

# USING THE SLIDING-MODE PWM METHOD IN AN ANTI-LOCK BRAKING SYSTEM

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## ABSTRACT

This study attempted to integrate the Pulse Width Modulation (PWM) method and sliding mode control theory to develop quasi-continuous control for an automobile anti-lock braking system. Two controllers are designed in this study. One applies directly by applying quasi-continuous control to achieve ABS slip control. In addition, the quasi-continuous control method was applied to develop pressure tracking control, and then this pressure tracking controller and the acceleration signal of the tire were implemented together to construct an anti-lock braking controller. Both controllers were investigated on a dynamic test stand. Wet road braking was simulated by spraying water on the contact surface between the tire and the flywheel. Excellent braking results not only verify the performance of the sliding PWM method but also provide an alternative to an ABS controller without slip feedback.

**KeyWords:** Quasi-continuous, pulse width modulation, sliding-mode control, slip, anti-lock braking control.

## I. INTRODUCTION

Because of progress in mechanical and electrical technology, it is now possible to use the originally discrete on-off behavior of solenoid valves to achieve quasi-continuous operation through high-frequency actuation. Muto, Yamada, *etc.* [1,2] applied pulse width modulation (PWM) in combination with high-speed solenoid valves in the linear and angular position controls of hydraulic systems and obtained good results. Shih and Huang [3] also applied PWM and high-speed solenoid valves in pneumatic position control and likewise obtained good results.

Vehicle braking performance, *i.e.*, braking efficiency and vehicle handling, can be enhanced by an anti-lock braking system (ABS). The objective of ABS braking is to increase the wheel tractive forces. ABS is conventionally achieved by controlling the wheel around the peak of the curve of the  $\mu - S$  tractive forces (as shown in Fig. 1) during ABS maneuvers [4]. The slip  $S$  is defined as

$$S = \frac{V_v - V_{tyre}}{V_v}, \quad (1)$$

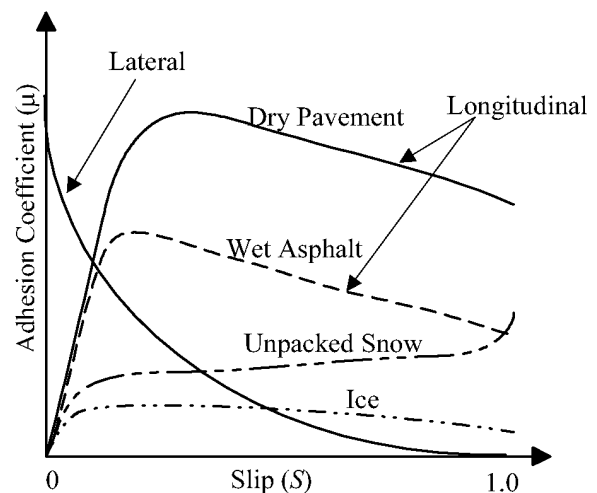


Fig. 1. Relationship between the slip and adhesion coefficients.

where  $V_v$  is the vehicle velocity and  $V_{tyre}$  is the tire speed.

Difficulties in designing an ABS controller include the nonlinear characteristics of the brake dynamics, the time-varying nature of the system components and unknown /changing environmental parameters. Sliding-mode control is a nonlinear control methodology, which allows a large class of nonlinear systems to be controlled despite system parameter variation. In this study, two controllers were designed for ABS. One employs slip feedback. The other applies the sliding-mode control

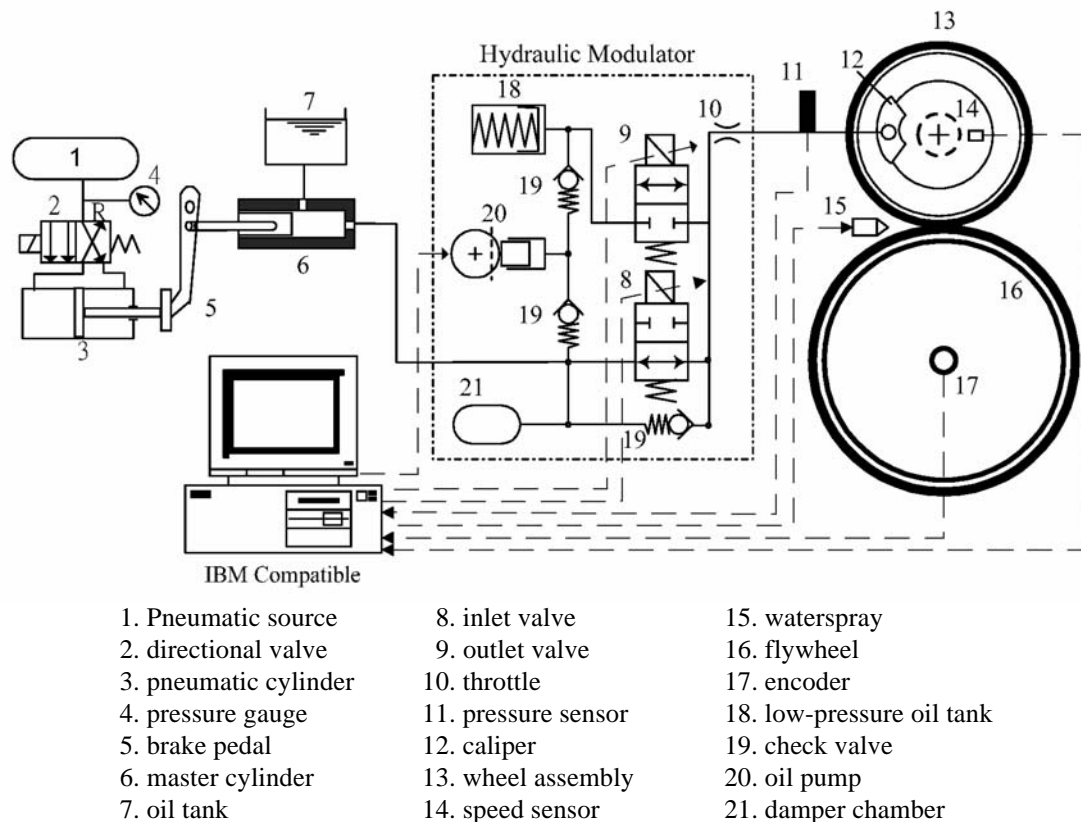


Fig. 2. Schematic diagram of the test stand.

method to design a braking pressure controller, which is then used to design an anti-lock braking controller. The control algorithms consider caliper pressure and deceleration. All the experiments were conducted on a dynamic test stand to study both dry and wet road surfaces.

## II. SYSTEM DESCRIPTION

Figure 2 shows a schematic diagram of our test stand. Initially, the flywheel and the tire are accelerated up to test speed via an AC motor. Next, the motor is turned off, and a pneumatic directional valve is actuated to cause a pneumatic cylinder to push the brake pedal. Brake fluid flows from the master cylinder through the hydraulic modulator into the calipers. The wheel speed sensor and the pressure sensor provide signals that are fed back to the computer. Data processing via the control algorithm yields control signals, which are amplified and fed to the corresponding solenoid valves to maintain reference pressure and prevent tire lock up.

## III. SLIDING-MODE CONTROL

Because the discrete on-off behavior of a solenoid valve is intrinsically nonlinear, it is difficult to obtain the solenoid valve's transfer function by means of linear approximation around the equilibrium point. Thus, the

traditional PID method cannot be applied in this system. Accordingly, sliding-mode control is adopted in this study because it allows a large class of nonlinear systems to be controlled despite system parameter variation [5].

The control algorithm begins with a sliding-mode switching control law, which, however, gives rise to discontinuous control signals and, as a consequence, chattering. In general, smoothing out control discontinuity in a thin boundary neighboring the sliding surface can eliminate chattering. Figure 3 shows the decision algorithms. The signal  $\phi$  is the thickness of the boundary layer. If the control signal  $u_o$  is between 1 and -1, this means that the pressure-increase state ( $u_o > 0$ ) or the pressure-decrease ( $u_o < 0$ ) state is continuous, where the respective open time is proportional to the absolute value of signal  $u_o$ .

In this study, PWM was realized using computer software as opposed to hardware, thus permitting easy and flexible control of PWM characteristics. Figure 4 shows the inference algorithm.

## IV. CONTROLLER DESIGN

As shown in Fig. 1, ABS performance strongly depends on the "slip" control. At the beginning, we applied the sliding-mode PWM method to design a slip controller, using slip as a feedback signal. Instead of trying to find the optimum slip curve, we assigned to the

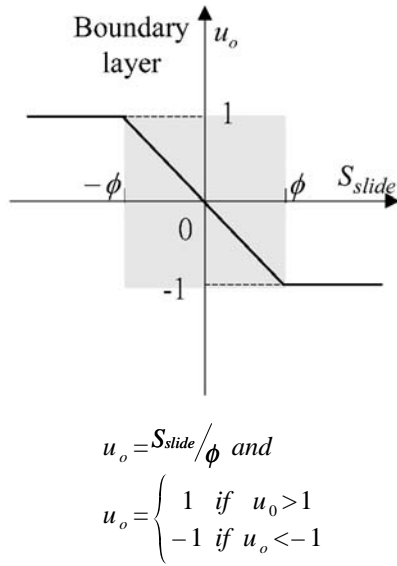


Fig. 3. PWM control algorithm with a boundary layer.

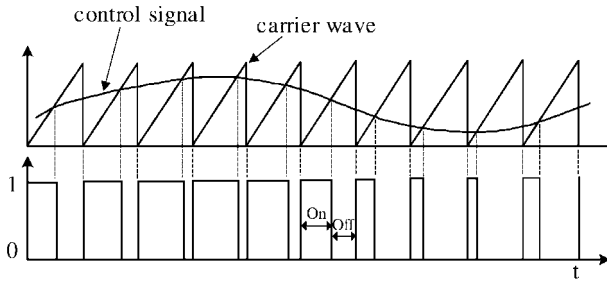


Fig. 4. Software PWM method.

controller some preset value to track so that we could evaluate the performance of the control algorithm. From the results, we could easily find out the performance of the quasi-continuous sliding-mode PWM controller.

However, in a real braking case, the real vehicle velocity is too hard or too expensive to obtain, making it difficult to use slip as the feedback parameter. Therefore, in this study, we introduced another ABS controller, which integrates braking pressure control and acceleration control of the tire. A computer obtains the deceleration of the tire  $\alpha_{tyre}$  by differentiating the tire speed signals. Figure 5 shows the decision algorithm. In this controller, there are five preset deceleration parameters,  $\alpha_A$ ,  $\alpha_B$ ,  $\alpha_C$ ,  $\alpha_D$  and  $\alpha_E$  ( $m/sec^2$ ), where  $\alpha_A > \alpha_B > \alpha_C > \alpha_D > \alpha_E$ .  $\alpha_C$ ,  $\alpha_D$  and  $\alpha_E$  are used to determine whether the deceleration of the tire is lower, slightly higher or much higher than the normal value.  $\alpha_A$  and  $\alpha_B$  are two criteria used to make sure that the tire rotation speed has already been restored from serious slip or light slip conditions. These five parameters are determined based on experience, and the corresponding parameters differ under dry or wet road surfaces.

Once braking occurs, the controller supervises deceleration of the tire  $\alpha_{tyre}$ . If its absolute value is smaller

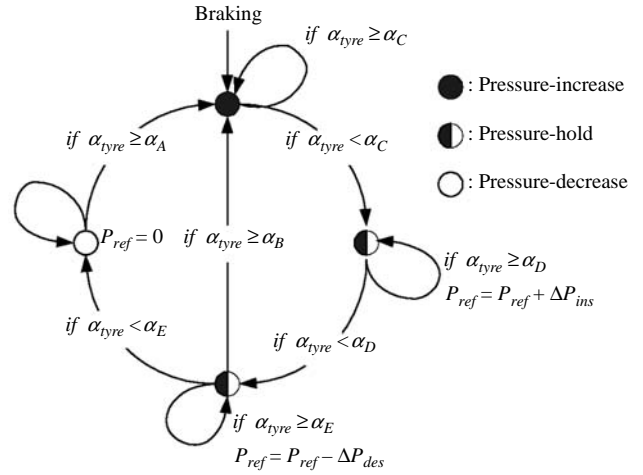


Fig. 5. ABS decision logic algorithm.

than that of the criterion, regarding the negative sign, we obtain  $\alpha_{tyre} \geq \alpha_C$ , which reveals that there is no tendency to lock up, and the computer does not take over control. Otherwise, i.e., if  $\alpha_{tyre} < \alpha_C$ , it is assumed that slippage approaches the peak of the  $\mu - S$  curve, and it is necessary to continue checking whether the slippage has passed the peak. The reference pressure  $P_{ref}$  is held constant (pressure-hold state) during the checking operation. The second criterion,  $\alpha_D$ , which is slightly larger than the maximum deceleration value of dry road surface braking, is chosen to determine whether deceleration has passed the peak value of the  $\mu - S$  curve. In the case of  $\alpha_{tyre} \geq \alpha_D$ , slippage between contact surfaces should not yet have reached the optimum slip value. In the meantime, the reference brake pressure is incremented as shown in equation 2, thus increasing the braking force and causing slippage to approach the optimum value. If  $\alpha_{tyre} < \alpha_D$ , it is assumed that slippage has passed the optimum slip value, and that the braking pressure is now too high. Therefore, the reference pressure is decreased and modified using equation 3 until deceleration increases and again exceeds  $\alpha_C$ . The reference pressure is then held constant until  $\alpha_{tyre} > \alpha_B$ ;  $\alpha_B$  is the criterion for restoring  $\alpha_D$ . The restoring criterion is used to prolong the tire rotation-restoring time to make sure that rotation of the tire has been restored. A pressure-increase step then follows:

$$P_{ref} = P_{ref} + \Delta P_{step}, \quad (2)$$

$$P_{ref} = P_{ref} - \Delta P_{dec}, \quad (3)$$

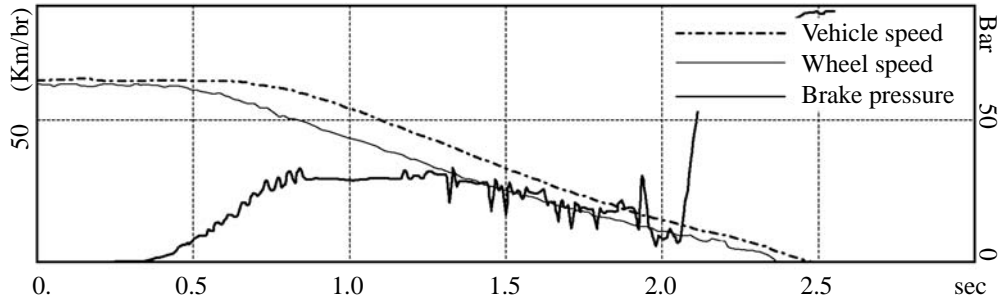
where  $\Delta P_{step}$  is a small increment and  $\Delta P_{dec}$  is a small decrement. If equation 3 does not reduce the brake pressure successfully and deceleration reaches the worst-case, i.e.,  $\alpha_{tyre} < \alpha_E$ , then the reference pressure is set to 0, resulting in the maximum pressure-decrease rate. The reference pressure is then held constant until deceleration increases and passes  $\alpha_A$ , i.e.,  $\alpha_{tyre} \geq \alpha_A$ .  $\alpha_A$  is the criterion

for restoring  $\alpha_E$ . When the tire starts to rotate again, a pressure-increase step follows immediately.

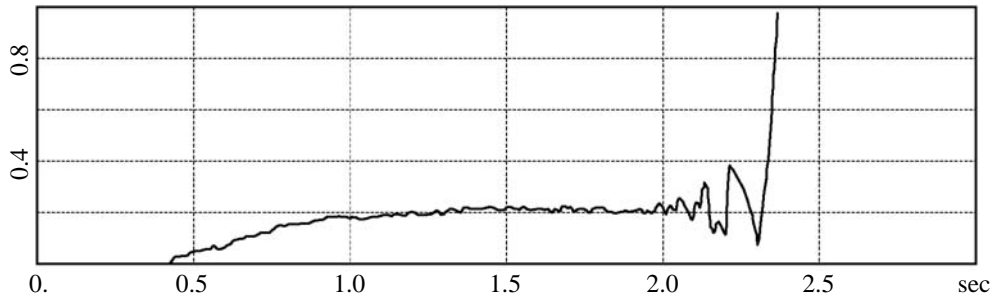
### V. RESULTS AND DISCUSSION

All the controllers designed in this study were veri-

fied on a dynamic test stand. For dry and wet road surfaces, a water-sprayed flywheel was used to simulate a road surface with a low adhesion coefficient. For the purpose of simplification, all the experiments were conducted using a single tire, i.e., a quarter-car model. The initial velocity was 40 miles/hr (64Km/hr), and the sam-

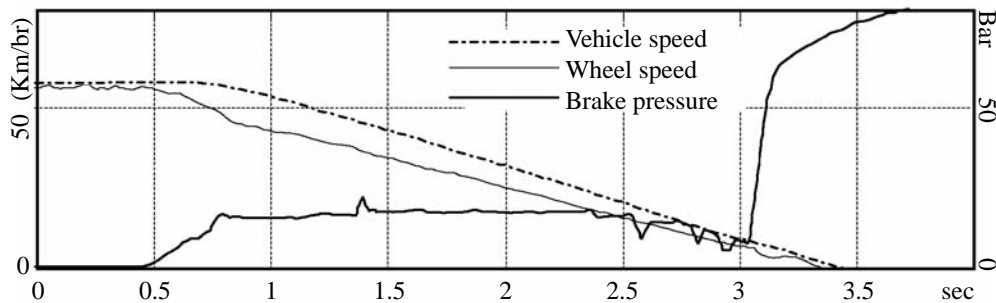


(a) Vehicle speed, wheel speed and brake pressure

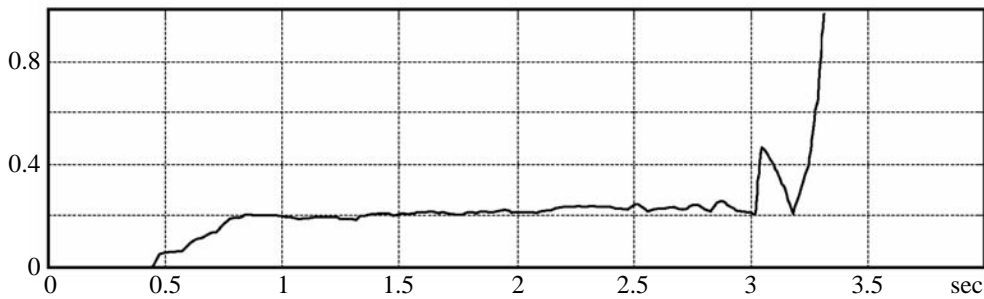


(b) Slip

Fig. 6. Slip control results obtained using sliding-mode PWM control (dry surface).



(a) Vehicle speed, wheel speed and brake pressure



(b) Slip

Fig. 7. Slip control results obtained using sliding-mode PWM control (wet surface).

pling rate was 50Hz.

Initially, a sliding-mode PWM slip controller was designed. Slippage was used as a feedback signal, and the tracking target was preset at 0.2. From Fig. 6(b), we can see that slippage was controlled smoothly at around 0.2. Even in the case of braking on a wet surface (Fig. 7), we

also obtained very good control results.

Secondly, a sliding-mode PWM ABS pressure controller was designed using a pressure controller in combination with a tire deceleration signal. Although we did not use slippage as the feedback signal, real slippage was used to evaluate the control algorithm. After breaking began,

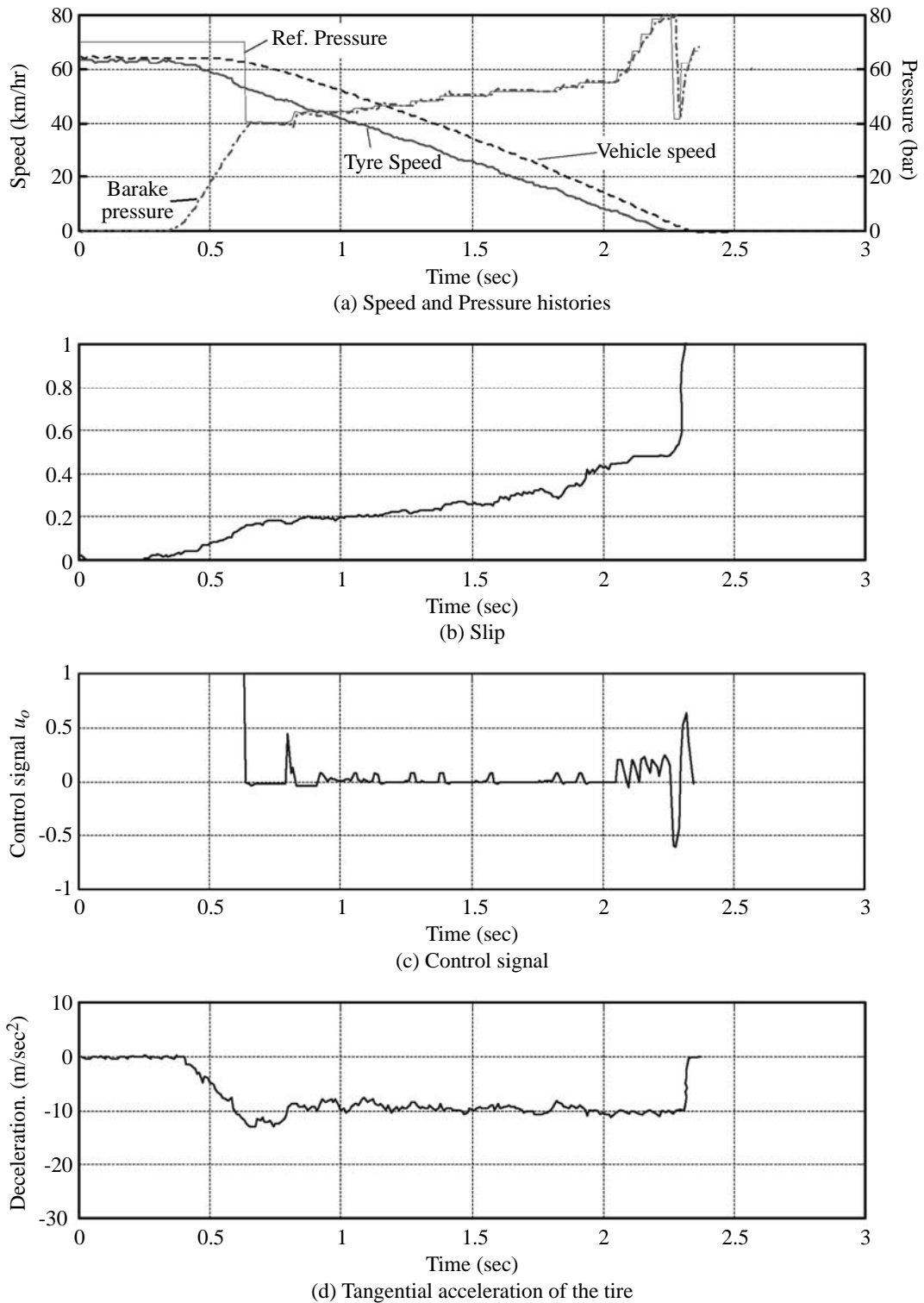
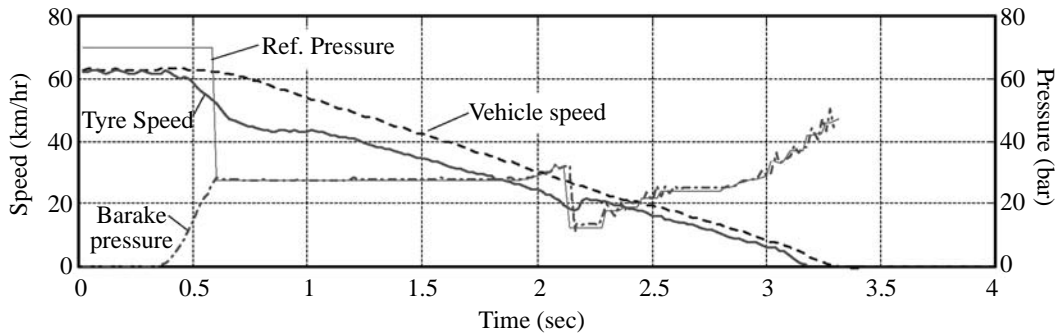


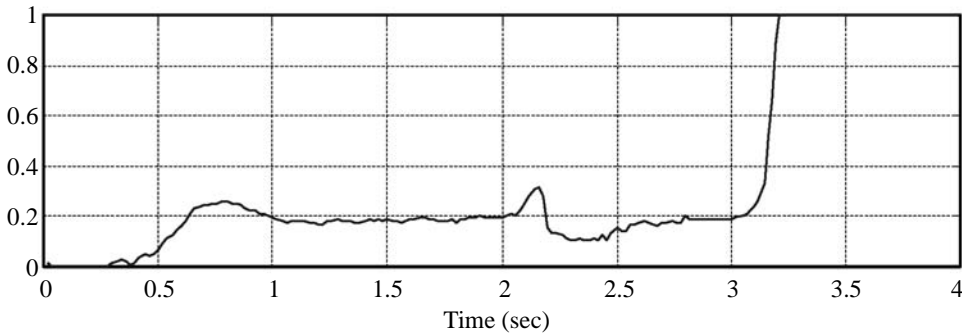
Fig. 8. Time responses of speed, pressure, slip, control signal and deceleration for emergency braking on a dry road surface.

the controller continuously supervised the tire deceleration signal. As can be seen in Fig. 8(a), the reference pressure determined by the anti-lock braking controller varied; nevertheless, the pressure controller provide good tracking results. It is also evident that both the tire and flywheel stopped smoothly. The measured slippage, shown

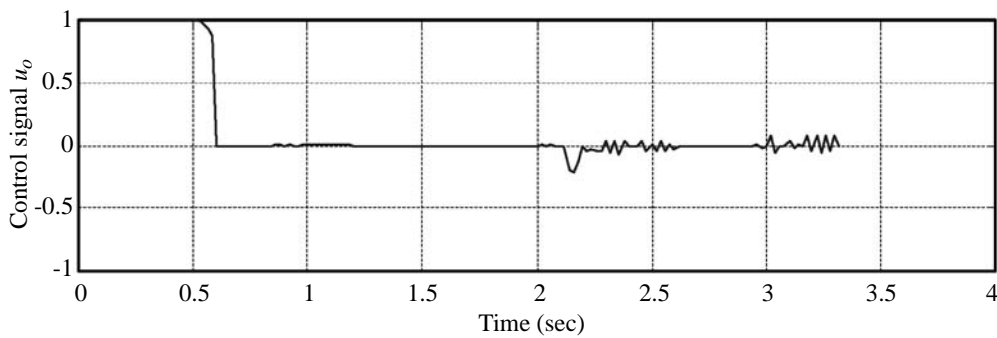
in Fig. 8(b), was maintained between 0.2 and 0.4, indicating excellence performance of this controller. Figure 9 shows the results obtained when water spray was used to simulate a wet road surface. Because of the low adhesive force of the wet road surface, the brake pressure shown in Fig. 9(a) was clearly maintained at a level lower than that



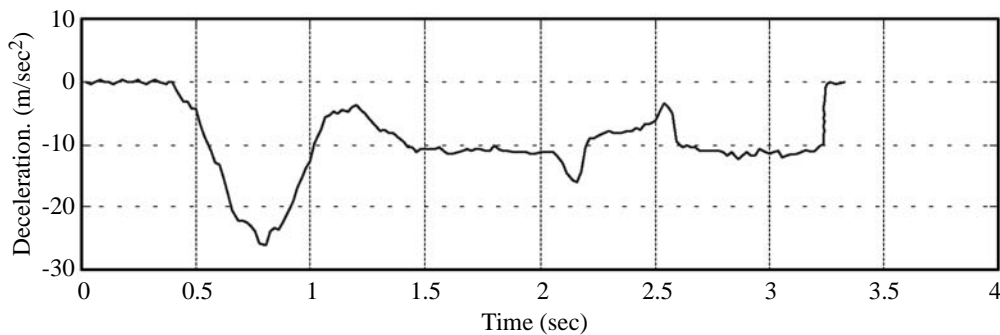
(a) Speed and Pressure histories



(b) Slip



(c) Control signal



(d) Tangential acceleration of the tire

Fig. 9. Time responses of speed, pressure, slip, control signal and deceleration for emergency braking on a wet road surface.

shown in Fig. 8, and deceleration of the tire varied much more. Therefore, it was difficult to keep the slippage curve around the optimum value; as a consequence, it varied around a value of 0.2.

## VI. CONCLUSION

Although discrete operation of solenoid valves could easily cause some chattering during control, the software PWM method can be effectively used to smooth the control results. In this study, two kinds of anti-lock braking controllers with software PWM algorithm were designed. In the ABS slip controller, slippage is smoothly controlled around a preset value, no matter whether a wet or dry road surface is assumed. In the ABS pressure controller, not only is the pressure tracked very well, but slippage is also kept within the optimum range. The excellent braking results obtained not only verify the performance of the sliding PWM method but also provide an alternative to implementing an ABS controller without slip feedback.

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