac{1}{2} s^2(\lambda,t) \quad (15)$$

The above control law guarantees the system trajectories move toward and stay on the sliding surface s=0 for any initial condition, if the following condition is satisfied:

$$V' = \frac{1}{2}\frac{\partial}{\partial t}(s^2(\lambda,t)) = s(\lambda,t).s'(\lambda,t) \le -\eta \left| s(\lambda,t) \right| \quad (16)$$

where η is a positive constant that makes the system trajectories meet the sliding surface in a finite time.

In these sliding surface designs the derivative of the surface is determined by:

$$s'(\lambda,t) = -k_1\lambda_e - \lambda'_d + (a\lambda + b) + cu(t) + D \quad (17)$$

After substituting (17) into (16) we obtain:

$$\mathrm{sign}(s(\lambda,t))[-k_1\lambda_e - \lambda'_d + (a\lambda + b) + cu(\mathrm{t}) + D] \le -\eta \quad (18)$$

with:

$$\mathrm{sign}(s(\lambda,t)) = \begin{cases} -1 & if \quad s < 0 \\ 0 & if \quad s = 0 \\ 1 & if \quad s > 0 \end{cases}$$

The command law or Control of braking torque (T_b) guarantees that the trajectory of the system is coming at the desired sliding surface. In this specified sliding surface the equivalent control is decided from the condition s =0 separating the first sliding surface and the equivalent control brake torque T_b is obtained:

$$U = \frac{1}{c}[-(a\lambda + b) + k_1\lambda_e + \lambda'_d - D^u \mathrm{sign}(s(\lambda,t))] \quad (19)$$

where D^u is a positive constant that represents the gain of discontinuous control.

The sliding mode control law is given by:

$$U = U_e + U_{ht} \quad (20)$$

where U_e is the equivalent command and U_{ht} the discontinuous command:

$$U_e = \frac{1}{c}\left[-(a\lambda + b) + k_1\lambda_e + \lambda'_d\right] \quad (21)$$

$$U_{ht} = c^{-1}\left[-D^u \mathrm{sign}(s(\lambda,t))\right] \quad (22)$$

V. FUZZY SLIDING MODE CONTROL

SMC is a nonlinear control technique. Intelligence can be added to this controller by combining FL to the conventional SMC. The reactions comprising of input control (brake torque) and slip ratio tracking error, are undesirable and full of chattering. In other words, when the vehicle is stopped, elevated oscillation is observed in control signals that causes deterioration of elements in the braking system. FL is a comprehension based system which is very much useful in systems whose models are not developed fully or precisely or the information about the system is uncertain. Figure 3 shows the principals of FSMC controller for ABS.

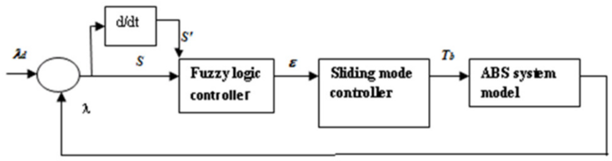

Fig. 3. Close loop of the FSMC controller for the ABS system.

A. Description of the Fuzzy Adaptive System

Fuzzy control is the proposed approach to overcome the problem. It is developed with two inputs, sliding surface s and derivative sliding surface s', and the output is the error ε. Triangular and Gaussian membership functions are used as input and output for de-fuzzification (Figure 4).

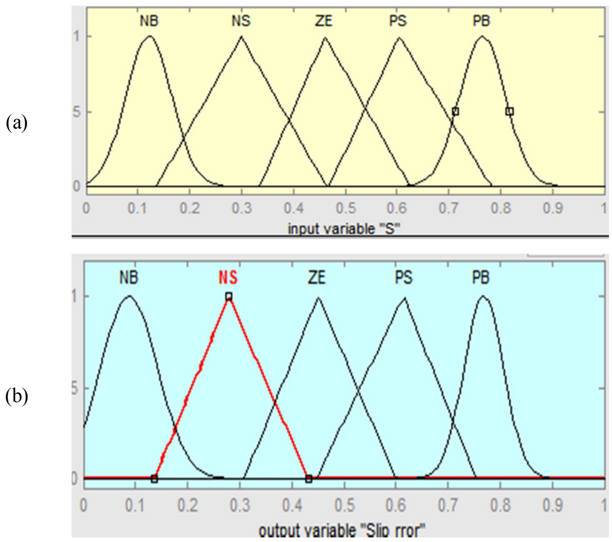

Fig. 4. The membership functions of (a) input and (b) output

The inputs and outputs are all divided into five fuzzy subsets:[NB, NS, ZE, PB, PS] (meaning negative big, negative small, zero, positive small, and positive big respectively). The fuzzy rules are listed in Table I.

TABLE I. RULES OF THE FUZZY LOGIC CONTROLLER

ε	s					
		NB	NS	ZE	PS	PB
$\dot{S}$	NB	NB	NB	NB	NB	ZE
	NS	NB	NS	NS	ZE	PB
	ZE	NB	NS	ZE	PS	PB
	PS	NB	ZE	PS	PS	PB
	PB	ZE	PS	PB	PB	PB

B. Implementation of the Order

Chattering phenomena is an undesirable effect of discontinuous control commands during sliding mode control. In one of the solutions in order to reduce the chattering phenomena, the sign function $D^u\text{sign}(s)$ is replaced by the saturation function in the control input of the first sliding surface:

$$U_f = K_f \text{sat}\left(\frac{s}{\phi}\right) \quad (23)$$

where $\text{sat}\left(\frac{s}{\Phi}\right)$ is a saturation function that is defined as:

$$\text{sat}\left(\frac{s}{\phi}\right) = \begin{cases} \dfrac{S}{\phi} & if \left|\dfrac{S}{\phi}\right| \le 1 \\ \text{sign}\left(\dfrac{S}{\phi}\right) & if \left|\dfrac{S}{\phi}\right| \ge 1 \end{cases} \quad (24)$$

where Φ *is* a positive constant. In this case, we can only ensure convergence tracking error in a neighborhood around zero. It can be concluded that this particular FSMC works as a boundary-layer of the switching surface.

$$u_{FSMC} = u_{eq} - K_f \text{sat}\left(\frac{s}{\Phi}\right) \quad (25)$$

VI. RESULTS AND DISCUSSION

The ABS system parameters used in this study are: m_v=370Kg, J=1.13Kgm^2, R_ω=0.33M, g=9.8m/s^2, λ_d=0.2, *Vv0=70*Km/h, for $t\in$ [0, 12]. Simulations were conducted for various street conditions. Matlab/Simulink is used for the simulations to assess the performance of proposed controller. The Simulink model of the ABS system with the FSMC controller is shown in Figure 5.

A. Results of the SMC Controller

Using (14) we get:

$$\lambda_e'(t) + k_1\lambda_e(t) = 0$$

The model selected reference is:

$$\lambda_d'(t) = -10\lambda_d(t) + 10\lambda(t)$$

In the first case, a wet road (μ=0.25) was chosen and the control law for simple conventional SMC had the sign function $u=D^u\text{sign}(s)$ with k_l=125 and D^u=60. Figure 6 presents the vehicle speed and wheel when the brake force is applied. The change of road surface obviously influences the stopping distance and effects wheel slip but the SMC has more robustness under the changes of various road conditions.

Figure 7 shows the longitudinal slip ratio. We can see the tracking ability with enough response time (0.3s). It can be seen from the zoomed part of Figure 8, that there is a rapid changeover between the maximum and minimum values of braking torque to maintain the wheel slip at the set point. This is called the chattering. The simulation results illustrate that the SMC can achieve satisfactory control performance for wet road, but the result using a conventional sliding mode controller shows chattering in all the response results. The oscillation in these time responses tends to increase when the vehicle tends to stop. This phenomenon is highly undesirable as it may damage the system.

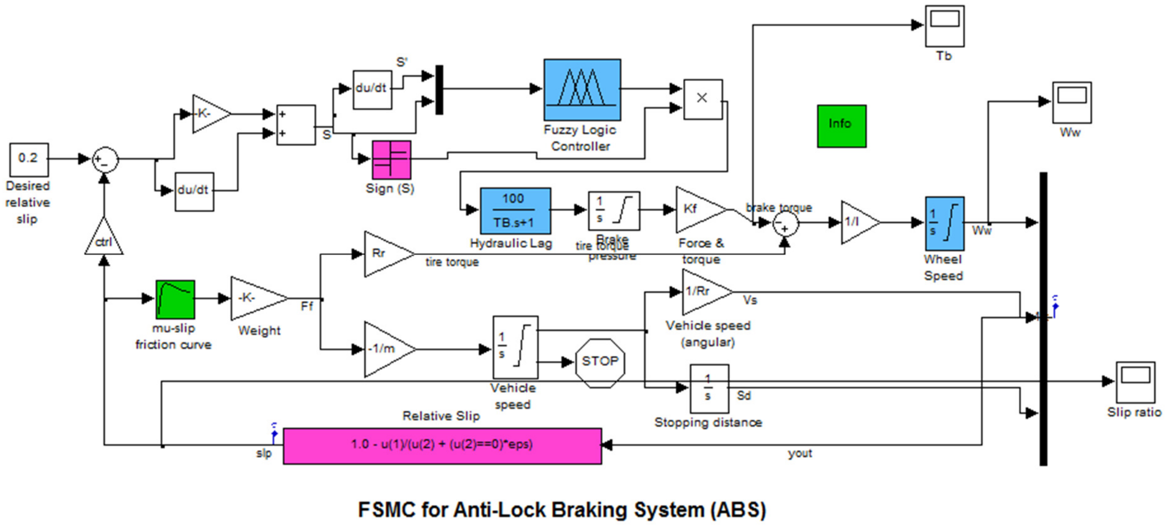

Fig. 5. Simulink FSMC controller for the ABS system model.

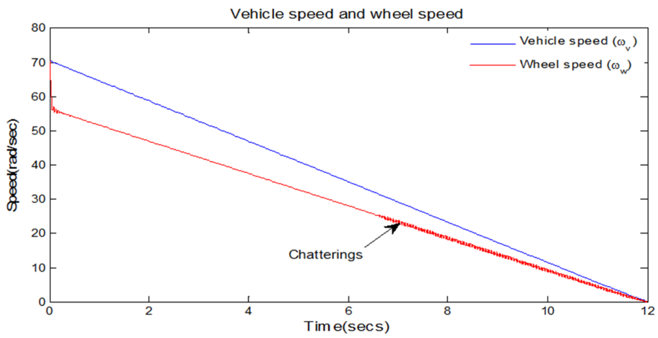

Fig. 6. Vehicle and wheel speeds for ABS system with SMC for μ=0.25

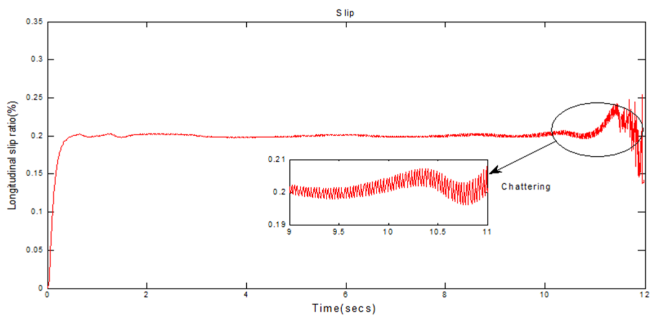

Fig. 7. Longitudinal slip ratio for ABS system with SMC for μ=0.25

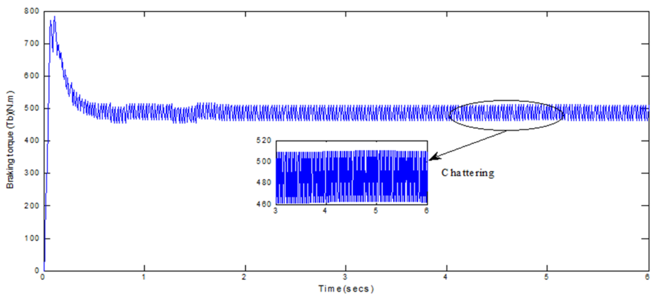

Fig. 8. Braking torque (T_b) for ABS system with SMC for μ=0.25

Table II summarizes the performance comparison between FSMC and PI controller in terms of step response of slip rate which is maintained at a desired value. It can be seen that the proposed FSMC presents the optimum performance. Figure 9 shows the distended view of the step response of slip ratio with FSMC and PI.

TABLE II. PERFORMANCE COMPARISON

	PI	FSMC
Rise time	0.7s	0.25s
Peak repose	0.3	0.2
Overshoot	50%	0%

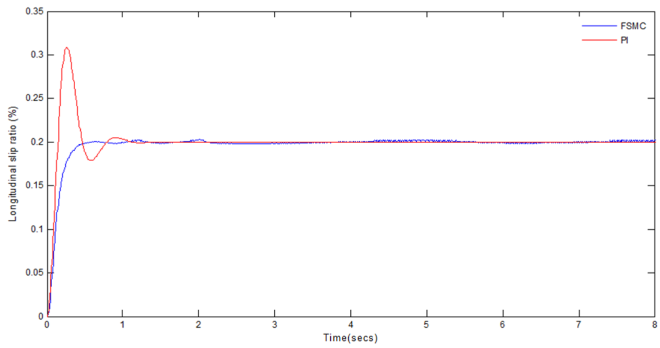

Fig. 9. Step response of slip rate with FSMC and PI controllers.

VII. CONCLUSION

In this study, a robust controller, based on the fuzzy sliding mode approach has been proposed to control the wheel slip ratio. The FSMC control strategy was able to eliminate the chattering problem with elevated tracking precision and to improve the performance of the wheel slip control. The presented simulation results show that the FSMC converges to the desired value for various road conditions.

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