Journal of Engg. Research **Vol. 4 No. (2) June 2016** pp. 132-150

نظام ضبابي للتحكم في انزلاق العجلات في نظام المكابح الانزلاقي

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الخلاصة

أصبحت مزايا السلامة مثل انظمة المكابح المانعة للانزلاق سمة أساسية في المركبات على الطرق الوعرة الآن. تم تصميم تلك المكابح لغرض الحفاظ على انزلاق العجلات أثناء الفرملة المفاجئة لضمان سهولة توجيه السيارة وعدم الانزلاق. يوجد عوامل غير مؤكدة مثل نوع سطح الطريق، وضغط الهواء في الإطارات، وكتلة السيارة، وما إلى ذلك، تتسبب في انزلاق العجلات باستمرار. وبالتالي فإن السيطرة على انزلاق العجلات يبقى مهمة صعبة دائما. هذا الوضع يؤدي إلى الحاجة إلى تصميم وحدة تحكم والتي سوف تكون قادرة على التعامل مع هذه الشكوك. واحدة من وحدات التحكم التي يمكن التعامل معها بشكل فعال مع عشوائية النموذج والمتغيرات هي التحكم بنظام الانزلاق. نظام المنطق الضبابي هو نظام قائم على المعرفة وهو مفيد جدا في التعامل مع الأنظمة التي لم تتطور بشكل كامل أو بشكل دقيق أو المعلومات حول نظام غير مؤكد النموذج. في هذه الورقة، نقترح نظام ضبابي تحكم الانزلاق عن طريق الجمع بين المنطق الضبابي مع نظام التحكم الانزلاقي. ويتم تقييم أداء النظام المقترح من خلال المحاكاة الرقمية لمختلف الظروف الأولية من سرعة السيارة وظروف سطح الطريق.

Adaptive fuzzy sliding mode controller for wheel slip control in antilock braking system

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ABSTRACT

Safety features like antilock braking systems (ABSs) have become an essential feature of road vehicles now a days. ABSs are designed for the purpose of maintaining the wheel slip in the required value during sudden braking to ensure the vehicle steerablility and non-skidding. Uncertain factors such as type of road surface, tyre pressure, vehicle mass, etc., cause the required wheel slip to be continuously changing. Hence, controlling the wheel slip remains a difficult task always. This situation leads to a need for design of a controller, which will be capable of dealing with these uncertainties. One of the controllers which can effectively deal with the parametric and modeling uncertainties is sliding mode controller (SMC). Fuzzy logic is a knowledge based system which is very much useful in handling the systems whose models are not developed fully or accurately or information about the system is uncertain. In this paper, a robust and adaptive Fuzzy sliding mode controller (FSMC) is proposed for a laboratory ABS model by combining fuzzy logic with sliding mode controller. The performance of the proposed FSMC is assessed through digital simulations for various initial conditions of vehicle velocity and road surface conditions.

Keywords: Adaptive control; antilock braking system; fuzzy logic control; fuzzy sliding mode control; sliding mode control.

NOMENCLATURE

x_1, x_2 : Angular velocity of upper & lower wheels, rad/s

M_1 : Braking torque, Nm

r_1, r_2 : Radius of upper & lower wheels, m

J_1, J_2 : Moment of inertia of upper & lower wheels, Kgm^2

d_1, d_2 : Viscous friction coefficients of upper & lower wheels, Kgm^2/s

F_n : Total force generated by upper wheel on lower wheel, N

$\mu(\lambda)$: Friction coefficient between wheels

λ : Slip – relative difference of wheel velocities

M_{10}, M_{20} : Static friction of upper & lower wheels, Nm

M_g : Gravitational and shock absorber torques acting on the balance lever, Nm

L : Distance between the contact point of the wheels and the rotational axis of the balance lever, m

φ : angle between the normal in the contact point and line L, °

INTRODUCTION

The primary objective of antilock braking system (ABS) is to ensure the steerability of vehicle when the brake is applied suddenly, while it is on the move. ABS control is influenced by nonlinear behavior of the dynamics of brake and other factors like tyre pressure, mass of vehicle, type of road surface, etc. Thus, the controller for ABS needs to be efficient to handle these uncertainties. The ABS controller aims to ensure that the best adhesion of the wheel is maintained with the road surface by controlling the road adhesion coefficient (μ).

The road adhesion coefficient (μ) is a nonlinear function of the relative difference between the wheel and vehicle velocities, which is called as wheel slip (λ). The expression for wheel slip is given by;

$$\lambda = 1 - \frac{R\omega}{V} \tag{1}$$

Where V is vehicle velocity, ω is angular velocity of wheel and R is the radius of wheel. When sudden brake is applied, the wheel comes to rest abruptly whereas the vehicle remains on the move. At this condition, the value of slip becomes unity. This condition leads to skidding of wheel, and thereby loss of steerability. The relationship curves between μ and λ are different for different types of road surfaces. By regulating the wheel slip in optimum level, the ABS controllers maintain the road adhesion coefficient at its maximum value (Topalov *et al.,* 2011).

A wheel slip regulating controller using neuro-fuzzy adaptive control method was proposed in Topalov *et al.* (2011). This controller has a conventional controller with a neuro-fuzzy feedback controller in the feedback. An input-output feedback linearization approach is used in John & Pedro (2013) for a non-linear control design for ABS. An integral feedback was used to enhance the robustness of the proposed controller. A nonlinear state feedback based controller to make the wheel slip converged in to a desired equilibrium state was proposed in Jing *et al.* (2011). Convergence of this robust switched control scheme was assessed by Lyapunov theory in Filippov framework. An ABS control scheme assisted with an active suspension system to track the slip rate was proposed using an integral nested sliding mode controller in Sánchez-Torres *et al.* (2011). In this, a sliding mode controller is used for the active suspension system. In Poursamad (2009), a hybrid controller is given, which is based on feedback linearization with two feed forward neural networks to learn the nonlinearities of ABS. The control law is derived using steepest descent gradient approach and back propagation algorithm. Using the Grey system theory for wheel slip prediction, a grey sliding mode controller was proposed in Oniz *et al.* (2009) and Oniz (2007). The sliding mode controller used is a first order one. In Radac *et al.* (2008), a low cost Fuzzy PI control solution for Inteco ABS model through identification, modeling and knowledge from experiments. A nonlinear sliding-mode-type controller was designed for an electromagnetic brake-by-wire system in Anwar & Zheng (2007) for slip regulation during braking. This controller adjusts the brake torque generated by a supervisory controller based on the brake applied to the pedal.

A sliding mode controller (SMC) was proposed for ABS in Harifi *et al.* (2005). Integral switching surface is used for reducing the chattering due to SMC. A self-learning fuzzy sliding mode controller was proposed for ABS without relying on vehicle-braking model in Lin & Hsu (2003). A gain scheduling approach using LQR approach for designing gain matrices for various road conditions was presented (Johansen *et al.,* 2003). An electrically controlled ABS using electrorheological valves was first presented and then a sliding mode controller was developed for the control of wheel slip and yaw rate in Choi *et al.* (2002). Another sliding mode controller based on nonlinear observer was presented in Unsal & Kachroo, 1999) to control the vehicle traction. A controller presented in Mauer (1995) combines a fuzzy logic element and a decision logic network, which can identify the current road conditions, detect wheel blockage and takes action to avoid the wheel blockage. A fuzzy sliding mode controller combined with a neural network was presented (Kueon & Bedi, 1995). This controller provides a good stopping ability of the vehicle without sacrificing stability and steerability. Uncertainties in parameters such as friction coefficient, road elevation, wind gust and absolute speed of vehicle are considered. In Layne *et al.* (1993), a fuzzy model reference learning control technique is proposed, which utilizes a learning mechanism to observe the plant outputs and adjusts the rules in fuzzy controller. This system works as a reference model, which characterizes the desired behavior. Recently, a firefly algorithm tuned fuzzy inference system has been proposed by Boopathi & Abudhahir (2015) for set-point weighted PID Controller to control the ABS wheel slip. This controller, with an objective of minimizing the integral square error, performs well at various initial conditions and external disturbances.

It is seen from the literature that SMCs are very widely used for ABS control, because they are insensitive to parameter variations and capable of rejecting the disturbances completely (Young *et al.,* 1999). Also, it is a well known fact that the fuzzy logics are highly capable of understanding complex systems and systems whose models cannot be easily developed mathematically (Passino & Yurkovich, 1998). Since the ABS control system is highly uncertain due to varying parameters such as vehicle mass, tyre pressure, road surfaces, etc., a fuzzy logic can be employed with the controller to deal with these uncertainties. Hence, a fuzzy sliding mode controller for the quarter car ABS model is proposed in this paper. The SMC maintains the wheel slip at the desired value very closely, in spite of the disturbances. The fuzzy logic is employed to improve the performance of SMC.

The organization of this paper is as follows; Section 2 presents the description of ABS model. The proposed FSMC control scheme for ABS is given in section 3. In section 4, the simulation results and discussions are presented with the conclusion in section 5.

DESCRIPTION OF INTECO ABS MODEL

The model of ABS by Inteco Ltd., is widely used by the researchers, hence it is considered in this work as well (User's manual, 2006). This model has two rolling wheels, as shown in Figure 1. The lower wheel animates the relative road motion and the upper wheel stays in a rolling contact with the lower wheel. The wheel mounted to the balance lever is equipped in a tire. The wheel imitating road can be covered by different materials to animate different surfaces of the road. The car velocity can be determined by multiplying the angular velocity of the lower wheel and the radius of this wheel. However, the angular velocity of the wheel of vehicle is simply the angular velocity of the upper wheel. The longitudinal dynamics of the vehicle are only considered and the lateral and vertical motions are neglected. Also, interaction between the four wheels of the vehicle is assumed to be zero and hence it is called as quarter car model.

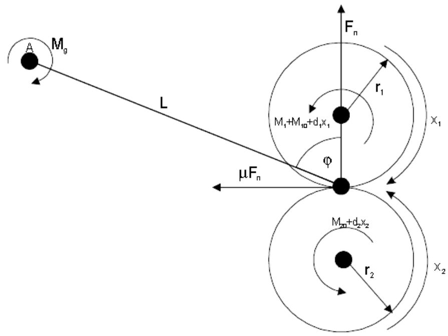

Fig. 1. Schematic diagram of Inteco ABS quarter car model

The equations of motion of wheels can be written using Newton's second law as;

$$\begin{aligned} J_1 \dot{x}_1 &= F_n r_1 \mu(\lambda) - d_1 x_1 - M_{10} - M_1 \\ J_2 \dot{x}_2 &= -F_n r_2 \mu(\lambda) - d_2 x_2 - M_{20} \end{aligned} \tag{2}$$

The road friction force (F_t) by Coulomb Law can be written as;

$$F_t = \mu(\lambda) F_n \tag{3}$$

The normal force F_n is given by;

$$F_n = \frac{d_1 x_1 + M_{10} + T_B + M_g}{L(\sin\phi - \mu(\lambda)\cos\phi)} \tag{4}$$

When the vehicle is driven in normal conditions, the angular velocity of wheel matches with the velocity of the vehicle. When the driver applies sudden brake, the wheel velocity reduces abruptly and becomes lesser than the car velocity. The relative velocity difference of wheels, called wheel slip (μ) can be written mathematically as;

$$\lambda = \frac{r_2 x_2 - r_1 x_1}{r_2 x_2} \tag{5}$$

The dependence of wheel slip (μ) on road adhesion coefficient (λ) can be obtained through experiments. One such μ-λ curve for various road surfaces is shown in Figure 2.

These μ-λ curves can be mathematically written as; (User's manual, 2006).

$$\mu(\lambda) = \frac{w_4 \lambda^p}{a + \lambda^p} + w_3 \lambda^3 + w_2 \lambda^2 + w_1 \lambda \tag{6}$$

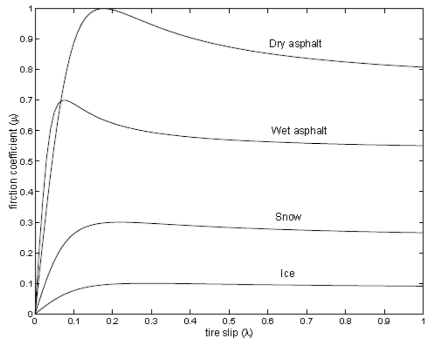

Fig. 2. μ-λ curve for various road surfaces

Equations (2) to (6) are realized in MATLAB -SIMULINK to make the simulation model of ABS. Various parameters of this model are taken as given in the user's manual of Inteco ABS model (User's manual, 2006). The model takes the applied braking force as input. The vehicle and wheel velocities, slip and stopping distance are the outputs of the model.

SLIDING MODE CONTROL (SMC)

Sliding mode controllers (SMCs) can be used for control of uncertain systems or systems whose modeling information is poorly known. A SMC has to be designed in such a way that first it guarantees the reachability of the sliding surface and then the stability of the sliding motion on the sliding manifold in spite of disturbances or parameter variations in process.

Let a non-linear system be represented as;

$$\lambda^{(n)} = g(\lambda,t) + u(t) + d \tag{7}$$

where, λ is the state vector, d is the disturbance, u is the input and g is a nonlinear time varying function whose estimate is $\hat{g}(\lambda,t)$.

A control law is developed to maintain the actual wheel slip (λ) at the set-point (λ_{sp}) by nullifying the error (e) which is the difference between λ and λ_{sp}. The time varying surface in which this error is zero is the sliding surface. It can be mathematically written as;

$$s(\lambda;t) = \left(\frac{d}{dt} + \xi\right)^{n-1} e\,; \tag{8}$$

where, ξ is a positive constant.

For a second order SMC, putting n as 2 yields,

$$s(\lambda;t) = \frac{de}{dt} + \xi e \tag{9}$$

Consider a Lyapunov function $V(s) = \frac{1}{2}s^2$.

The condition for stability can be defined as (Utkin, 1997).

$$\frac{dV(s)}{dt} = s\frac{ds}{dt} \leq -\eta|s| \; ; \eta > 0 \tag{10}$$

Hence, the condition for reaching the sliding surface in finite time is

$$\frac{ds}{dt}\operatorname{sgn}(s) \leq -\eta \tag{11}$$

From equation (9) we can have,

$$\frac{ds}{dt} = \frac{d^2e}{dt^2} + \xi\frac{de}{dt} = \xi\frac{de}{dt} + \frac{d^2\lambda}{dt^2} - \frac{d^2\lambda_{sp}}{dt^2} \tag{12}$$

Therefore, $s\frac{ds}{dt} = s\left(\frac{d^2e}{dt^2} + \xi\frac{de}{dt}\right)$

$$= s\left(\xi\frac{de}{dt} + g(\lambda,t) + u(t) + d - \frac{d^2\lambda_{sp}}{dt^2}\right) \leq -\eta|s| \tag{13}$$

Thus, the control law can be written as;

$$u = -\left(\hat{g} + \xi\frac{de}{dt} + K(\lambda,t)\operatorname{sgn}(s)\right), K(\lambda,t) > 0 \tag{14}$$

Where, $\operatorname{sgn}(s) = \begin{cases} -1 & if\ s < 0 \\ 0 & if\ s = 0 \\ 1 & if\ s > 0 \end{cases}$

FUZZY SLIDING MODE CONTROL (FSMC)

The value of gain (K) in control law given in equation (14) needs to be applied by large amount to move the system to the sliding surface and vice versa. Hence, the fuzzy logic component has to be developed in such a way that when $|s|$ increases, the absolute value of the control signal $|u|$ is also to be increased (Antić *et al.,* 2010).

The fuzzy logic is developed with one input (s) obtained from error and rate of change of error and one output (braking force). A mamdani type fuzzy inference system with triangular membership functions are defined over the range of input and output variable values, which are represented in seven linguistic variables as given in

Table 1. The most widely used Centroid method is employed for defuzzification. The defuzzified output signal of fuzzy logic (K_f) can be mathematically represented as,

$$K_f = \frac{\int \mu_{\underset{\sim}{A}}(z)\, z\, dz}{\int \mu_{\underset{\sim}{A}}(z)\, dz} \tag{16}$$

Where, $\mu_{\underset{\sim}{A}}(z)$ is the degree of membership of element 'z' in the Fuzzy set '$\underset{\sim}{A}$'.

Table 1. Fuzzy linguistic variables for FSMC

NB	Negative Big
NM	Negative Medium
NS	Negative Small
ZE	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big

The developed rule base is presented in Table 2.

Table 2. Fuzzy rule base for FSMC

If 's' is	Then 'u' is
NB	PB
NM	PM
NS	PS
ZE	ZE
PS	NS
PM	NM
PB	NB

The FSMC performs the control action by moving the system towards the sliding surface and maintaining on the sliding surface continuously. The relationship between sliding mode hyperplane and fuzzy hyperplane is depicted in Figure 3. This shows the way how the system states at the sliding surface are taken as input to the fuzzy logic and thereby the fuzzy logic generates the gain 'K_f' based on the rules given in Table 2.

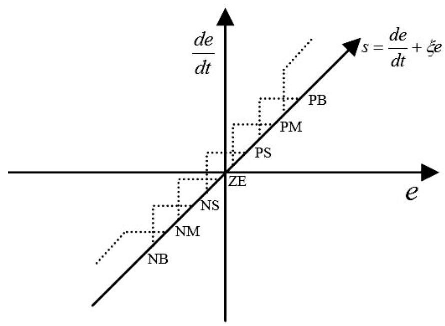

Fig. 3. Mapping between sliding mode and fuzzy hyperplanes

The scheme of proposed fuzzy-sliding mode controller for ABS slip control is shown in Figure 4.

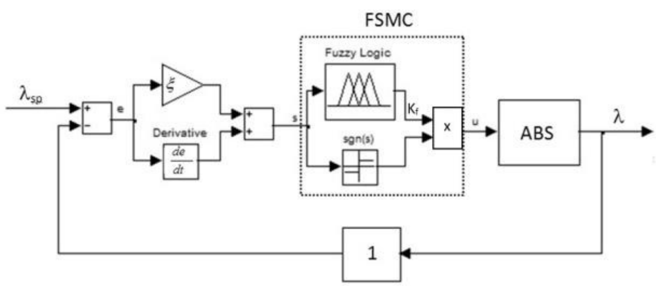

Fig. 4. Fuzzy sliding mode control scheme for ABS Slip control

The actual wheel velocity is measured and from which the wheel slip is evaluated. The measured wheel slip (λ) is compared with the set-point (λ_{sp}) and the resulting error (e) and its derivative are used to form the sliding surface (s). Based on the value of 's', the fuzzy logic produces a gain (K_f) as given in Table 2. The output of fuzzy logic multiplied with *sgn(s)* is the controller's output, which is given as brake input (u) to the ABS.

SIMULATION RESULTS & DISCUSSIONS

MATLAB®-SIMULINK® is used for the simulations to assess the performance of proposed controller. As every system in real life is experiencing the noise, this is imitated by adding a band-limited white noise at slip and velocity measurements. The noise power in slip measurement is selected as 10^{-5} and for the speed measurements it is selected as 0.2 (Oniz, 2007; Oniz *et al.*, 2009).

A. Sliding mode controller (SMC) for ABS

The set-point for wheel slip is set as 0.3. The control law for simple SMC is $u = K\,\mathrm{sgn}(s)$. The values of ξ and K are assigned as 100 and 2 respectively. The brake is applied when the vehicle is moving at the initial velocity of 30 km/h. Figure 5 shows the velocity of vehicle and wheel, when the brake force is applied.

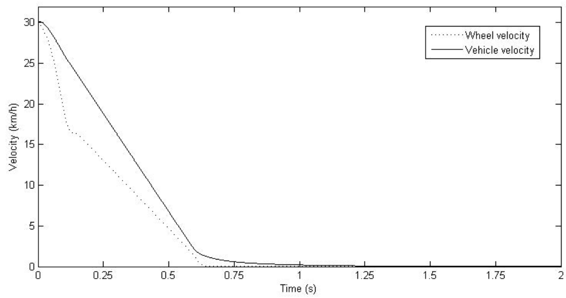

Fig. 5. Vehicle and wheel velocities during braking with SMC

Figure 6 shows how the actual wheel slip is maintained at the set-point by the controller.

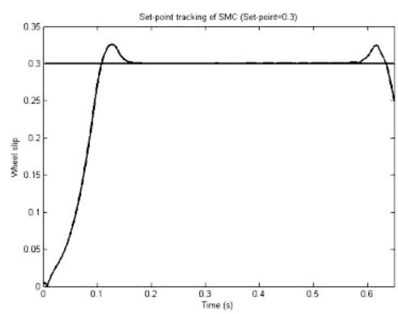

Fig. 6. Set-point tracking of SMC

It can be seen from Figure 7 that there is a rapid changeover between maximum and minimum values of braking torque to maintain the wheel slip at the set-point. This is called as ‘chattering’. Chattering lead to frequent opening and closure of the final control element, which will adversely affect its life.

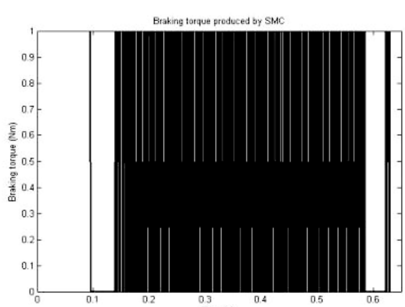

Fig. 7. Brake torque produced by SMC

The SMC stops the vehicle in 0.6 seconds at the distance of 2.07 meters.

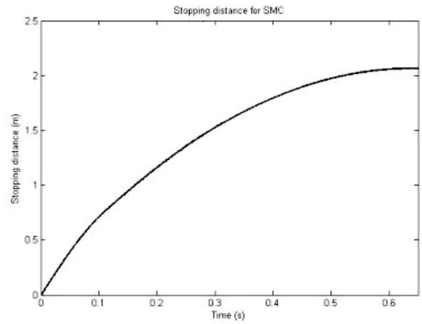

Fig. 8. Stopping distance of SMC

To overcome chattering problem, a Quasi-Relay (QR) (Antić *et al.,* 2010) has been used with the SMC as $u = K|e|\,\mathrm{sgn}(s)$. Figures 9 and 10 show the velocity profile and set-point tracking of SMC+QR respectively. It is evident from Figure 11 that the chattering in brake torque has been reduced to a very good extent. However, there is an overshoot in both SMC and SMC+QR responses, which is not admissible in the practical case. Also, there is no change in the stopping time and stopping distance.

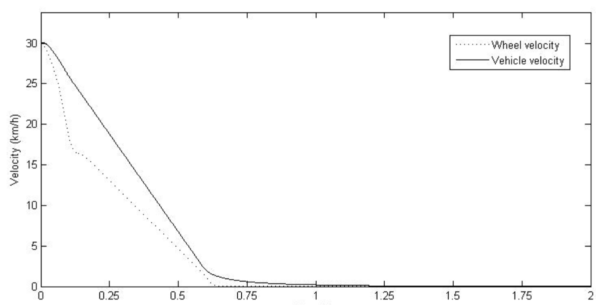

Fig. 9. Vehicle and wheel velocities during braking with SMC+QR

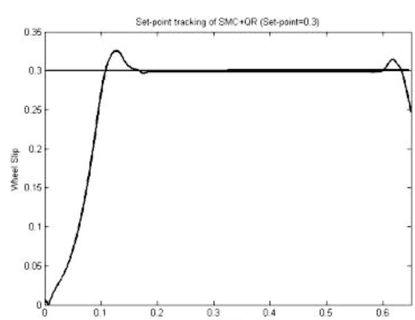

Fig. 10. Set-point tracking of SMC+QR

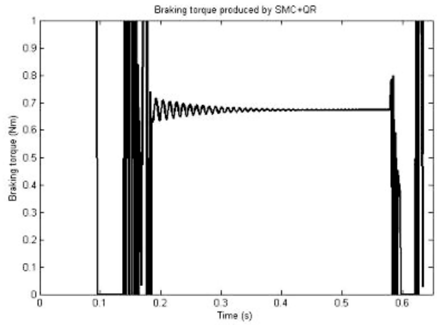

Fig. 11. Brake torque produced by SMC+QR

B. Fuzzy sliding mode controller (FSMC)

1) FSMC with set point = 0.3 and initial velocity = 30 km/h:

By combining the fuzzy logic and SMC, the overshoot present in wheel slip could be reduced further with a reduction in chattering as well. The proposed FSMC control law can be written as $u = K_f(s)|e|\,\mathrm{sgn}(s)$. The initial velocity of the vehicle is kept as 30 km/h as in the previous case. The results of this simulation are shown in Figures 12 to 14. It is found that the FSMC has reduced the overshoot in the slip response to a very good extent.

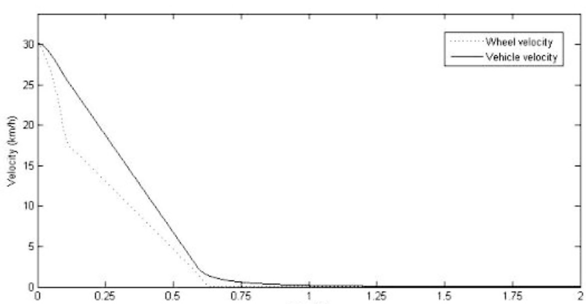

Fig. 12. Velocity profile

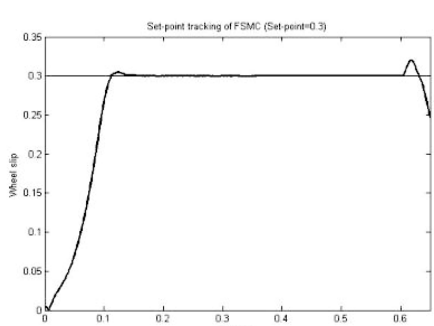

Fig. 13. Slip response of proposed FSMC

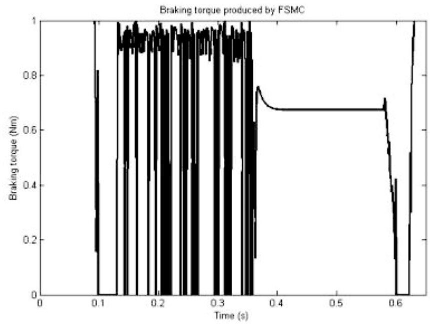

Fig. 14. Brake input for proposed FSMC

The responses of SMC, SMC+QR and FSMC are shown together in Figure 15 for comparison. The same response has been zoomed and shown in Figure 16, which shows that the proposed FSMC maintains the wheel slip very much close to the set-point than the SMC and SMC+QR.

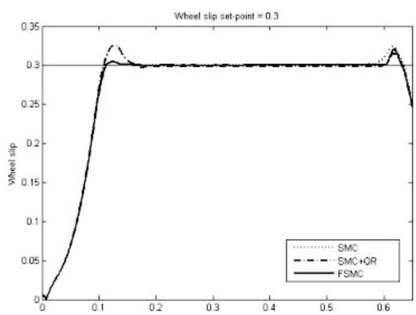

Fig. 15. Slip responses of controllers (Set-point = 0.3)

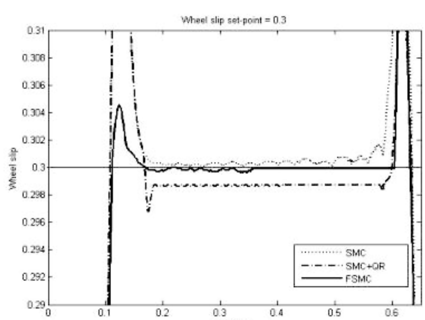

Fig. 16. Slip responses of controllers - Zoomed

2) FSMC with set point = 0.3 and initial velocity = 60 km/h:

Further, the simulation is performed by applying the brake when the initial velocity is 60 km/h. The results are shown in Figures 17-19.

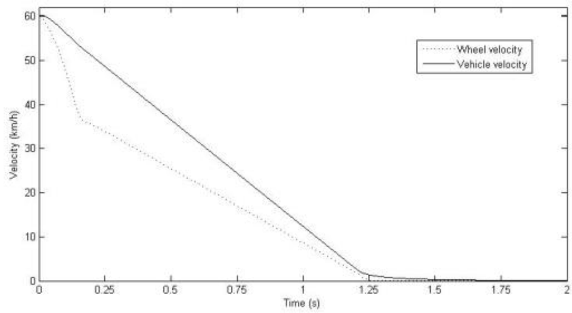

Fig. 17. Velocity profile

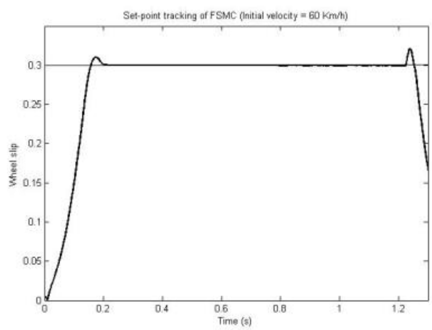

Fig. 18. Slip response of FSMC

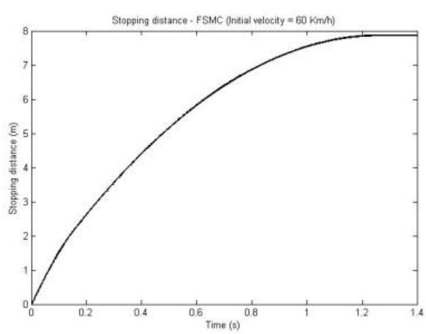

Fig. 19. Stopping distance of FSMC

These figures clearly show that the proposed FSMC is performing better for higher initial velocity also by smoothly stopping the vehicle at the distance of 7.87 meters in 1.2 seconds.

3) FSMC for changing road conditions with initial velocity = 60 km/h:

The required value of wheel slip needs to be increased, when the vehicle moves from a wet road to the dry road surface so as to maintain the vehicle stability and steerability. In the next simulation, it is assumed that the vehicle moves out from a wet ice road surface and enters in to a dry asphalt road surface. The wetness of the road surface gradually reduces along the road from wet ice to dry asphalt road. This change in road condition needs a continuously increasing set-point wheel slip to ensure the vehicle steerability. The responses of proposed FSMC for this scenario are presented in Figures 20-22. The initial vehicle velocity is now set as 60 kmph.

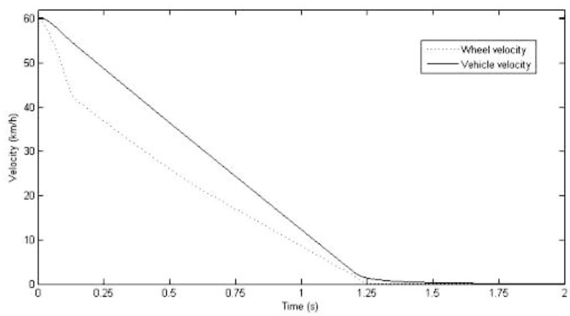

Fig. 20. Velocity profile of FSMC for change in road conditions

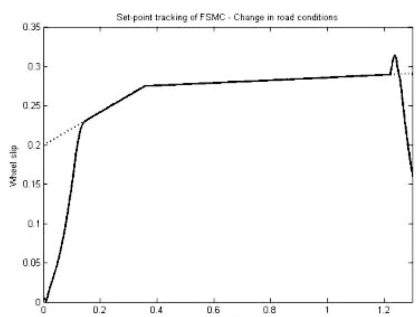

Fig. 21. Set-point tracking of FSMC for change in road conditions

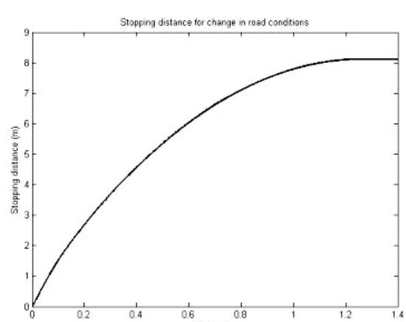

Fig. 22. Stopping distance of FSMC for change in road conditions

The Figures 20 to 22 show that the FSMC stops the vehicle smoothly without any overshoot in the slip response. The stopping distance is found to be 8.12 meters.

It can be seen in all set-point tracking responses (Figures 6, 10, 13, 15, 18 and 21) that there is a sudden hike in wheel slip just before the vehicle is stopped. It is due to the fact that the vehicle stops only after the wheel comes to rest. Hence, as seen in Equation (5), the value of wheel slip increases for a short time till the vehicle also stops.

Comparison of performance with existing control methods

A comparison of set-point tracking capability has been made between the proposed FSMC and other controllers found in literature (Oniz, 2007; Boopathi & Abudhahir, 2015) in terms of the error in wheel slip, which is maintained at a desired value. Table 3 and Figure 23 summarize this comparison. The proposed FSMC exhibits the smallest amount of error while tracking the set point amongst all other controllers. Also, it is clearly evidenced that the proposed FSMC is more adaptive for disturbances and changes in set point.

Table 3. Set point tracking of controllers

	Controller	Error in Slip (%)
Oniz, 2007	SMC	-4.5
	GSMC	-2
Boopathi & Abudhahir, 2015	SPWPID	0.4
	GAFSPWPID	0.35
	FAFSPWPID	0.35
Proposed Controllers	SMC	0.2
	SMC+QR	0.35
	FSMC	0.1

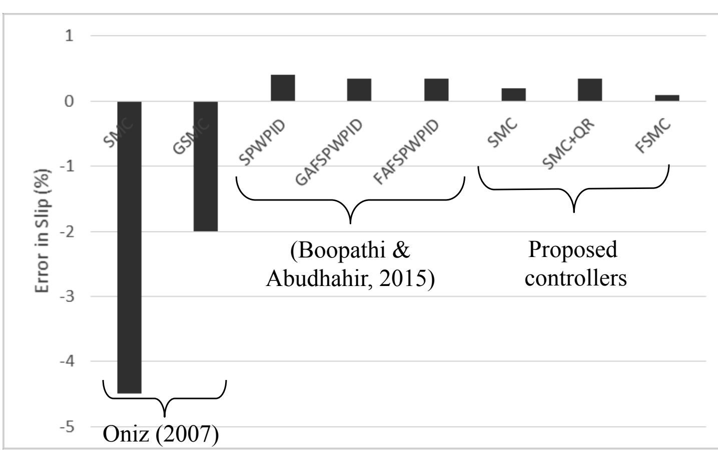

Fig. 23. Error in slip for various controllers

CONCLUSION

A fuzzy sliding mode control (FSMC) strategy has been proposed for wheel slip control of laboratory antilock braking system. The proposed second order SMC combined with the fuzzy logic maintains the wheel slip in the set-point accurately, inspite of the presence of noise in slip and velocity measurements. The stability of proposed FSMC is ensured through Lyapunov's stability theory. The performance of proposed FSMC is assessed through simulations with various initial conditions. The proposed control strategy is found very effective for various initial conditions and changes in road conditions as well. Combining fuzzy logic component with the SMC makes it more adaptive and robust to disturbances introduced in measurements and system parameters. Smooth stopping of vehicle and reasonable stopping distances are achieved using the proposed FSMC.

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Submitted: 18/2/2015
Revised: 28/12/2015
Accepted: 6/2/2016