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Sliding Mode Control Algorithm for Regenerative Braking of an Electric Bus with a Pneumatic Anti-lock Braking System

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Abstract. Equipped with regenerative braking system, electric vehicles have the function of coordinating regenerative braking and friction braking simultaneously in normal braking situations. However, the usual operation is withdrawing the regenerative braking when the anti-lock braking system (ABS) is triggered. In order to make full use of regenerative braking, this article focuses on the cooperative control between the regenerative braking and the pneumatic friction braking during emergency stops. A sliding mode control (SMC) algorithm for regenerative braking is proposed to control the electric motor and help improve the braking performance and braking comfort. The proposed control algorithm is validated in the MATLAB/Simulink environment. A maximum mean deceleration of 25.3% is achieved and the stopping distance is shortened by 13.2m comparing to the pure pneumatic ABS on the wet gravel road, which verifies the feasibility and effectiveness of the developed control algorithm greatly.

1. Introduction

Recent years, with the development of new energy technologies and the necessity of environmental protection, electric vehicles come into our lives gradually [1]. Compared to conventional vehicles, the electric motor of an electrified vehicle can work as a generator and capture the kinetic energy when the vehicle is braking [2]. However, due to the restrictions of an electric motor and the batteries, the friction braking system is also indispensable. Thus, it is essential to achieve the coordinated control between the regenerative braking system and the friction braking system.

Meanwhile, in order to guarantee the safety under emergency conditions, ABS is mounted on most of the vehicles. It is also an aspect which should be noticed of the cooperative control between the regenerative braking and the friction braking when ABS is activated.

By far, the cooperative control between the regenerative braking and the friction braking is researched worldwide [3-6], but rarely related to the participant of electric motor in a panic stop. For electric vehicles, when the vehicle takes an emergency braking, the regenerative braking force is withdrawn immediately [7], [8], leaving the friction braking to take over the ABS function only. It is a simple and convenient way, but the potential advantages of the electric motor are not fully utilized.

Based on these facts, there are also some researchers to carry out innovations beyond the simplification. A pure electric motor regenerative braking method was developed in [9]. Test results indicate the advantages of the method, but the braking capability is limited. This in turn validates that



the friction braking is indispensable to guarantee the safety. According to this thought, reference [10] recommended three control modes to realize the cooperative control, namely PQ-method, frequency selection by filter and model following control. The effectiveness is confirmed by simulations and road tests. Reference [11] developed a strategy in which the regenerative braking is prior to load to respond the braking command. Once the regenerative braking force can't meet the total braking force, the hydraulic braking force will compensate immediately. A phase-theory method, dividing the total braking torque to a stable one and a dynamic one, was proposed by reference [12]. The friction braking and regenerative braking take responsible for the two torques respectively. Reference [13] introduced the optimal control theory and thus obtained maximal available adhesion. A robust wheel slip ratio controller was designed for in-wheel-motors-driven vehicles in [14] and reached a good compromise between stopping distance and regenerative braking torque. Other control methods could also be found in references [7], [15], [16].

Nevertheless, most of the strategies are not fully using the logic threshold control method and are about the hydraulic braking system of passenger cars. Due to the widespread utilization of the pneumatic logic threshold control on buses and the significant dynamic differences between the hydraulic braking system and the pneumatic braking system [17-19], it is essential to explore the regenerative braking control method on the basis of the pneumatic logic threshold ABS of a bus.

In this paper, a SMC algorithm of regenerative braking is proposed to help control the slip ratio on an electric bus with the pneumatic ABS. A system model is built in the MATLAB/Simulink environment and simulations are carried out in four typical road surfaces. The rest of this paper is organized as follows. In section 2, the logic threshold ABS is introduced. In Section 3, the SMC algorithm of regenerative braking is designed. Simulation results and conclusions are displayed and concluded respectively in section 4 and section 5.

2. Logic threshold ABS and the ideal slip ratio section of your paper

2.1. Logic threshold ABS

The logic threshold control of ABS is the most widely used control method nowadays. The control core is to calculate the real slip ratio and judge the state of the wheel according to the wheel angular speed and the wheel angular deceleration. Once the wheel has the tendency of locking up, the ABS is activated and the system switches the pneumatic proportional valve among increasing pressure, holding pressure and decreasing pressure to prevent the lock-up of the wheel. The five threshold values, namely three angular decelerations and two slip ratios are the triggered values and used to switch the control zones.

In practical usage, the threshold values are obtained through a number of tests and need to be validated for a long time. Because of the control logic, the complexities and the uncertainties of road conditions, the slip ratio is controlled in a range but not an ideal value during the procedure. Thus, although the wheels will not be locked during the emergencies, it is believed that the braking performance will be worse than the situation in which the slip ratio is stabilized at the ideal one.

Table 1. Constants of C_1 , C_2 and C_3 on different roads.

Road surface	C_1	C_2	C_3
Ice	0.05	306.39	0.001
Snow	0.1946	94.129	0.0646
Wet gravel	0.4404	33.708	0.1204
Wet bituminous	0.857	33.822	0.347

2.2. The relations between the road adhesion and the slip ratio

The relations between the road adhesion and the slip ratio are complicated. This article adopts the following equation to calculate the ideal slip ratio on different roads [20].

$$\mu(\lambda) = C_1(1 - e^{-C_2\lambda}) - C_3\lambda \quad (1)$$

where μ is the road adhesion, λ is the slip ratio, C_1 , C_2 , C_3 are constants on different roads. According to Table 1, the ideal slip ratio could be gotten in usual road surfaces.

3. The SMC algorithm of regenerative braking

The SMC algorithm has the advantages of good control accuracy and strong robustness. Once the controller is well designed and the control input is able to be guaranteed, the control performance is only affected by the convergence rate. It is especially proper for the control of a nonlinear system.

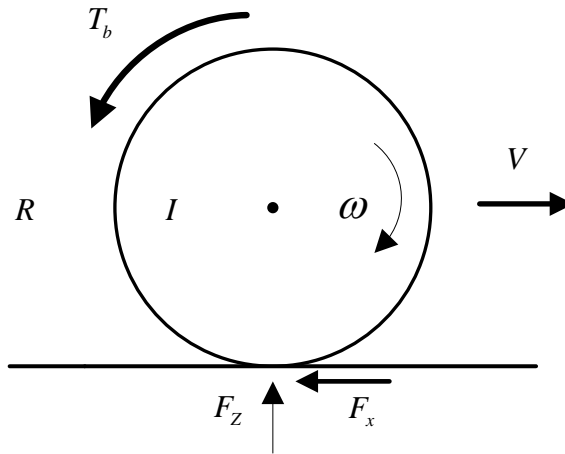


Figure 1. Longitudinal dynamical model of the wheel.

The motion equations of the researched electric bus can be described as (The wind resistance is neglected.):

$$m\dot{V} = -F_x \quad (2)$$

$$I\dot{\omega} = F_x R - T_{b_total} \quad (3)$$

where m is the quarter mass of the vehicle, V is the vehicle velocity, F_x is the longitudinal force, R is the wheel radius, ω is the wheel's angular speed, I is the inertia of the wheel and T_{b_total} is the total braking torque.

As for the rear-left wheel,

$$T_{b_total} = T_b + 0.5i_0i_gT_m + T_{wheel_drag} \quad (4)$$

where T_b is the pneumatic braking torque, T_m is the motor torque, T_{wheel_drag} is the wheel's drag torque, i_g is the transmission ratio of the gearbox and i_0 is the final drive ratio.

The slip ratio of the wheel is defined as

$$\lambda = \frac{V - R\omega}{V} \quad (5)$$

Conduct the derivation of equation (5),

$$\dot{\lambda} = \frac{\dot{V}(1-\lambda) - R\dot{\omega}}{V} = \frac{-\dot{V}}{V}\lambda + \frac{\dot{V}}{V} - \frac{R\dot{\omega}}{V} \quad (6)$$

Let

$$\frac{-\dot{V}}{V}\lambda = f(\lambda) \quad (7)$$

$$\frac{\dot{V}}{V} - \frac{R\dot{\omega}}{V} = u \quad (8)$$

where $|f(\lambda)| < \rho * \lambda$, $\left| \frac{-\dot{V}}{V} \right| < \rho$ and ρ is one of the upper limits of $\left| \frac{-\dot{V}}{V} \right|$, then we have

$$\dot{\lambda} = f(\lambda) + u \quad (9)$$

Define the tracking error of the slip ratio as:

$$e = \lambda_d - \lambda \quad (10)$$

where λ_d is the ideal slip ratio of the corresponding road. Perform derivation of equation (10) and equation (11) is obtained

$$\dot{e} = \dot{\lambda}_d - \dot{\lambda} \quad (11)$$

Let

$$u_1 = \dot{\lambda}_d + ke + \rho \frac{|e|}{e} \quad (12)$$

$$u_1 = u \quad (13)$$

where $k > 0$, thus,

$$\frac{\dot{V}}{V} - \frac{R\dot{\omega}}{V} = \dot{\lambda}_d + ke + \rho \frac{|e|}{e} \quad (14)$$

Define the Lyapunov function as follows.

$$V(e) = \frac{1}{2}e^2 \quad (15)$$

Then

$$V(\dot{e}) = e\dot{e} = -ke^2 - f(\lambda)e - \rho|e| < -ke^2 < 0$$

From $V(\dot{e}) < 0$, it can be concluded that the system is stable. It means that given the input of u , the slip ratio of λ will convergence to λ_d in a limited time and the convergence rate is decided by the value of k .

Combine equations of (2) (3) (4) (14), the motor torque command can be expressed as follows:

$$T_m = \frac{2}{i_0 i_g} \left[\frac{I\dot{V}}{R} - \frac{kVI}{R} (\lambda_d - \lambda) - \frac{VI}{R} \dot{\lambda}_d - \frac{VI\rho}{R} \text{sgn}(e) + F_x R + T_b + T_{wheel_drag} \right] \quad (16)$$

where $\text{sgn}(e)$ is the sign function and equation (16) is the motor torque command during the braking. In practical usage, in order to decrease the chattering of the motor command, the sign function is usually replaced by saturation function. After replacement, the final motor torque command is shown in (17).

$$T_m = \frac{2}{i_0 i_g} \left[\frac{I\dot{V}}{R} - \frac{kVI}{R} (\lambda_d - \lambda) - \frac{VI}{R} \dot{\lambda}_d - \frac{VI\rho}{R} \text{sat}(e) + F_x R + T_b + T_{wheel_drag} \right] \quad (17)$$

Thus, the controller design of the SMC is completed.

4. Simulation and analysis

In order to evaluate the proposed control algorithm, the simulation model is built in a Matlab/Simulink environment.

4.1. Simulation scenarios

Because the maximum possible deceleration of the researched bus is about 5 m/s^2 (absolute value) and skid is much easier to occur on slippery roads. The simulations are carried out on the snow, ice

and wet gravel roads, of which the maximum adhesion coefficients are 0.2, 0.1 and 0.5 respectively. And a transitional road (from 0.8 to 0.2) is also conducted. The details of simulation are: set the initial velocity of 60 km/h and press the brake pedal fully to trigger the ABS. The simulation results are displayed as follows.

4.2. Analysis of simulation results

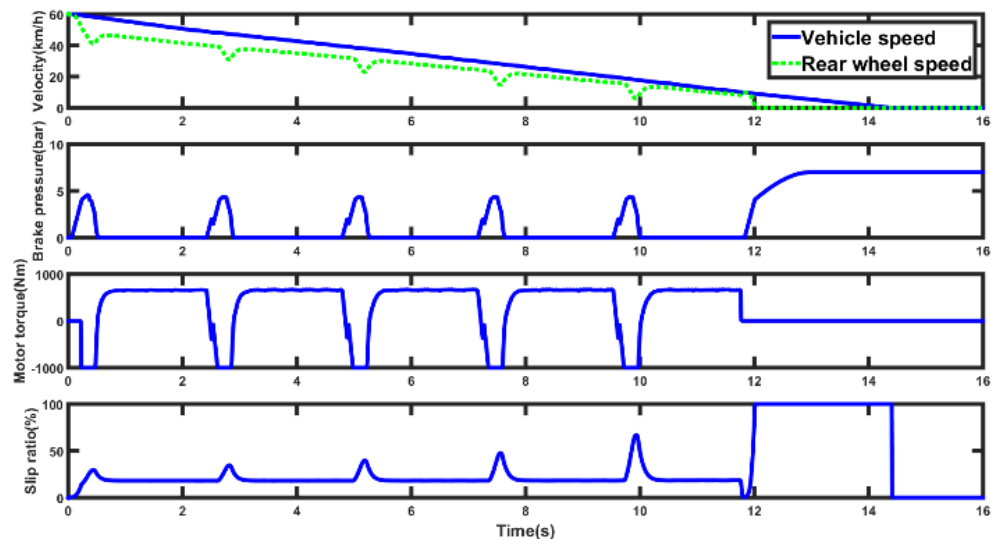


Figure 2. Simulation results of the SMC algorithm on a snow road.

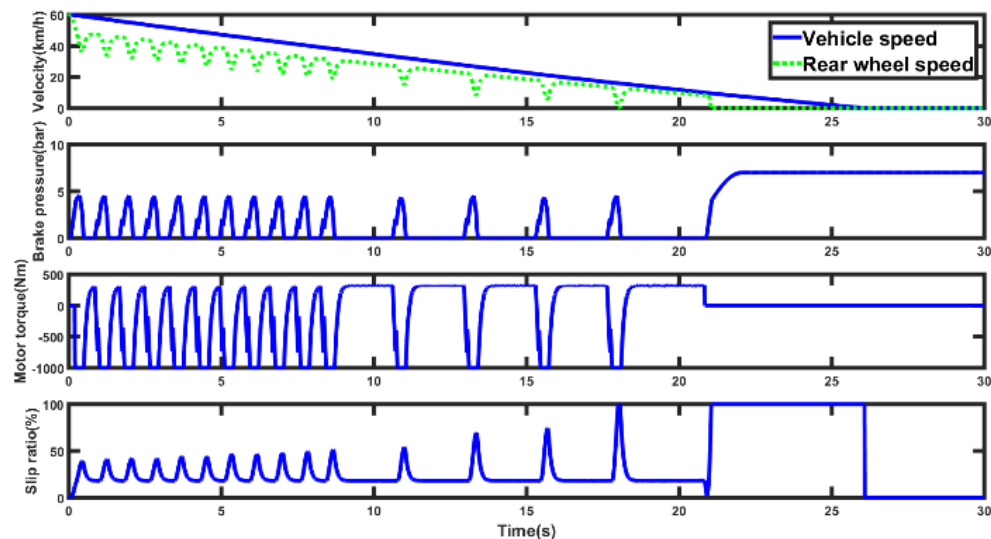


Figure 3. Simulation results of the SMC algorithm on an ice road.

Figure 2 is conducted on the snow road. When the brake pedal is fully depressed, the pressure of pneumatic braking increases greatly, following the increase of the slip ratio. The system detects the tendency of lock-up and prevents the slip ratio from increasing any further. Because of the slow response of pneumatic system, the proposed control strategy sets the motor torque immediately to negative value (drive torque) to resist the oversize slip ratio. When the pneumatic pressure decreases to a low value, the slip ratio has the tendency of less than the ideal value. The proposed control strategy sets the motor torque from negative to positive to help maintain the slip ratio to the ideal value.

When the pneumatic pressure is high enough again, the motor torque is set to negative value once more. These cycles come into play again and again until the vehicle speed is below 10 km/h, at which the motor torque is removed and only the pneumatic braking takes over the rest braking process.

Viewed from the full range, the proposed strategy is able to control the braking smoothly and no skid occurs during the procedure. Meanwhile, the slip ratio is stabilized at the ideal value most of the time, which achieves the expected control performance.

Then the ice road is conducted following the snow road. Similar to the snow road, no skid appears in Figure 3. The real slip ratio is also kept at the ideal one at some time. The difference is that the adjustment cycles are more frequently than the snow road. This is understandable. Due to the lower adhesion of ice road, the wheel is easier to lock up, so the control logic is triggered frequently to perform more control cycles. But the proposed strategy is able to handle them appropriately.

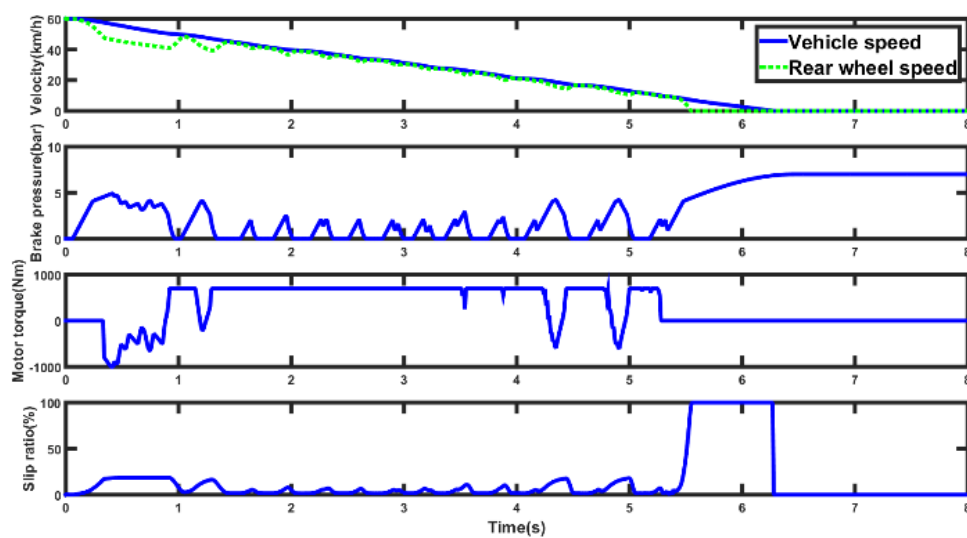


Figure 4. Simulation results of the SMC algorithm on a wet gravel road.

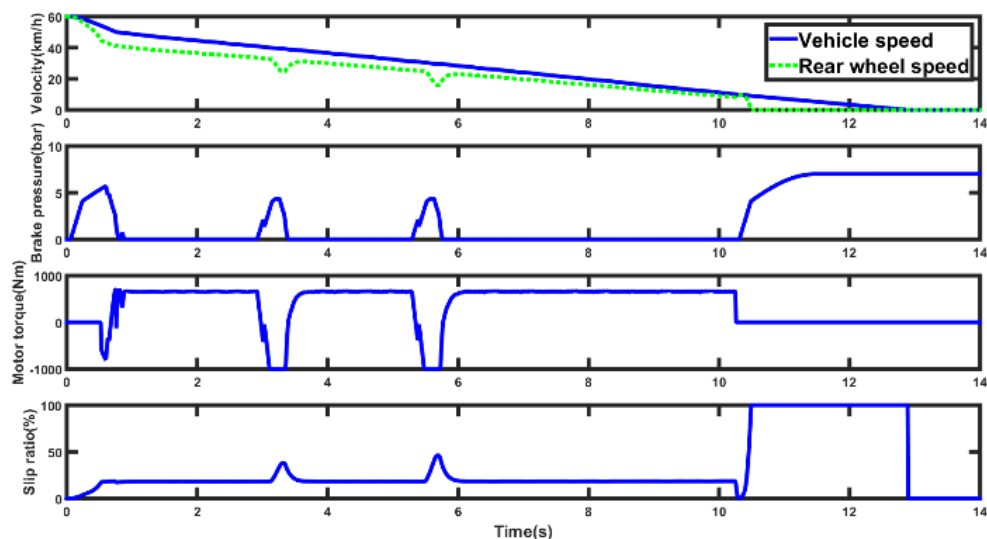


Figure 5. Simulation results of the SMC algorithm on a transitional road.

Besides the above two situations, the simulations are also performed on a wet gravel road and a transitional road. The Figure 4 and 5 show that the control results are desirable and no locking up

occurs on both roads. However, owing to the motor's capability, the slip ratio can't always adjust to the ideal value but close enough to the ideal value.

From the above results and analyses, it can be concluded that the braking performance and braking stability are guaranteed, demonstrating the feasibility and effectiveness of the SMC strategy.

4.3. Comparison to the other two strategies

In order to assess the SMC strategy further, the simulations of a proportional-integral-differential (PID) control strategy and the pure pneumatic control strategy are carried out in the same scenarios. The difference between the SMC strategy and the PID control strategy is replacing the SMC algorithm to a PID control algorithm.

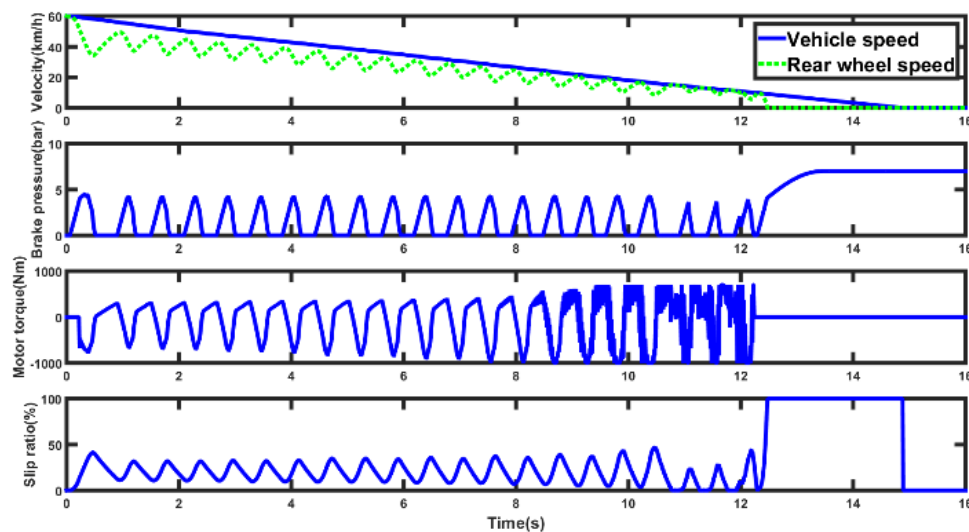


Figure 6. Simulation results of the PID control strategy on a snow road.

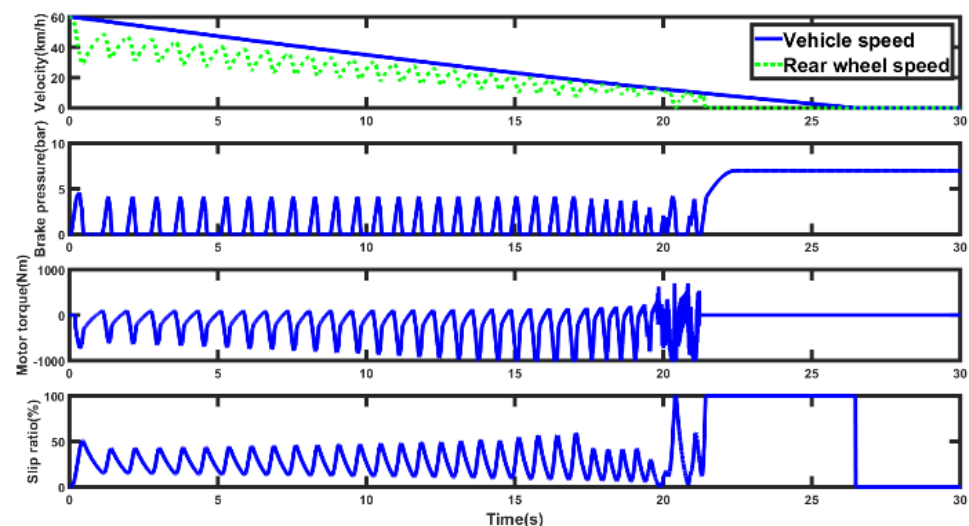


Figure 7. Simulation results of the PID control strategy on an ice road.

Figure 6 and Figure 7 are the simulation results on the snow and ice road. Results indicate that the PID control strategy can also realize the anti-locking of the wheels. But being restricted to the control characteristics of the PID controller, the slip ratio is hard to stabilized to the ideal value but a smaller range around the ideal value. This can be seen from the variation trend of the motor torque.

Meanwhile, in order to correct the error of the slip ratio ahead, the differential control will cause the strong chattering of the motor torque, which will increase the jerk and worsen the braking comfort during the braking. The chattering can be seen from Figure 8 and Figure 9 as well.

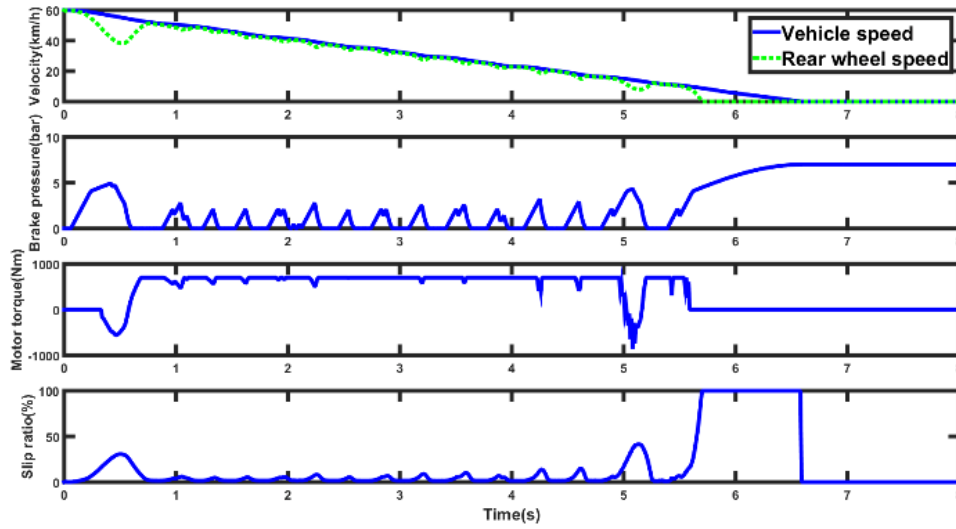


Figure 8. Simulation results of the PID control strategy on a wet gravel road.

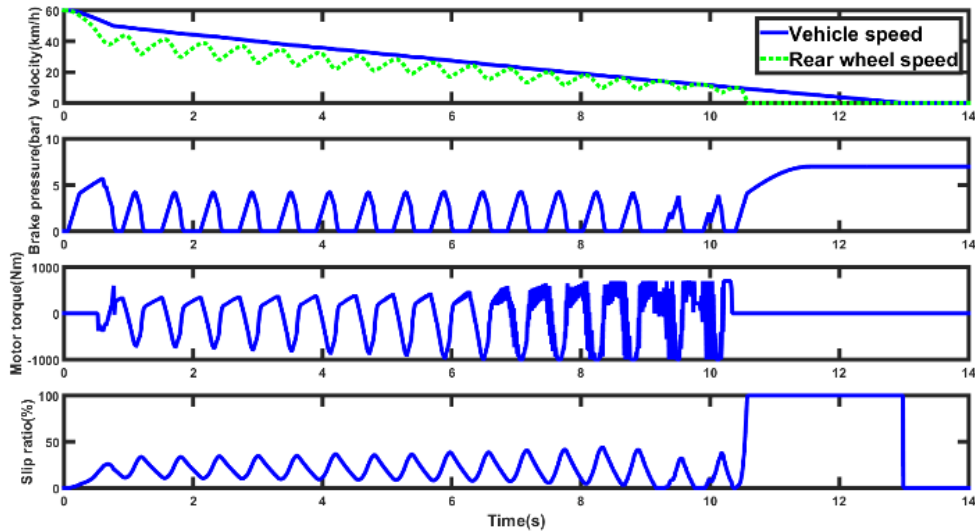


Figure 9. Simulation results of the PID control strategy on a transitional road.

In order to evaluate the control strategy more comprehensively, the root mean square of jerk (RMSJ) which can be used to weigh the braking comfort is introduced.

The RMSJ is defined as:

$$RMSJ = \sqrt{\frac{1}{n} \sum_{k=1}^n J^2} \quad (18)$$

where

$$J = \frac{d^2V}{dt^2} \quad (19)$$

Thus, the Table 2 is obtained.

From the table, it can be concluded that both the PID control strategy and the SMC strategy can achieve a better braking performance regarding of the stopping distance and the mean braking deceleration. However, on the one hand, due to the control characteristics of the PID controller, it need a lot of work to adjust the control parameters but not SMC. On the other hand, the SMC strategy can greatly improve the braking comfort (Except the wet gravel road which is affected by the control strategy of the original pneumatic ABS.), but the PID control strategy deteriorates the braking comfort to a great extent. The comparisons demonstrate the advantages of the SMC strategy greatly.

Table 2. Comparison of the three control strategies.

Road condition	Strategy	Stopping distance (m)	Mean deceleration (m/s^2)	Deceleration improvement (%)	RMSJ	RMSJ improvement (%)
Ice	Pneumatic	217.30	0.639	—	0.288	—
	PID	207.60	0.669	4.68	0.308	-6.76
	SMC	204.90	0.678	6.10	0.258	10.37
Snow	Pneumatic	130.00	1.069	—	1.035	—
	PID	120.10	1.156	8.14	1.212	-17.10
	SMC	117.70	1.180	10.40	0.928	23.43
Wet gravel	Pneumatic	65.40	2.124	—	5.566	—
	PID	54.82	2.534	19.30	6.777	-21.76
	SMC	52.15	2.663	25.30	6.143	-10.37
Transitional	Pneumatic	109.30	1.270	—	1.529	—
	PID	93.70	1.482	16.69	1.953	-27.73
	SMC	94.95	1.463	15.20	1.048	31.46

Therefore, comparing to the other two control strategies, it is encouraging that the SMC strategy is much better.

5. Conclusion

A SMC strategy for regenerative braking of an electric bus equipped with an anti-lock braking system is proposed in this paper. The SMC strategy is able to coordinate the pneumatic ABS strategy and to help maintain the slip ratio at the ideal value or a more precise range. Meanwhile, the PID control strategy and the pure pneumatic strategy are taken as benchmarks to compare the SMC strategy.

Simulation results indicate that owing to the strong robustness and low parameter adjustment workload of SMC, not only better braking performance can be achieved, but better braking comfort. The mean deceleration and braking comfort are improved by 15.2% and 31.46% on the transitional road respectively comparing to the pure pneumatic ABS control strategy. Simulation results in four typical roads fully demonstrate the adaptability and effectiveness of the SMC strategy.

Future work will focus on the hardware-in-loop tests to verify the strategy further. Meanwhile, the impact on energy usage of overall mileage will also take into consideration.

Acknowledgments

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