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Design of Grey-Verhulst Sliding Mode Controller for Antilock Braking System

A. Manivanna Boopathi* and A. Abudhahir

Abstract: In this paper, an adaptive controller called Grey-Verhulst Sliding Mode Controller (GVSMC) is proposed for the laboratory Antilock Braking System (ABS). The developed Grey-Verhulst Model (GVM) does a better prediction of wheel slip than a simple Grey Model. The first order Sliding Mode Controller (SMC) maintains the wheel slip at the desired value. By combining the GVM and SMC, the resulting GVSMC controls the wheel slip at the desired optimum value at which the vehicle control, non-skidding and steerability are ensured during sudden braking. The proposed controller also reduces the stopping distance considerably. Simulation results show that the performance of the proposed GVSMC is better than the simple SMC and Grey SMC reported in literature earlier. Change in road conditions has also been considered.

Keywords: ABS, Grey model, Grey system theory, Grey-Verhulst model, sliding mode control, slip-control.

1. INTRODUCTION

Antilock Braking System (ABS) is one of the important safety features of road vehicles in present days. It is an electronic system designed to improve vehicle control during braking through monitoring and controlling wheel slip by applying and withdrawing of braking force alternately in spite of the brake pedal being fully pressed. It also reduces the stopping distance on slippery road surfaces by limiting wheel slip and minimizing lockup. Maintaining the wheel slip around an optimum value also improves vehicle stability and control during braking. However, it is a highly challenging task because of the highly nonlinear braking dynamics and uncertainties in parameters such as road conditions, vehicle speed, tire pressure, tire temperature, steering angle, and etc. Also, it is difficult to obtain an accurate model of ABS due to these uncertainties. Hence, it is necessary to develop the controller which will be capable of dealing with these uncertainties.

The primary aim of the controller is to ensure the best adhesion of the wheel to the road surface by controlling the road adhesion coefficient (μ). The road adhesion coefficient (μ) is the coefficient of proportion between the friction forces generated by the wheel on the road surface during the acceleration and braking phases, and the normal load of the vehicle. It is in nonlinear dependence with the wheel slip (λ), which is the relative speed difference between the wheel and vehicle.

In the early stages of research in ABS control, a feedback compensator was proposed to offer antiskid behavior using describing function analysis [1]. Later, a fuzzy model reference learning control technique for maintaining adequate performance under adverse road conditions was proposed [2]. This controller utilizes a learning mechanism which observes the plant outputs and adjusts the rules in fuzzy controller so that the whole system works like a reference model which characterizes the desired behavior. In [3], a control algorithm was proposed to maintain the friction force between tire and road at maximum value during sudden braking, without knowing the optimal value of slip, which keeps changing. Further, a Fuzzy-Neural Sliding Mode Controller [4] was presented to stop the vehicle sufficiently without compromising its stability and steerability. A fuzzy logic controller given in [5], identifies the current road condition and generates a command braking pressure signal, based on current and past readings of the slip ratio and brake pressure. A nonlinear observer-based design for control of vehicle traction was presented in [6]. An adaptive controller using fuzzy logic and genetic algorithm for the base-braking problem was given in [7], to ensure the braking torque commanded by the driver is fully achieved. A genetic-neural-fuzzy controller in [8] consists of a non-derivative neural optimizer and fuzzy-logic component to compute the optimal wheel slip and the required braking torque to track the optimum wheel slip respectively.

In [9], a robust sliding mode controller is designed first

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and then the direct state feedback is replaced with nonlinear observers to estimate the vehicle velocity from the wheel velocity. A self-learning fuzzy sliding-mode control, independent of a vehicle-braking model was presented in [10]. A hybrid controller was presented in [11], which has an RNN uncertainty observer as a primary controller and a compensator for the difference between the actual and estimated uncertainties. A gain scheduling approach was developed [12] by considering the vehicle speed as a slowly time-varying parameter and designing the gain matrices for various operating conditions using LQR method. A sliding mode controller with integral switching surface to reduce the chattering was presented in [13]. A robust controller combining the fuzzy logic and sliding mode controller was proposed in [14] to maintain the maximum braking force and robust in various road conditions. In [15], a Fuzzy PI controller is proposed for the laboratory Inteco ABS model based on modelling, identification and knowledge from experiments. An alternative sliding-surface design to improve the convergence speed and oscillation damping around the desired slip was proposed for a nonlinear vehicle model in [16]. A method to forecast the wheel slip using grey predictors and control the same using a Sliding mode controller is given in [17–19]. Here, the order of differentiation of SMC is taken as n=1. In [20], a first order sliding mode controller is proposed for the Inteco ABS model to reduce the chattering due to discontinuous function used in the controller. A neuro-fuzzy adaptive control approach was proposed to design a wheel slip regulating controller in [21]. An approach presented in [22] uses a nonlinear state feedback and a switching strategy to assure that the wheel slip converges into the target equilibrium set. A neural network based feedback linearization control method was proposed in [23] which is robust to external disturbances and feasible for various values of slips.

In many of these recent researches, ABS controllers are designed to regulate the wheel slip in optimum level so that the road adhesion coefficient is maintained at its maximum value. In [17–19], a Grey predictor is coupled with SMC to predict wheel slip based on its value at the present instant and few previous instants and control the wheel slip at the desired value. The results show that the wheel slip is maintained around the desired value with a considerable amount of steady state error. This motivated to develop a better controller which can maintain the wheel slip constantly at the desired value without any steady state error irrespective of the amount of disturbances introduced to the system.

In this paper, a Grey-Verhulst Sliding Mode Controller (GVSMC) is proposed for control of wheel slip. The Grey-Verhulst (GV) model is used to predict the future values of wheel velocity based on the velocity at present and few previous instants. The Sliding mode Controller (SMC) ensures that the wheel slip is maintained at the desired optimum value at which the wheel locking can be avoided during braking. Simulations have been performed in MATLAB-SIMULINK, version 7.11.0 (R2010b) and the performance of proposed GVSMC has been compared with GSMC for ABS presented in [17, 18].

This paper is organized as follows: the mathematical model of laboratory ABS is presented in Section 2. Design of SMC is given in Section 3. The descriptions of GM, GVM and GVSMC for ABS are presented in Section 4. The simulation results and discussions are given in Section 5 with the conclusions in Section 6.

2. MATHEMATICAL MODEL OF ABS

To assess the performance of proposed controllers, the simulation model of Inteco laboratory ABS [24] has been used. Its schematic diagram is shown in Fig. 1.

This is also called as Quarter car model, since it is assumed that there is no interaction between the four wheels of the vehicle. This model has two rolling wheels. The lower and upper wheels imitate the relative road motion and the vehicle's tire respectively. The lower wheel can be made to imitate various road surfaces by covering it with different materials. The vehicle velocity is considered as equivalent to the product of angular velocity of the lower wheel and its radius. The angular velocity of the wheel is equivalent to the angular velocity of the upper wheel. While deriving the mathematical model, only the longitudinal dynamics of the vehicle are considered by neglecting the lateral and the vertical motions.

The variables and parameters of Inteco ABS model are listed in Table 1.

The equations of motion of upper and lower wheels are written based on Newton's second law as;

$$\begin{aligned} J_1 \dot{\omega}_1 &= F_n r_1 \mu(\lambda) - d_1 \omega_1 - M_{10} - M_1, \\ J_2 \dot{\omega}_2 &= -F_n r_2 \mu(\lambda) - d_2 \omega_2 - M_{20}. \end{aligned} \tag{1}$$

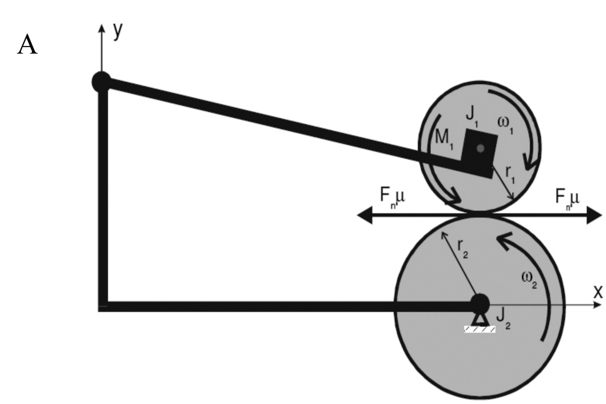

Fig. 1. Schematic diagram of Inteco ABS model.

Table 1. Variables and parameters of Inteco ABS.

ω_1, ω_2	Angular velocity of upper & lower wheels
M_1	Braking torque
r_1, r_2	Radius of upper & lower wheels
J_1, J_2	Moment of inertia of upper & lower wheels
d_1, d_2	Viscous friction coefficients of upper & lower wheels
F_n	Total force generated by upper wheel pressing on lower wheel
$\mu(\lambda)$	Friction coefficient between wheels
λ	Slip
M_{10}, M_{20}	Static friction of upper & lower wheels
M_g	Gravitational and shock absorber torques acting on the balance lever
L	Distance between the contact point of the wheels and the rotational axis of the balance lever
ϕ	Angle between the normal in the contact point and the line L

F_t is the road friction force given by Coulomb Law;

$$F_t = \mu(\lambda)F_n. \quad (2)$$

Sum of torques acting on the point A can be written as;

$$F_n L(\sin\varphi - \mu(\lambda)\cos\varphi) = M_g + M_1 + M_{10} + d_1\omega_1. \quad (3)$$

The normal force F_n can be obtained further as;

$$F_n = \frac{d_1\omega_1 + M_{10} + M_1 + M_g}{L(\sin\phi - \mu(\lambda)\cos\phi)}. \quad (4)$$

During the normal driving conditions the rotational velocity of the wheel remains matched with the forward velocity of the vehicle. During braking, the applied braking force causes the wheel velocity to reduce. Hence the wheel velocity becomes lesser than the vehicle velocity thereby changes the slip (λ). The expression for slip in this case can be written as;

$$\lambda = \frac{r_2\omega_2 - r_1\omega_1}{r_2\omega_2}. \quad (5)$$

Zero slip means that the wheel and vehicle velocities are equal. During sudden braking, the wheels do not rotate while the vehicle tends to move. The value of slip becomes one at this situation, which leads to loss of steerability.

The dependence of wheel slip with road adhesion coefficient for different types of roads is shown in Fig. 2 [21]. Expression for this λ-μ curve is given in (6). This was obtained by the manufacturer of Inteco ABS Model through various experiments performed by imitating different types of road surfaces [24].

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

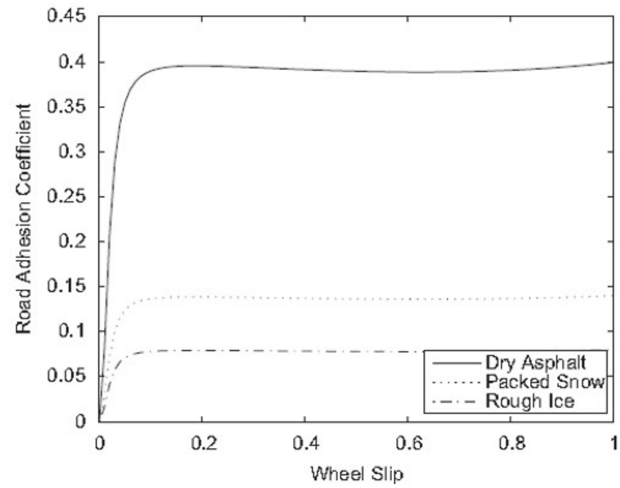

Fig. 2. Wheel Slip (λ) Vs Road Adhesion Coefficient (μ).

where a, p, w_1, w_2, w_3 and w_4 are model coefficients whose values have been taken as given in [24].

The relationship between λ and μ only during vehicle acceleration is shown in Fig. 2. The deceleration part will be in the 3rd quadrant. The λ-μ relationship curve for acceleration and deceleration phases together is given in [32], which can be clearly visualized from the conditions $r_2\omega_2 < r_1\omega_1$(Deceleration) $r_2\omega_2 \geq r_1\omega_1$ (Acceleration).

From (1) and (2) we can write;

$$M_1 = -\left\{\frac{r_2}{r_1}(J_2\dot{\omega}_2 + d_2\omega_2 + M_{20}) + J_1\dot{\omega}_1 + d_1\omega_1 + M_{10}\right\}. \quad (7)$$

From (1) and (4) we can get;

$$F_n = \frac{M_g + M_1 + M_{10} + d_1\omega_1}{L(\sin\phi - \mu(\lambda)\cos\phi)} = -\frac{J_2\dot{\omega}_2 + d_2\omega_2 + M_{20}}{\mu(\lambda)r_2}.$$

Hence,

$$\mu(\lambda) = \frac{\frac{L\sin\phi}{r_2}\left(J_2\dot{\omega}_2 + d_2\omega_2 + M_{20}\right)}{\left(J_2\dot{\omega}_2 + d_2\omega_2 + M_{20}\right)\left(\frac{L\cos\phi}{r_2} + \frac{r_2}{r_1}\right) + J_1\dot{\omega}_1 - M_g}. \quad (8)$$

From (8), the road adhesion coefficient and slip rate are calculated. The accelerations in this equation are observed based on the velocities.

The mathematical model of ABS is simulated in MATLAB-SIMULINK with the numerical values of various parameters as given in the user's manual of Inteco ABS model [24].

3. SLIDING MODE CONTROL

Sliding Mode Controllers (SMCs) are suitable for the systems with modeling inaccuracies, parameter variations and disturbances. Design of Sliding mode controller provides a systematic approach to the problem of maintaining stability and satisfactory performance in the presence of modeling imperfections. Designing a SMC involves two steps; Guarantee the reachability of the sliding surface and ensure the stability of the motion on the sliding manifold.

Consider a system of the form;

$$\lambda^{(n)} = f(\lambda,t) + g(\lambda,t)\,w + d, \tag{9}$$

where $\lambda = (\lambda,\, \dot{\lambda},\, \ddot{\lambda},\, ...,\, \dot{\lambda}^{(n-1)})^T$ is the state vector, d is the disturbance, w is the control input and f, g are nonlinear functions of state vector and time. The objective is to find a control law such that for a given desired trajectory λ_d, the tracking error $e = \lambda - \lambda_d$ tends to zero despite the presence of the model uncertainties and disturbances.

In this paper, SMC is designed to maintain the wheel slip (λ) at the desired slip (λ_d) by tracking their difference which constitutes the sliding surface. The time varying sliding surface $s(\lambda,t) = 0$ can be defined as;

$$s(\lambda,t) = \left(\frac{d}{dt} + \delta\right)^{n-1} e; \tag{10}$$

δ- strictly positive constant.

Assigning the order of differentiation of SMC as 2 gives

$$s = \dot{e} + \delta e. \tag{11}$$

The sliding condition for stability can be defined using Lyapunov function [25] as,

$$V(s) = \frac{1}{2}s^2 \Rightarrow \dot{V}(s) = \frac{1}{2}\frac{d}{dt}s^2 \le -\eta\,|s|\,;\; \eta > 0. \tag{12}$$

The condition for reaching the sliding surface in finite time can be derived from the above expression as

$$\dot{s}sgn(s) \le -\eta. \tag{13}$$

From (11) we can write

$$\begin{aligned} s\dot{s} &= s(\ddot{e} + \delta\,\dot{e}) \\ &= s(\delta\dot{e} + f(\lambda,t) + g(\lambda,t)w + d - \ddot{\lambda}_d \le -\eta\,|s|\,. \end{aligned} \tag{14}$$

Hence, a control law can be obtained for a sliding surface as;

$$w = g^{-1}\left(\hat{f} + \delta\dot{e} + K(\lambda,t)sgn(s)\right),\; K(\lambda,t) > 0. \tag{15}$$

The nonlinear function $f(\lambda,t)$ is replaced by its approximation $\hat{f}$, since it cannot be measured directly. $K(\lambda,t)$ is the variable control gain of SMC which is selected based on the current value of wheel slip (λ).

4. GREY-VERHULST SLIDING MODE CONTROLLER (GVSMC)

4.1. Grey systems

Grey theory was first proposed by Deng [26]. If the information about the system is partially known or incomplete, it is called as Grey system. Grey models (GM) are capable of dealing with such grey systems. Grey models possess a very good prediction capability based on the small amount of known data and they are widely used in variety of fields including economy, medicine, industry, geology, hydrology, irrigation strategy, environment, management, etc. [27].

4.2. Grey model (GM)

Differential equations are used to represent the dynamic behaviour of stochastic systems whose amplitudes change with time. These differential equations are called as Grey models (GM). Though there are many types of grey models used in various situations, a grey model of first order differential equation with one variable is often used for time series predictions. This model is simply denoted as GM(1,1).

Three basic operations are performed in constructing the GM(1,1).

- Accumulating Generation Operation (AGO) to smooth the randomness in the raw data.
- Mean operation to compute the background value of the grey differential equation.
- Inverse Accumulating Generation Operation (IAGO) to predict the values corresponding to the original data.

Let an actual non-negative sequence be denoted as

$$P_a = (p_a(1),\, p_a(2), \ldots\ldots, p_a(n))\,, \tag{16}$$

where $n-$ sample size, $n \ge 4$.

The AGO can be mathematically expressed as

$$p_{ago}(k) = \sum_{i=1}^{k} p_a(i),\; k = 1,2,\ldots.,n. \tag{17}$$

Performing AGO on P_a to smoothen the randomness yields,

$$P_{ago} = (p_{ago}(1),\, p_{ago}(2), \ldots\ldots, p_{ago}(n))\,. \tag{18}$$

Then the mean operation is performed on P_{ago} as

$$q_{ago}(k) = \frac{p_{ago}(k) + p_{ago}(k-1)}{2},\; k = 2,3,\ldots.,n. \tag{19}$$

The resulting mean sequence of P_{ago} is defined as,

$$Q_{ago} = (q_{ago}(1),\, q_{ago}(2), \ldots\ldots, q_{ago}(n))\,. \tag{20}$$

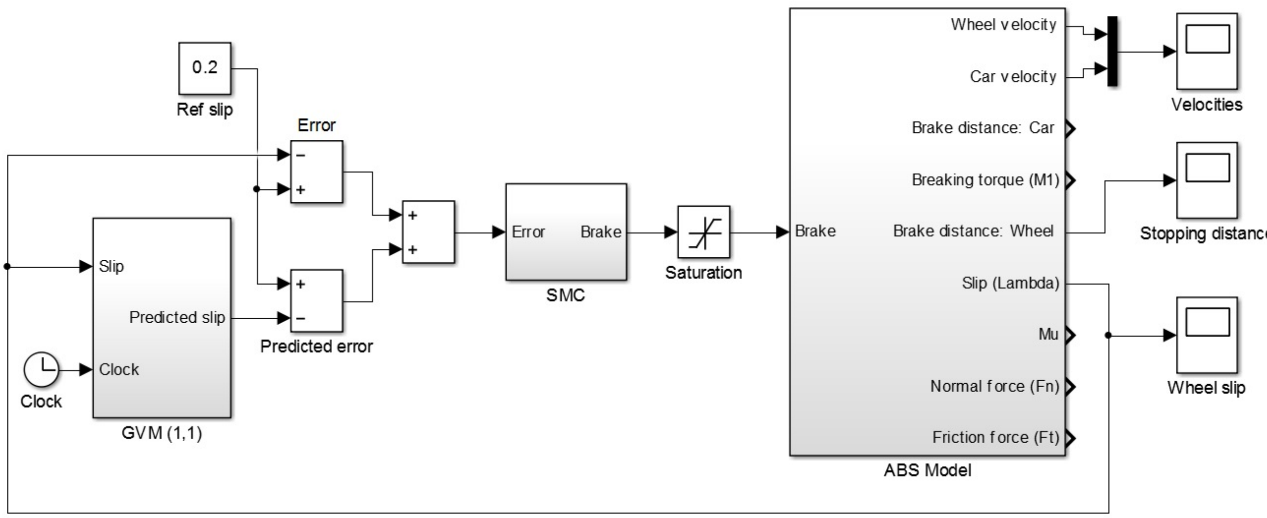

Fig. 3. GVSMC scheme for ABS.

A grey differential equation of GM(1,1) can be formed using AGO in the following form [26],

$$p_a(k) + u\,q_{ago}(k) = v. \tag{21}$$

Expression for whitening of (21) can be written as,

$$\frac{dP_{ago}}{dt} + uP_{ago} = v, \tag{22}$$

where u is development coefficient and v is grey action quantity.

The grey differential equation (21) can be whitened by considering (22) as its shadow [27].

Using Least squares method, u and v can be found as,

$$\begin{bmatrix} u \\ v \end{bmatrix} = (B^T B)^{-1} B^T Y, \tag{23}$$

where

$$B = \begin{bmatrix} -q_{ago}(2) & 1 \\ -q_{ago}(3) & 1 \\ \cdots & \cdots \\ -q_{ago}(n) & 1 \end{bmatrix} \text{ and } Y = \begin{bmatrix} p_a(2) \\ p_a(3) \\ \cdots \\ p_a(n) \end{bmatrix}. \tag{24}$$

The prediction ($\hat{p}$) can be obtained from GM(1,1) as

$$\hat{p}_{ago}(k+1) = \left(p_a(1) - \frac{v}{u}\right) e^{-uk} + \frac{v}{u},\ k = 1,2,\ldots.,n. \tag{25}$$

Finally, the predicted value of the actual non-negative sequence can be found out using IAGO as,

$$\hat{p}_a(k+1) = \hat{p}_{ago}(k+1) - \hat{p}_{ago}(k),\ k = 1,2,\ldots.,n. \tag{26}$$

4.3. Grey-Verhulst model (GVM)

The basic Verhulst model has a single variable second order equation of the form,

$$\frac{dP_{ago}}{dt} + uP_{ago} = v\,(P_{ago})^2. \tag{27}$$

The values of u and v can be found from the expressions,

$$\begin{bmatrix} u \\ v \end{bmatrix} = (B^T B)^{-1} B^T Y, \tag{28}$$

where

$$B = \begin{bmatrix} -q_{ago}(2) & (q_{ago}(2))^2 \\ -q_{ago}(3) & (q_{ago}(3))^2 \\ \cdots & \cdots \\ -q_{ago}(n) & (q_{ago}(n))^2 \end{bmatrix};\ Y = \begin{bmatrix} p_a(2) \\ p_a(3) \\ \cdots \\ p_a(n) \end{bmatrix}. \tag{29}$$

The predicted values of the original sequence can be directly had from GVM(1,1) as [28],

$$\hat{p}_{ago}(k+1) = \frac{u p_{ago}(0)}{v p_{ago}(0) + (u - v p_{ago}(0)) e^{uk}},\ k = 1,2,\ldots.,n. \tag{30}$$

4.4. Grey-Verhulst sliding mode controller (GVSMC)

It has been stated earlier that a Grey predictor can be combined with a Sliding Mode Controller to improve its robustness [29]. The higher-order Sliding Mode Controllers have many advantages such as they are robust with respect to bounded perturbation and chattering reduction [30]. Also, the GVM has a better capability of prediction than the simple GM [28]. Hence, a GVSMC is developed as a combination of a first order SMC and a GVM(1,1). The block diagram of the proposed GVSMC scheme for an ABS model is given in Fig. 3.

The vehicle and wheel velocities, stopping distance and wheel slip are the outputs taken from the ABS model. The applied brake force is the input. In this control scheme, the GVM predicts the future value of the wheel slip. Two errors are calculated; the difference between actual wheel slip at the present instant and the reference wheel slip (error) and the difference between the predicted wheel slip

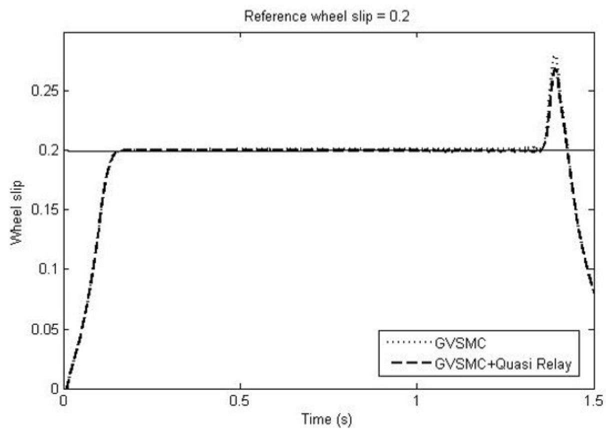

Fig. 4. Set-point tracking of GVSMC's (Initial velocity=70km/h).

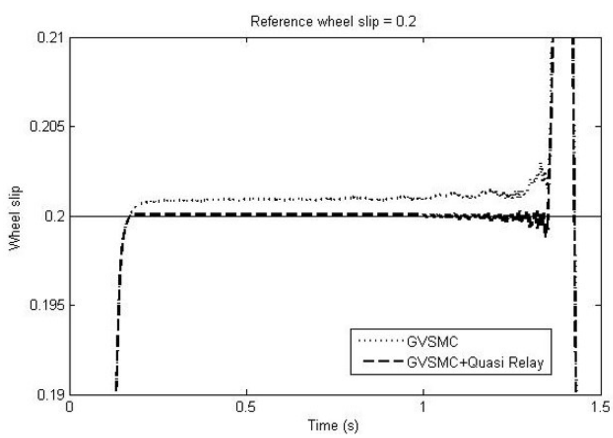

Fig. 5. Set-point tracking of GVSMC's (Initial velocity = 70 km/h - Zoomed.

and the reference wheel slip (predicted error). The sum of these errors is given as input to the Sliding Mode Controller. The SMC designed as in (15), performs the control action to maintain the wheel slip at the given reference value.

5. SIMULATION RESULTS AND DISCUSSIONS

The performance of the developed GVSMC's has been investigated through simulations performed in MATLAB-SIMULINK 7.11.0 (R2010b) with a fixed step size of 0.01 for various initial velocities of vehicle and road conditions. A band-limited white noise is introduced in to the slip and velocity measurements of the system to imitate the noise introduced in the practical situations. The values of noise power for these measurements are selected as 10^{-5} and 0.2 respectively as used in [17, 18].

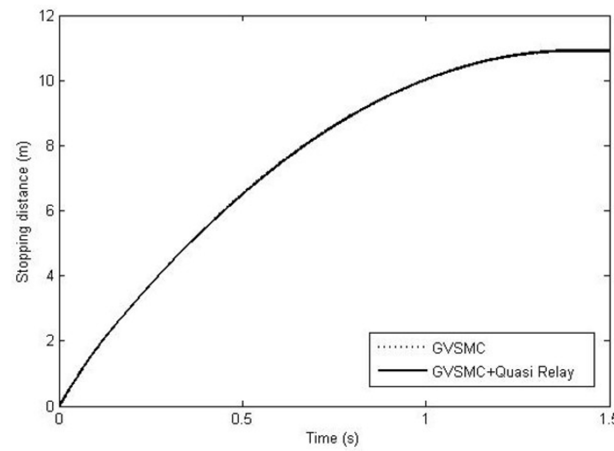

Fig. 6. Stopping distances of GVSMC's (Initial velocity=70 km/h).

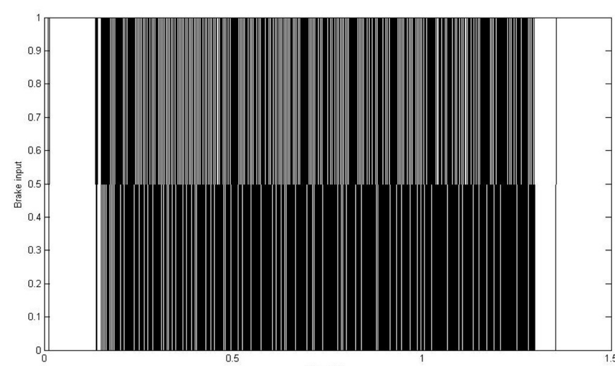

Fig. 7. Brake input – GVSMC.

5.1. Condition - I

The brake is applied when the velocity of vehicle is at 70 km/h. The desired value of slip is taken as 0.2. Initially, SMC is simulated with the control signal as $u = u_o sgn(s)$ with the values $\delta = 100$ and $u_o = 1$ along with a GVM(1,1). The results are given in Figs. 4-7. Fig. 4 and its zoomed view in Fig. 5 show that the wheel slip is constantly maintained by GVSMC at the desired value of 0.2 without overshoot and oscillations. The stopping distance of vehicle is 10.75 meters and the stopping time is 1.4 seconds, as seen in Fig. 6.

The braking force produced by the GVSMC is shown in Fig. 7.

There is a high frequency switching present in the control signal, which is called as chattering. Chattering will lead to premature wear, or even breaking of actuators [30]. Hence, a Quasi-relay is used to reduce the chattering in brake input [31]. Thus, the control law is modified as $u = u_o |e| sgn(s)$ resulting a GVSMC + Quasi Relay. The set-point tracking capability of GVSMC+ Quasi Relay has improved as seen in Fig. 4 and Fig. 5 compared to simple GVSMC. It is also found that there is no change in the

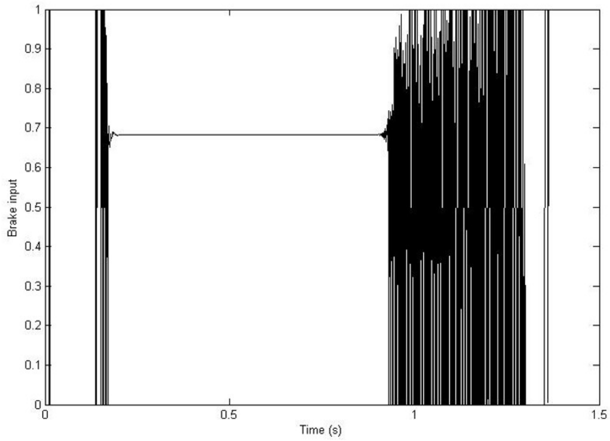

Fig. 8. Brake input – GVSMC + Quasi Relay.

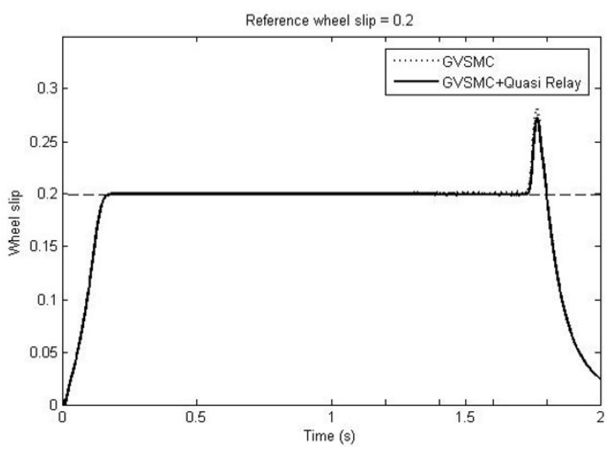

Fig. 9. Set-point tracking of GVSMC's (Initial velocity = 85 km/h).

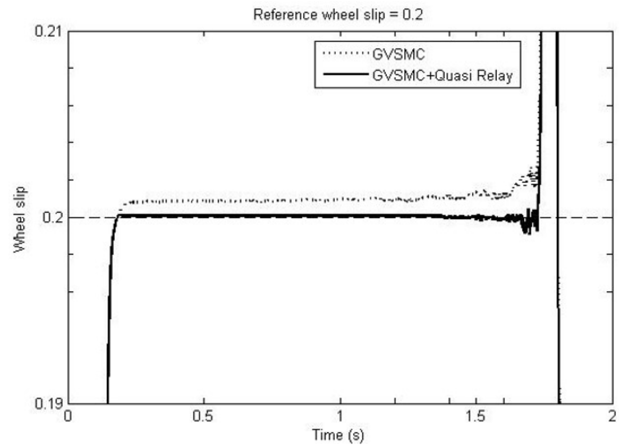

Fig. 10. Set-point tracking of GVSMC's (Initial velocity = 85 km/h) – Zoomed view.

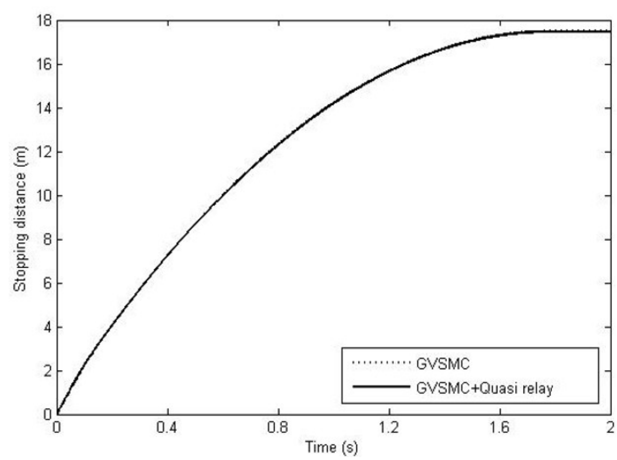

Fig. 11. Stopping distances of GVSMC's (Initial velocity = 85 km/h).

stopping distance and stopping time when the control law is modified. However, it can be appreciated that the chattering has been reduced to the maximum extent as seen from Fig. 8. The same GVM(1,1) has been employed in both GVSMC and GVSMC+Quasi Relay schemes to predict the wheel slip.

5.2. Condition - II

Brake is applied when the velocity of vehicle is 85 km/h. The desired value of slip is taken as 0.2. The Set-point tracking capabilities of proposed GVSMC's are shown in Fig. 9. Though the controlled wheel slips for both GVSMCs seem to be same in Fig. 9, the difference in it can be clearly evidenced from its zoomed version which is given as Fig. 10.

Both GVSMC's stop the vehicle in 1.66 seconds at the stopping distance of 17.8 meters, as seen in Fig. 11.

5.3. Condition - III

As seen in Fig. 2, the reference wheel slip needs to be different for different road conditions. To imitate the change in road conditions, the change in reference slip is used. It is assumed that the vehicle is moving out from a dry asphalt road and entering in the wet ice road. The response of proposed GSMC's for this condition is shown in Fig. 12. The brake is applied when the velocity of vehicle is at 65 km/h.

Though the responses of GVSMC and GVSMC + Quasi Relay seem to be same in Fig. 12, there is a considerable difference in the responses which can be evidenced in the zoomed view of the same response, as shown in Fig. 13. Figs. 12 and 13 confirm that the proposed GVSMC + Quasi Relay performs better than the GVSMC for variable reference slips as well.

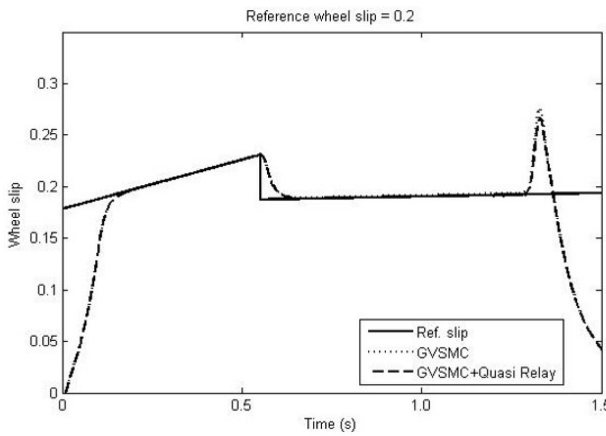

Fig. 12. Tracking capability of GVSMC's for variable reference slips (Initial velocity = 65 km/h).

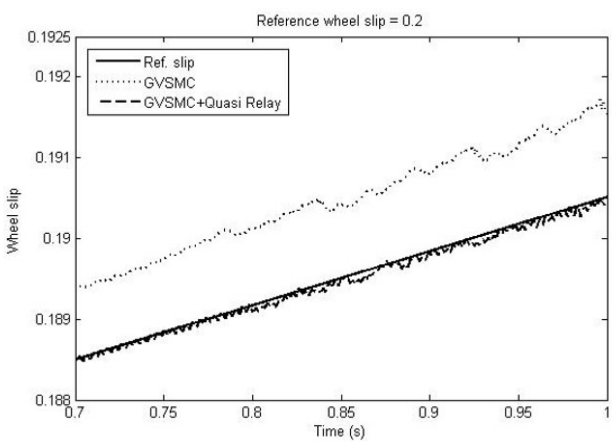

Fig. 13. Tracking capability of GVSMC's for variable reference slips (Initial velocity = 65 km/h) – Zoomed view.

5.4. Performance comparison

Further, the set-point tracking capability of proposed GVSMC's is compared with that of SMC and GSMC reported in [17, 18]. It has been shown in Fig. 14 and summarized in Table 2. It is found that the proposed GVSMC's maintain the wheel slip constantly with a very small and negligible steady state error than the existing SMC and GSMC.

Further, to show the accuracy of proposed GVSMCs, the Integral Square Errors (ISE) have been calculated for all controllers as given in (31), and presented in Table 3.

$$ISE = \int_0^T e(t)^2 dt, \tag{31}$$

where T is the stopping time of vehicle.

The measures of ISE also indicate that the proposed GVSMC's perform better than the SMC and GSMC found in literature [17, 18].

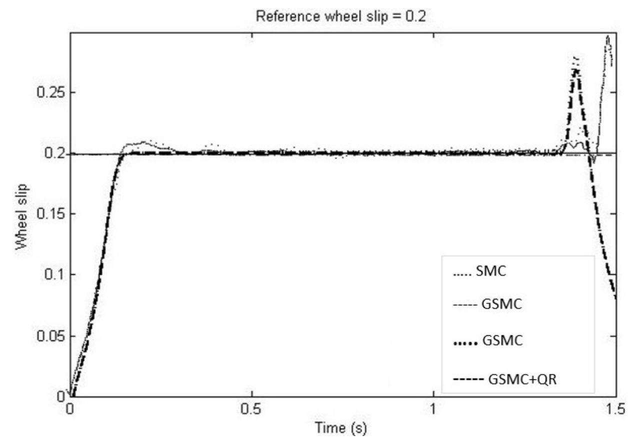

Fig. 14. Set-point tracking capability of controllers.

Table 2. Comparison of set-point tracking capability of controllers.

Controllers (Initial velocity = 70 km/h)		Controlled Wheel Slip (Set-point = 0.2)		
		Min.	Max.	Deviation (%)
[17, 18]	SMC	0.196	0.209	2 to -4.5
	GSMC	0.198	0.204	1 to -2
Proposed GVSMC	GVSMC	0.1986	0.2	−0.7 to 0
	GVSMC + QR	0.1995	0.2	−0.2 to 0

Table 3. ISE for controllers.

Controller	ISE
SMC	28.72
GSMC	25.58
GVSMC	19.86
GVSMC + Quasi Relay	19.71

6. CONCLUSION

In this paper, an adaptive controller called Grey-Verhulst Sliding Mode Controller (GVSMC) has been proposed for the Inteco laboratory ABS quarter car model. The Grey-Verhulst Model (GVM) predicts the wheel velocity and thereby the wheel slip. The error input to the controller is calculated by comparing the actual and predicted wheel slips with the desired slip. The developed first order SMC maintains the wheel slip at given set-point by nullifying this error, in spite of the presence of disturbances in the system. The SMC introduces the chattering in brake input, which is reduced by introducing a Quasi-relay in SMC. The stability of the proposed GVSMC is ensured through Lyapunov's theory. The simulation results show that the improved prediction capability of GVM and the better performing first order SMC, together lead to a better control performance of the proposed GVSMC's than the SMC and GSMC reported in literature earlier. Different road conditions have also been considered.

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