All-electric intelligent anti-lock braking controller for electric vehicle under complex road condition

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Abstract– All-electric intelligent ABS is a new technology to be developed and applied in the Electric Vehicles(EVs). It could completely replace the traditional mechanical brake as well as hybrid ABS system which is not suitable for electric vehicles. Thus it greatly improves the reaction speed, shorten the braking time, and is more easily to be integrated in the electric vehicle central control unit. It improves the braking performance by optimizing the coefficient of tire adhesion to the ground to obtain Maximum braking force. This paper presents simulation of integrated controllers of the vehicle anti-lock braking system based on Simulink/Stateflow module of Matlab, which consists of a traditional continuous PID and logic limits controller based on finite state machine theory. The two controllers regulate slip ratio and deceleration simultaneously, which can effectively optimize the braking characteristics and improve the safety of the vehicle of anti-lock braking system. Vehicle speed, wheel speed, braking distance, pressure state and slip ratio are investigated to reveal the performance of anti-lock braking system. This method is simple and suitable for all electric ABS. More importantly, it could solve braking problem under complex road condition and a sudden change of road condition. Single-wheel system is studied in this paper to prove that the controller can effectively reduce braking distance and time and also can improve the stability of anti-lock braking system and has potential to applied to all electric vehicle

Keywords– Anti-lock braking system; All-electric; intelligent ABS, Road condition, Electric vehicle, state machine theory

I. INTRODUCTION

The vehicle safety is more and more concerned by public especially with the quantity and demand in speed performance of the automobiles on the road in recent years. Braking ability is the most important to vehicle security, especially for over length and sideslip, which can bring serious damage to people's life and property. Therefore, braking stability has become an urgent issue for the automotive industry. Anti-lock braking system is brought out and verified as an active method to enhance the safety problem and improve the braking performance of the automobiles, which can effectively prevent the wheels from skidding and shorten braking distance when an emergency incident occurs. The controller is the most important to the design of ABS.

Conventional ABS consists control unit, solenoid valve, hydraulic drive system and sensing system. At present, the research on antilock braking system is mainly focused on the control algorithm, using advanced control algorithm to obtain the maximum braking force and lateral adhesion coefficient, in order to obtain the maximum braking force, as far as possible to shorten the braking distance. Wheel acceleration and tire slip control are the two main solutions of the ABS control [1]. The first approaches indirectly control the wheel slip by controlling the deceleration/acceleration of the wheel through brake pressure from the actuator [2]. The second directly slip control has many different approaches, which includes obtaining the maximum friction by PID control [3], wheel-slip peak localization [4], fuzzy control [5-9], and neural network control [10], and the controller for future electrical vehicle[11,12]. Generally, the major difficulty involved in the design of a vehicle control system is that the performance depends strongly on the knowledge of the tire/road characteristic which depends on the wheel slip as well as road condition [4]. The slip ratio is defined different on the road conditions. Most anti-lock braking system choose slip ratio as the controlled parameter for its direct influence on the braking force. A plurality of signals from the sensors are input to the calculating unit, and the control signal is input to the solenoid valve by the calculation method to control the opening and closing of the hydraulic system. These control algorithms combined with the hydraulic brake, known as the electric braking and mechanical braking hybrid braking method, is the most typical ABS system composition.

All- electric intelligent ABS would be developed and applied in the EVs which could completely replace the traditional mechanical brake as well as hybrid brake ABS system which is not suitable for electric vehicles. Wheel acceleration and tire slip control are integrated in this paper since they have been verified to be an active method to improve the vehicle braking stability. PID and logic limits control based on finite state machine theory [13,14] are applied to regulate slip ratio and wheel acceleration respectively. Both of the controllers are aimed to obtain a desired braking force and to maintain adequate stability. The integrated controller proposed in this paper is simple and practical. The output of proposed integrated controller is logic signal, which could directly be the gate driving signal for bi-directional power converter to produce a positive or negative braking torque to the motor, therefore, it is suitable for all electric anti-lock braking system for EVs. Modeling considering uphill/downhill and simulation based on Matlab are given in this paper. Simulink/State flow module used to build the integrated controllers can simplify the logic limits operation of the ABS into visual graphic diagram which is also convenient to modify and optimize the controller in further design. The new ABS controller will improve dynamic response, reduce the reaction time and of course the braking time and distance, improve ABS braking efficiency while removing the traditional mechanical brake part to achieve full automatic control of ABS.

Simulation [16-17] is an effectiveness research method which would be used to evaluate the proposed controller.

II. VEHICLE MODEL

Vehicle model with single-wheel is shown as Fig.1, where the wind force, hill climbing force and rolling resistance are neglected. The slip ratio s is defined as

$$s = \frac{v - \omega r}{v} \tag{1}$$

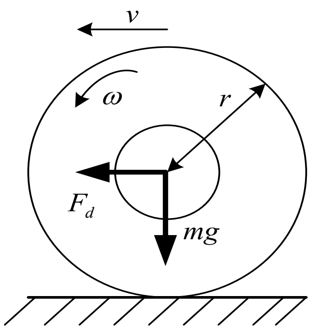


Fig.1 single wheel dynamics model

where v is the longitudinal velocity, ωr is the wheel velocity, ω is the wheel angular velocity, r the radius of wheel.

The friction force (Fd) between road surface and tire is described by

$$F_d(s) = \mu(s)mg \tag{2}$$

Where m is quarter vehicle weight, g is gravitation acceleration. $\mu(s)$ is the adhesive coefficient between road surface and tire. According to Newton's second low, the dynamics of single wheel braking system can be represented by the following equations

$$m\frac{dv}{dt} = -F_d(s) \tag{3}$$

$$J_\omega \frac{d\omega}{dt} = -T_m + rF_d(s) \tag{4}$$

Where T_m is the braking torque applied directly to the motor, J_ω is the wheel's moment of inertia.

When road condition gradient is included, the dynamics system of up/down hill is modeled as shown in Fig. 2.

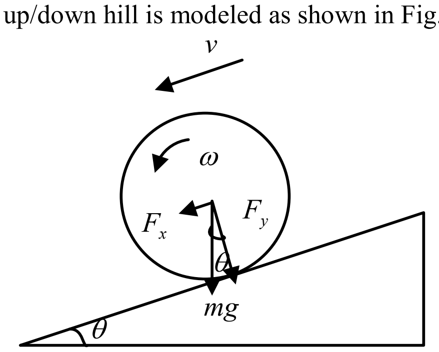


Fig. 2 single-wheel on hill road dynamics mode

The following equations (6) and (7) are representing vehicle downhill and uphill respectively.

$$J_\omega \frac{d\omega}{dt} = -T_m + r(F_y(s) + F_x) \tag{6}$$

$$J_\omega \frac{d\omega}{dt} = -T_m + r(F_y(s) - F_x) \tag{7}$$

Where, $F_y(s) = \mu(s)mg\cos\theta$ (8)

$$F_x = mg\sin\theta \tag{9}$$

III. CONTROL ALGORITHM

A. State flow and finite state machine theory

A state machine is a model which consists a finite number Tire slip ratio control has been developed as a control parameter for most the anti-lock braking system. In this simulation, the desired wheel slip ratio is set to be a constant (0.2), it will sufficient for most of the vehicles' velocity require. The vehicle model and slip ratio calculation based on the mathematical model of vehicle has been discussed in section two. The parameter of the vehicle is obtained from the experiment car and is shown in Table 2. The block diagram of the control system was shown in Fig. 5.

of state transition under certain regulations. The Regulations are mainly logic control, which is simple and suitable for EVs. Matlab/Simulink is powerful and effective software to model and simulate a system for researchers and engineers. Visual modules are used to simplify and avoid complicated code work. The controller of the ABS consists of a lot and complicated logic operations because of different road conditions and braking parameters limitation. The state flow toolbox can use flowchart symbols and state hopping diagram to describe the loop and conditional statements clearly and precisely based on finite state machine theory. The controller proposed here is simulated and analyzed based on Simulink/stat flow, which simplified the controller and is convenient to process further design.

B. Tire slip control

The braking force is relative to the adhesive coefficient between the tire and the pavement. The adhesive coefficient is determined by the road surface, the tire condition, and the slip ratio. Typical road adhesive coefficients are shown in Fig. 3 [11].

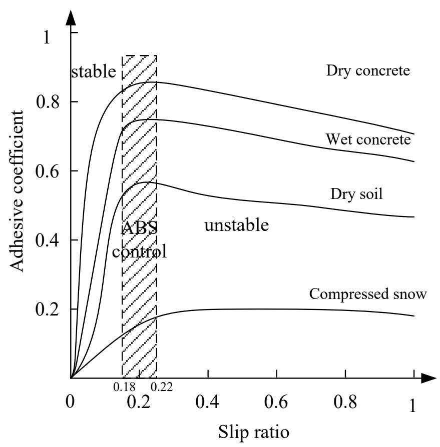


Fig.3 typical μ-slip characteristics for various road conditions

The purpose of vehicle antilock braking control is to achieve maximum braking torque and prevent wheels from being locked during panic braking or braking on a slippery road such as wet or snow road. As the Fig. 3 shown that the adhesive coefficient reaches the maximum value when the slip ratio at the shadow part. After that, the adhesive coefficient decreases while slip ratio increases which is unstable area. Therefore, the maximum braking force can be provided to the wheel at around 0.2 while the vehicle is braking.

In this study, the relations of friction coefficient and the slip ratio which is shown in Fig.3 are described as two linear equations. [12]

Those are expressed as

$$\mu = \begin{cases} \dfrac{\mu_p}{s_p} s & s \le s_p \\ \dfrac{\mu_p - \mu_0 s_p}{1 - s_p} - \dfrac{u_p - \mu_0}{1 - s_p} s & s > s_p \end{cases} \tag{10}$$

The piecewise linear curve is shown as Fig. 4. Where μ_p is peak adhesion coefficient; s_p is peak adhesion coefficient slip ratio; μ_0 is the adhesion coefficient when the wheel is locked. The peak adhesion coefficient slip ratio is set 0.2 in this paper. Table 1 shows the characteristics values of various road conditions.

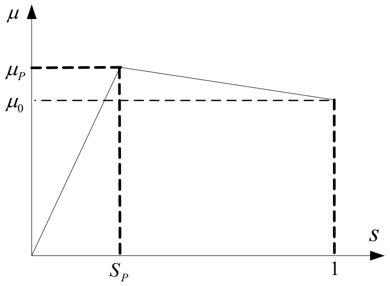


Fig.4 the piecewise linear μ-slip curve

Table 1 characteristics value of various road conditions [13]

Road Condition	Peak adhesive Coefficient μ_p	Slip Adhesive Coefficient μ_0
Dry concrete	0.9	0.75
Wet concrete	0.8	0.7
Dry soil	0.7	0.65
Compressed snow	0.3	0.2

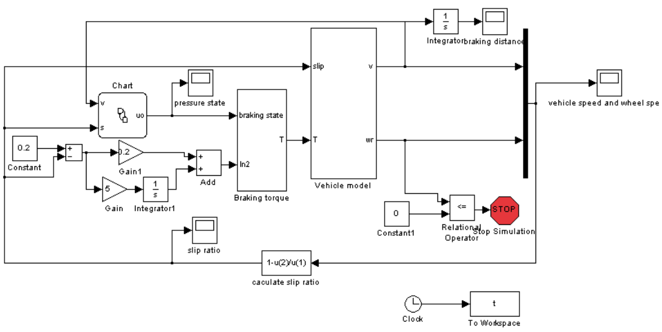


Fig. 5 braking system simulation model

The vehicle traction control consists to design a control law in order to optimize the braking force. This optimization consists to maximize the tire forces whatever the conditions of the road. Therefore, it must to localize the wheel slip ratio which corresponds to the peak tire road adhesion characteristic. the location and the value of these peak values varies in large range depending on the road, tire and many other different factors, for any rolling conditions, the optimal wheel slip rate, which will be used as control reference to optimize the braking force.

C. Integrated control

The anti-lock braking system proposed here, consists of an integrated controller. One is PID controller and one is built based on finite state machine theory, which regulates the skip ratio and acceleration simultaneously. Since the controller is for all electric anti-lock braking system for EVs, bi-directional power converter is employed to alternate the current of the motor, finite state machine theory is applied to simplify the logic operation and output gate driving signal of the bi-directional converter. In this part, deceleration and slip ratio are the main control parameters of the system; the control algorithm is shown in Fig.6. The slip ratio is still the main control parameter of the PID control, and is regulated in 20%, which is relative peak adhesive coefficient slip ratio. The control algorithm is mentioned as section 3.2. the parameter of the braking system is illustrated as below

Table2. The parameters of Vehicle model parameters

parameters	value	parameters	value
gravitation acceleration	9.8m/s²	peak adhesion coefficient	0.9
road gradient	0.15°	peak adhesion coefficient slip ratio	0.2
wheel moment of inertia	9.55 kg m²	1/4 vehicle mass	300 kg

Table3. The parameters of the braking system

parameters	value	parameters	value
gravitation acceleration	9.8m/s²	peak adhesion coefficient	0.9
road gradient	0.15°	peak adhesion coefficient slip ratio	0.2
wheel moment of inertia	9.55 kg m²	adhesion coefficient at wheel locked	0.75
1/4 vehicle mass	300 kg	Deceleration speed limit	-20 m/s²
wheel rolling radius	0.3 m	Acceleration speed limit	20 m/s²

In the controller built based on finite state machine theory, the control strategy proposed here is to limit acceleration speed between +20 m/s2 and -20m/s2, the optimum slip ratio is around 18%-22%. According to equation (1), the association of wheel's rotational speed with the optimum wheel ship can be rewrite as follows,

$$\omega_1 = \omega_0 (1 - s_1) \tag{11}$$

$$\omega_2 = \omega_0 (1 - s_2) \tag{12}$$

Replacing s_1, s_2 with 0.18 and 0.22. Since $s_1 < s_2$, it follows that $\omega_1 > \omega_2$ during braking. Therefore, whenever the angular velocity ω of the wheel is such that it lies between ω_1 and ω_2, that is whenever $\omega_2 \le \omega \le \omega_1$, the slip velocity is between s_1 and s_2, the braking torque will be held constant. If $\omega > \omega_1$, which represents that the slip ratio lies between 0 and s_1, the braking torque will be increased which move the slip ratio into the optimum area. If $\omega < \omega_2$, which represents that the slip ratio is large than the optimum value s_2, the braking torque will be reduced in an attempt to move the slip velocity back to the optimum area. Fig. 6 represents most, besides that, the angular acceleration from wheel angular velocity is calculated to anticipate velocity changes in the next few milliseconds. The ability to anticipate velocity changes accounts for the superior performance of complex road condition and a sudden change of road condition.

The ABS control is triggered by acceleration. In the first phase, the braking torque is increasing, when the acceleration calculated by the wheel speed is larger than the reference –A1. as it come across the reference acceleration or the slip ratio comes into the optimum area, 0.18-0.22, the braking torque generated by motor will hold until the slip ratio pass by the stable region in Fig. 3. The braking torque is going to decrease at the point the slip ratio is 0.22 and continue decreasing to the next stable region comes or the acceleration reverse and come across the negative reference value –A1. The torque will keep the value in the optimum area of the slip ratio. The braking torque will increase again in the fifth phase when slip ratio leaves the optimum area and will keep the constant when slip ratio comes into the area of 0.18-0.22, or the acceleration is less than A2, and then the control will step into the next phase.

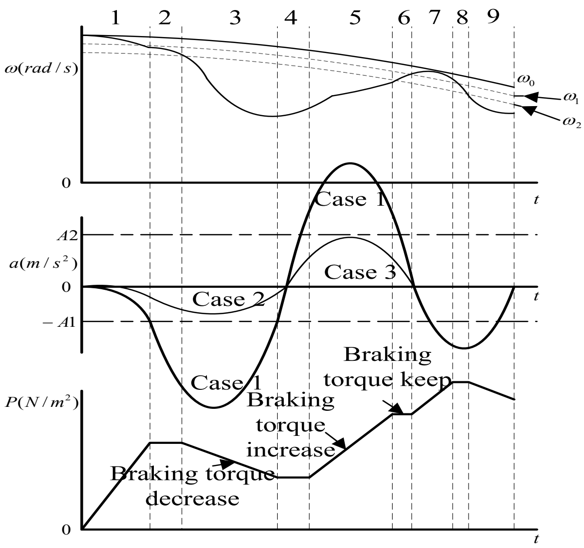


Fig. 6 the control algorithm of the integrated controller

In the study, a sudden road condition change which is shown as case 2 and case 3 in Fig. 6 [15]. If the road is suddenly slippery from case 2 to case 1, and the braking torque cannot be adjusted right at the moment, which indicates that an excessive brake torque is applied, and the wheel has passed the peak of the μ-slip curve and tend to lock. It will lead to increase the braking time and braking distance even wheel sideslip. The control algorithm which calculates the actual wheel slip and the acceleration and compares it with the desired value, detects this point will act and release the brake torque of the wheel. If a sudden high adhesive coefficient pavement occurs from case3 to case 1, and the applied braking torque is smaller than that provided by the controller with new characteristic of the road condition, the wheel will exceed the optimum value and the slip ratio is smaller than the optimum point. An insufficient braking will occur which also can increase the braking distance and braking time.

Control ABS scheme dynamic model is developed in State flow/Simulink as shown in Fig7. Fig. is the single wheel model braking system. Fig. 7a is the state flow chart based on finite state machine theory. Fig. 7b is the PID controller. The integrated controller is simple and applicable to the vehicle.

IV. Simulation and Analysis

The longitudinal characteristics of the anti-lock brake system are studied. In order to optimize the braking force, it is necessary to locate the slip ratio which corresponds to the peak tire road adhesion characteristic. In our study, acceleration limitation is built in this controller which can solve the complex road condition. Vehicle speed, wheel speed, braking distance, braking torque state and slip ratio are the principal investigation to reveal anti-lock brake system.

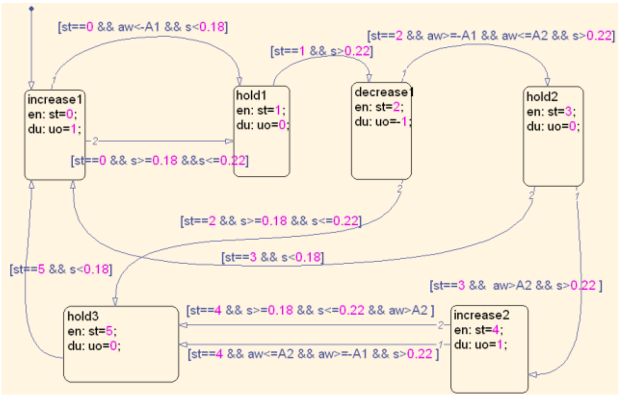


Fig.7a the controller based on the finite state machine theory

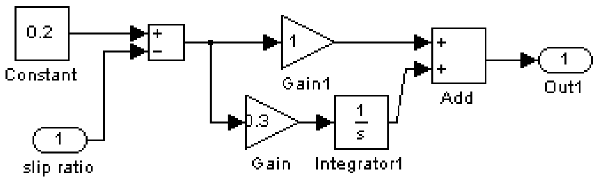


Fig. 7b the PID controller

Fig. 7 The integrated controller of the anti-lock braking system

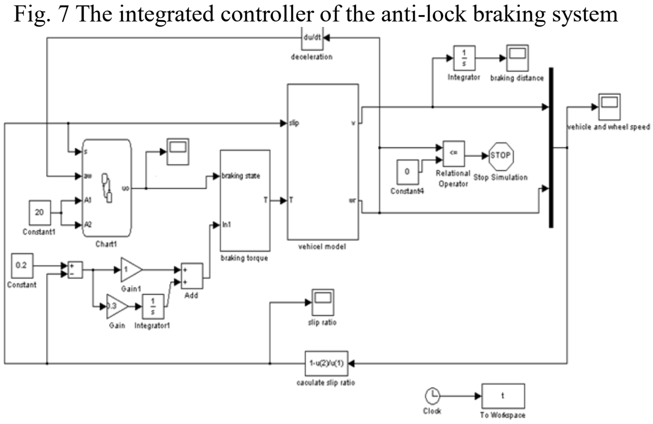


Fig. 8 Single wheel model braking system

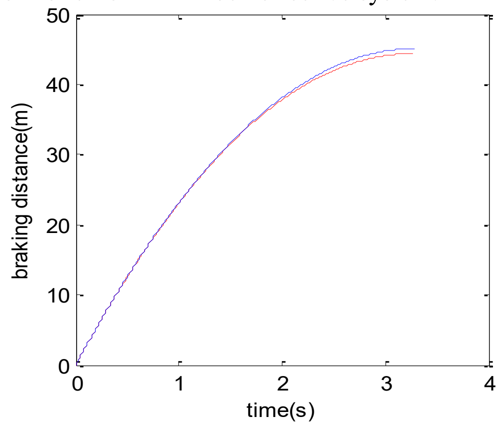
A. Simulation result of different control algorithm.

In this study, the anti-lock braking system consists of the design of control law in order to obtain an optimized braking force. Different controller is built to investigate the braking system, which is discussed in section 3. The control strategy shown in Fig.7 is to keep the slip ratio around 18%-22%, and limit acceleration between +20 m/s^2 and -20m/s^2. The corresponding simulation results are shown in Fig.9. The parameters of the braking system are listed in Table3. We can set different road condition and initial velocity to study the braking characterizes in different conditions.

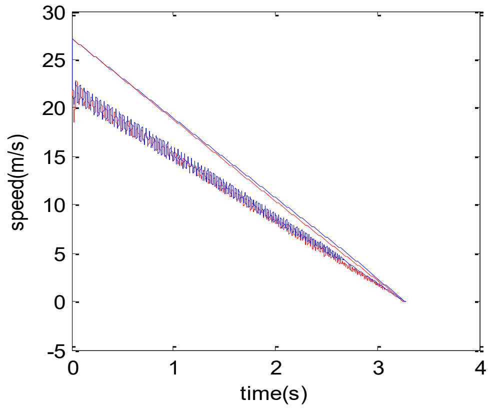
B. Simulation result of various road condition

Fig.10 is about the vehicle braking information on different road. With the brake mode, slip calculation mode and the simplified wheel, the dynamic model with an integrated controller is developed in Simulink. Fig.10 (a), (b), (c) show the vehicle braking information on the different road condition from high adhesive to low adhesion. The characteristic of the road condition is illustrated in Table 1. The blue line represents the integrate controller's simulation results, the red line is the tire slip control's results.

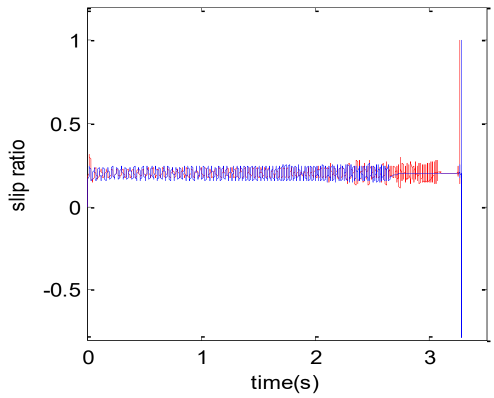
Fig.9 shows the information of the braking characterizes of the anti-lock brake system. These ABS controllers are simulated in dry concrete road surface. In Fig. 9 tire slip control strategy, the slip ratio is kept from 18% to 22%. In integrate control strategy, the slip ratio is also kept from 18% to 22%, deceleration speed limits are -20 m/s^2 and 20 m/s^2. The braking distance is shown in Fig. 9 (a). it is obvious that the braking distance is very close when the new controller is applied. Fig. 9 (b), which is wheel speed and vehicle speed shows that braking time is also close when we our new controller is installed. Fig. 9 (c), (d) and (e) are slip ratio and braking torque state of the braking system respectively, which shows the vehicle with integrated controller reaches stable state sooner than the traditional one. The simulation results indicate that the integrate controller is applicable. The braking system with new controller is an anti-lock effective system.



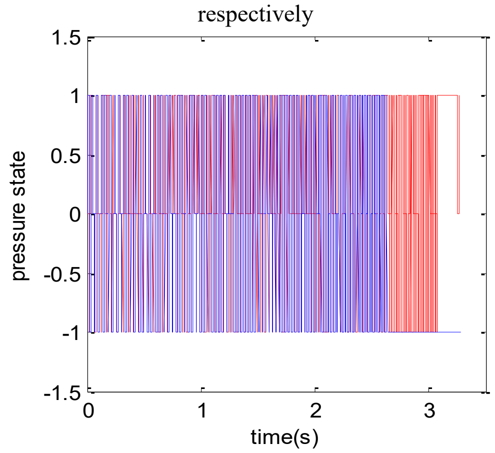
(a) Braking distance of two control strategy respectively



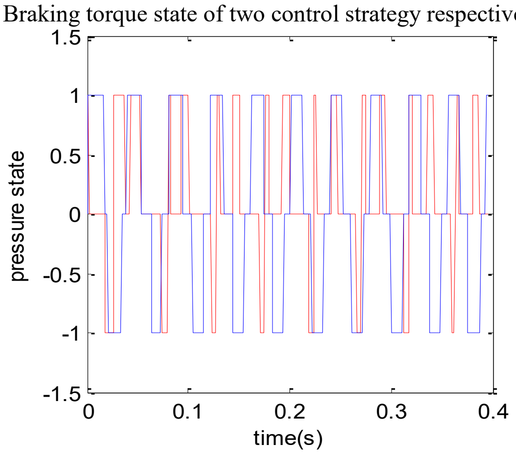
(b) Wheel speed and vehicle speed of two control strategy respectively



(c) Slip ratio is the control parameter of two control strategy respectively

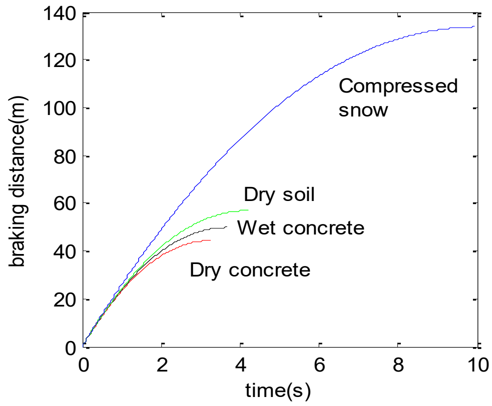


(d) Braking torque state of two control strategy respectively

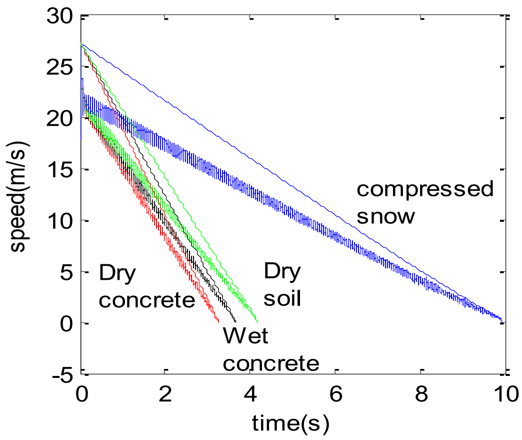


(e) Braking torque state of two control strategy respectively (close look)

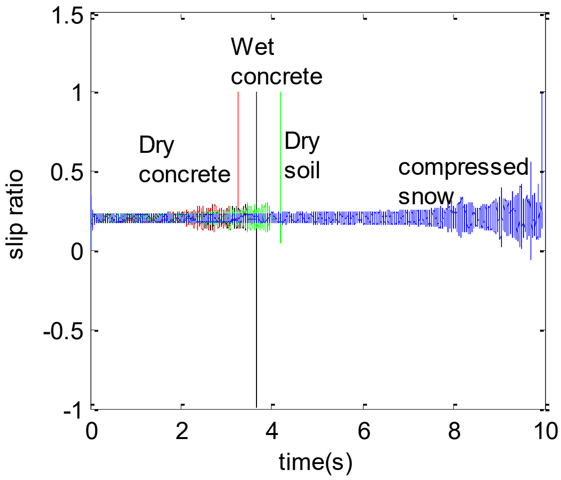
Fig. 9 Simulation results of two control strategy.



(a) Braking distance on different road condition



(b) Wheel speed and vehicle speed on different road condition



(c) Slip ratio at wet concrete road different road condition

Fig. 10 Braking information on different road condition.

It can be seen from the Fig.10, by controlling the slip stabilized between 0.2 and acceleration between -20 m/s^2 and 20m/s^2, even on the icy condition, the braking system can operate effectively. When the road adhesion is higher the braking will be quicker and the braking distance will be shorter. In this way it is able to keep wheel operation near the desired wheel slip value and acceleration between ideal areas.

IV. Conclusion

In this simulation study, two strategies are investigated to obtain an optimized braking force. In tire slip control, by regulating the slip ratio stable region especially in the optimum value (0.18-0.22), an optimum braking force is obtained through a simplified braking model from practical, the anti-lock braking system can effectively shorten the braking distance and braking time. However, the system cannot solve the complex road condition and a sudden change of road condition, a new controller is provided. An acceleration derivative by the wheel rotational speed indicates a sudden change of road condition or a complex condition, and is applied in the new controller. And simulation is produced on different road conditions. The simulation results reveal that the system with integrated controller can effectively reduce braking distance and braking time as good as tire slip control. The control strategy is applicable in different road conditions and also can obtain a maximum braking force and improve the braking performance, respectively, most important is that the new controller is adaptable to complex road condition and a sudden change of road condition. Since all-electric ABS will employ bi-directional power converter to alter the current of the motor, it is easy for the proposed controller to output a gate driving signal to control the current direction, it could provide an effective anti-lock braking system for all-electric ABS for EVs.

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