Wheel Slide Protection System by the Use of the Tangential Force in the Macro Slip Area

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Almost all railway vehicles have brake systems which use the tangential force between rails and wheels. It is difficult to stabilize braking performance and to prevent wheel damage because the tangential force is influenced by various conditions, such as weather, the contact surfaces of the rails and the wheels, etc. Wheel slide protection systems (WSP) are one solution adopted on many vehicles. However, in existing WSP systems, braking force is controlled using limited information from the rotational speed of the wheel. Therefore, they do not always offer optimal control when the tangential force varies frequently. This study proposes a new WSP system which can determine the quality of the tangential force from the brake cylinder pressure when wheel slips occur. The performance of the new WSP was verified through bench tests. As a result, application of the new WSP method reduced braking performance loss.

Keywords: adhesion, macro slip, wheel slide protection, air brake

1. Introduction

Braking on most railway vehicles today utilizes wheel/rail adhesion force. Adhesion force varies easily with the weather and surface conditions of the wheels and rails, etc. Therefore when braking force is increased to reduce braking distance, wheels can slide because of insufficient adhesion force. This leads to risks such as braking distances being exceeded or damage to wheels.

Thus, in order to prevent wheel sliding and to improve braking performance, some proven techniques [1, 2] for improving an adhesion between the wheels and the rails were applied. This report discusses how to improve the performance of existing wheel slide protection systems (hereafter “WSP”) which are activated after wheel sliding occurs to prevent wheel locking and braking distance being exceeded.

Existing WSP systems control the braking force when wheels slide based on information about the rotational speed of the wheels. It is difficult therefore, for the WSP to maintain control in relation to the adhesion force that fluctuates easily, because information about the various “forces” at play, such as braking force, is not available.

This study therefore proposes a new WSP method for air-brake systems, in which adhesion force is estimated on the basis of brake cylinder (BC) pressure information, in addition to wheel rotational speed used in existing systems. The braking performance of the proposed method was verified on a test bench.

2. “Adhesion” and “braking”

“Adhesion” generally refers to the phenomenon of force acting (with or without translation) between the wheels and rails. In this paper, the force acting between wheels and rails is simply referred to as the “tangential force.” Then, the motion equations of rotation and translation are expressed by (1) and (2) respectively, and the definition of the symbols used in Fig. 1 and the equations are shown as follows:

\[ J \frac{d\omega}{dt} = R(F_b - F_m) \]  \hspace{1cm} (1)
\[ \beta_c = \frac{F_m + F_r}{M} \]  \hspace{1cm} (2)

![Fig. 1 Process of braking utilizing adhesion force (a simplified single wheel model)](image)
It is shown by (2) that the tangential force is necessary for translational braking which is the purpose of braking.

It is said that the tangential force generally has the characteristics shown in Fig. 2, and that wheels slide slightly on rails even in normal braking, i.e. wheels and rails are in the "micro slip area." Then, assuming that the translational speed is equal to the rotational speed, i.e. the condition expressed by \( v = \omega r \) (hereafter "ideal adhesion condition"), deceleration of the translational speed and the tangential force are expressed by (3) and (4) as follows:

\[
\beta_e = \frac{F_b + F_r}{M + \frac{J}{R^2}} \tag{3}
\]

\[
\hat{F}_m = \frac{M}{M + \frac{J}{R^2}} F_b - \frac{J}{R^2} F_r \tag{4}
\]

It is shown by (3) that deceleration of the translational motion is directly proportional to the braking force \( F_b \), given that the external force \( F_r \) is not acting. It is shown by (4) that the tangential force which is hard to be measured practically is calculated using \( F_b \).

Wheel slide states correspond to "the macro slip area" in Fig. 2. Then the local maximum value of the tangential force that separates the "micro slip area" and the "macro slip area" is called the "adhesion force," and the value of the adhesion force divided by the contact load between the wheel and the rail (static wheel load) is called the "adhesion coefficient." In many cases, the tangential force is smaller in the macro slip area than in the micro slip area. In some cases, however, tangential forces in the macro slip area are larger than that in the micro slip area as shown by Fig. 3.

Using the definition of "sliding deceleration \( \Delta \beta = \beta_w - \beta_c \) [3]," deceleration of the translational motion and the tangential force in the macro slip area are expressed by (5) and (6) as follows:

\[
\hat{\beta}_e = \frac{F_b + F_r - \frac{J}{R^2} \Delta \beta}{M + \frac{J}{R^2}} \tag{5}
\]

\[
\hat{F}_m = \frac{M}{M + \frac{J}{R^2}} \left( F_b - \frac{J}{R^2} \Delta \beta \right) - \frac{J}{R^2} F_r \tag{6}
\]

Tangential force in the macro slip area is calculated by using the braking force and sliding deceleration because the inertia moment \( J \) is uniquely given by the mass and shape of the wheelset. Assuming "ideal adhesion conditions," \( \Delta \beta = 0 \) is obtained and the tangential force is equivalent to the value obtained by (4). Then, (6) can be applied to the micro slip area.

Equation (6) is considered as an evaluation function of the tangential force. An attempt was made to improve braking performance with the new WSP in accordance with the principle "Larger braking force \( F_b \), and smaller slip deceleration \( \Delta \beta \)."

3. Existing WSP systems

Railway vehicles are currently equipped with WSP systems such as "slip rate wheel slide control [4]," "Fuzzy WSP [5]," and so on. These WSP systems commonly use the following information as parameters and criteria to indicate sliding:

- deceleration (\( \beta \)), which is the differentiated value of the circumferential speed of the wheels,
- speed difference (\( \Delta V \)), which is difference between the circumferential speed of the wheels and the reference speed,
- slip rate (\( \eta \)), which is calculated by dividing speed difference by the reference speed,

where the reference speed is the maximum axle speed, or a value to be considered as the translational speed obtained after a compensational calculation. That is to say that all the information for existing WSPs are based only on speed.

These parameters and criteria used for existing WSPs are set beforehand based on the assumptions of the characteristics of the tangential force as shown in Fig. 2. Moreover, since they only use information about the speed these WSPs cannot properly modify the parameters and criteria if the tangential force deviates from the prescribed assumption during control because they cannot exploit tangential force data.

Figure 4 shows the results of braking tests with wheel sliding on a test bench. In this figure, "period X," called "lengthy slide," indicates that the wheel slips slightly for a long time, even though the WSP has detected a slide and reduces the braking force. It is difficult for existing WSP
systems to recognize such low adhesion and to modify the control parameters automatically during braking. (In practice however, railway vehicles in service are equipped with a protection function to avoid low braking force causing by sliding over long distances: the WSP stops controlling the brake and BC pressure release is inhibited if sliding continues beyond a preset time.)

This study therefore tries to estimate the tangential force from BC pressure on each axle in addition to speed (used for existing WSP systems) in order to modify the WSP.

4. Estimation of the tangential force

4.1 Estimation of the tangential force using a two-cylinder contact model

Figure 1 illustrates a two-cylinder contact model consisting of a roller rig (drive axle) and a wheel (driven axle), which reproduces conditions similar to those in the simple model shown in Fig. 1. The definition of the symbols used in Fig. 5 and the motion equations are as follows:

- $F_x$: Tangential force
- $T_{zw}$: External force for a driven axle
- $T_{zr}$: External force for a drive axle
- $\omega_w$: Angular speed for rotation of a wheel (Direction of braking is defined as positive)
- $\omega_r$: Angular speed for rotation of a roller rig (Direction of braking is defined as positive)
- $R_w$: Wheel radius
- $R_r$: Roller rig radius
- $J_w$: Inertia moment of a driven axle
- $J_r$: Inertia moment of a drive axle
- $\beta_w$: Deceleration of circumferential speed of a wheel ($=R_w \cdot \frac{d\omega_w}{dt}$)

The tangential force in the model is the couple of $F_x$ acting between a wheel and a roller rig moving in a mutually opposite direction. Given that on a real vehicle it is only possible to use wheel related information, the focus is put on the following wheel motion equation (driven axle),

$$J_w \frac{d\omega_w}{dt} = R_w \left\{ (F_b - F_x) + \frac{T_{zw}}{R_w} \right\}$$  \hspace{1cm} (7)

The equation then takes on the form shown below when there is external force effect:

$$F_x = F_b - \frac{J_w}{R_w} \beta_w$$  \hspace{1cm} (8)

Tests were conducted to estimate the tangential force using (8) with conditions corresponding to contact between the two-cylinders.

4.2 Estimation test using two-cylinder contact test bench

Figure 6 shows a two-cylinder contact test bench belonging to RTRI. Figure 7 shows how tangential force is estimated using the two-cylinder contact model test bench. Tangential force estimation was evaluated using (8) and comparing it with the tangential force, assumed to be the true one, calculated by converting the measured value from the torque meter set in the two-cylinder contact model test bench, into the force acting at the contact point between...
the wheel and the roller rig.

Test conditions are shown in Table 1 and Fig. 8. BC pressure applied to the estimated tangential force is the moving average value of every ten points measured at an inlet of the pneumatic-hydraulic converter at 10 ms intervals. Then the braking force $F_b$ is calculated by multiplying BC pressure by the area of the brake cylinder, leverage of the pneumatic-hydraulic converter, and the friction coefficient of the brake block. In the end the tangential force is estimated by $F_b$ and (8).

Figure 9 shows some examples of the estimation results. Figure 9(a) shows brake command, speed, and BC pressure. Figures 9(b) - (d) show the tangential forces estimated from BC pressure compared with the true values calculated with the measured torque values on the drive axle.

As shown in the period 10 - 15 s in Fig. 9 (c), the estimated values agreed reasonably well with the true values even during wheel sliding if the change in BC pressure was small. However, the error between the estimated values and the true values increased due to the transfer delay from BC pressure to the braking force as BC pressure was more frequently exhausted or supplied.

As shown in the period 2-8 s in Fig. 9 (b), the values estimated on the assumption that the brake block friction coefficients were constant differ from the true value to some extent because the friction coefficients varied depending on
speed, pushing force, etc., in practice.

In order to acquire the accurate tangential force, transfer delay and variation in friction coefficients have to be taken into account, and it is assumed that these values differ from vehicle to vehicle and from braking device to braking device. Moreover, in the case of real vehicles consisting of many axles which mutually influence each other’s braking, much more information is required to accurately estimate tangential force.

5. New WSP to estimate quality of adhesion conditions

This chapter proposes a new WSP method derived from one of the practically used WSP systems: the “slip rate wheel slide control [4].” The proposed method was designed to be able to estimate the quality of adhesion conditions.

5.1 Slip rate wheel slide control

Figure 10 outlines the slip rate wheel slide control [4] (hereafter “SR-WSP,”) in which a slip is handled in three states based on preset thresholds, namely “slide,” “stay,” and “re-adhesion (restoration),” while BC pressure is applied or released by the WSP dump valve operating according to the state-specific rules. A slip is detected on the basis of the logical sum of speed difference / slip rate detection (hereafter “ΔV detection”) and deceleration detection (hereafter “β detection”). Speed difference ΔV (km/h) and slip rate η (%) are defined by (9) and (10) respectively.
\[ \Delta V = \text{Reference speed} - \text{Axle speed} \] (9)
\[ \eta = \frac{\Delta V}{\text{Reference speed}} \cdot 100 \] (10)

Reference speed essentially indicates the vehicle speed. Either non-slipping axle speed or speed corrected for control application are practically substituted. SR-WSP helps to prevent braking distances being exceeded although slide detection and WSP dump valve control are determined by simple preset thresholds.

5.2 New criteria for slide detection

This section does not try to estimate the tangential force directly but attempts to design a WSP detection algorithm based on loss of tangential force calculated by (6) which is assumed to be an evaluation function.

The motion equation shown in (1) is rearranged below.

\[ \tilde{F}_m = F_b - \frac{J}{R^2} \cdot \beta_w \] (11)

On the other hand, the imaginary tangential force generated by the same braking force \( F_b \), without causing wheel sliding, i.e. in the micro slip area, is referred to as \( F_w^* \). Then the imaginary translational deceleration \( \beta^* \) (hereafter “imaginary deceleration”) satisfies \( \beta_w = \beta^* \) and \( F_w^* \) is expressed below.

\[ F_w^* = F_b - \frac{J}{R^2} \cdot \beta^* \] (12)

If a wheel is sliding when the same braking force is applied, the following equation is established;

\[ \tilde{F}_m = \frac{J}{R^2} \left( \beta_w - \beta^* \right) = \frac{J}{R^2} \cdot \Delta \beta^* \] (13)

where \( \Delta \beta^* = \beta_w - \beta^* \) is defined as “imaginary slide deceleration.” The equation (13) indicates that a loss of the tangential force due to a wheel slide is represented by an imaginary slide deceleration \( \Delta \beta^* \) instead of the tangential force itself.

Then the imaginary deceleration \( \beta^* \) is calculated using the newly added BC pressure of every axle and designed values such as brake cylinder diameter, mechanical efficiency of braking devices, etc., instead of the braking force \( F_b \) in (3). However, a new parameter “\( k \)” is put together in an imaginary deceleration \( \beta^* \) for tuning in practical use because an imaginary deceleration cannot be decided solely with BC pressure and designed values due to non-linearity of the friction coefficients of brake blocks, etc. Furthermore, new criteria using \( k \beta^* \) and \( \beta_w \) are defined as follows:

\[ \Delta \beta^* > 0 \Rightarrow \beta_w > k \beta^* \Rightarrow \tilde{F}_m > \tilde{F}_w^* : \text{Slide increasing process} \quad (14) \]
\[ \Delta \beta^* < 0 \Rightarrow \beta_w \leq k \beta^* \Rightarrow \tilde{F}_m \leq \tilde{F}_w^* : \text{Re-adhesion process} \quad (15) \]

Moreover, when a higher braking force is applied in the case of low adhesion, the SR-WSP often detects sliding through excessive deceleration. In such cases, it is known that the preset parameters based on the characteristics of the relationship between sliding and the tangential force are not so effective [6]. A new control method is therefore proposed, applying the criteria shown in Table 2, where the inequalities based on (14) and (15) are applied and detection is replaced by “TL detection (Fig. 11)” which maintains sufficient wheel-lock prevention performance for when all axles are sliding.

Table 2 Slide detection criteria and WSP dump valve action

<table>
<thead>
<tr>
<th>Logical sum</th>
<th>Additional criteria for deceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \beta_w \geq k \cdot \beta^* )</td>
</tr>
<tr>
<td>( \Delta V ) detection</td>
<td>( \eta \geq \eta_s )</td>
</tr>
<tr>
<td></td>
<td>( \eta &lt; \eta_s )</td>
</tr>
<tr>
<td>TL detection</td>
<td>( T_L \leq \bar{t}_s )</td>
</tr>
<tr>
<td>Re-adhesion</td>
<td>( \Delta V &lt; \bar{v}_s )</td>
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5.3 Performance evaluation through bench tests

The performance of the proposed method was compared to SR-WSP using the test bench shown in Fig. 6. Test conditions were the same as in Table 1 and parameters used are shown in Tables 3 and 4.

The average of the mean deceleration from 160 km/h to 50 km/h based on braking distance (hereafter “mean deceleration”) in dry conditions (no sliding) resulted in 4.72 km/h/s.

When SR-WSP was applied, the average of the mean deceleration under in wet conditions fell to 3.60 km/h/s. Figure 14 shows that SR-WSP often detected slips through deceleration detection and exhausted BC pressure before sliding reached the preset threshold of $\Delta V$ detection. Then sliding re-occurred just after BC pressure was supplied because re-adhesion was detected. This means that there were frequent cycles which began with a detection and ended in re-adhesion.

When the proposed WSP was applied however, the average of the mean deceleration in wet conditions was 4.09 km/h/s which was approximately 13% higher than with SR-WSP.

Figure 15 shows that the proposed WSP started phased-supply just after detecting sliding and exhausting BC pressure. BC pressure was then kept high under the new criteria for slide detection during wheel sliding because the proposed WSP deemed that adhesion conditions were sufficiently within the threshold of $\Delta V$ detection.

The proposed WSP therefore utilizes the new criteria for slide detection in which (6) is assumed to be an evaluation function of the tangential force. Furthermore, the tangential force can be effectively utilized by maintaining “higher braking force and lower slip deceleration $\Delta \beta$.”
Braking tests from 160 km/h to 50 km/h were performed on test benches to verify the method. The proposed approach showed approximately 13% higher deceleration than the existing method.

In order for the proposed method to be introduced in practice, a system for obtaining BC pressure and calculating the imaginary deceleration would have to be developed, in order to estimate the tangential force during wheel sliding, which does not happen with conventional WSPs because they have no system capable of acquiring BC pressure. The algorithm for calculating imaginary deceleration includes non-linear factors such as friction coefficients. Therefore, in order to improve accuracy, imaginary deceleration in the proposed method may need to be compensated.

The proposed WSP may be introduced onto real vehicles by choosing the available information considering the existing configuration and by validating the controlling performance.

6. Conclusion

In order to utilize the adhesion between the wheels and the rails more effectively, a method was proposed for estimating the tangential force between the wheels and the rails using BC pressure and the performance of the proposed method was evaluated in bench tests. A new WSP was then proposed, which used conventional slip detection criteria using slip rate and a new criteria which did not express tangential force directly but rather an excess or shortage of tangential force in terms of deceleration.

Braking tests from 160 km/h to 50 km/h were performed on test benches to verify the method. The proposed approach showed approximately 13% higher deceleration than the existing method.

In order for the proposed method to be introduced in practice, a system for obtaining BC pressure and calculating the imaginary deceleration would have to be developed, in order to estimate the tangential force during wheel sliding, which does not happen with conventional WSPs because they have no system capable of acquiring BC pressure. The algorithm for calculating imaginary deceleration includes non-linear factors such as friction coefficients. Therefore, in order to improve accuracy, imaginary deceleration in the proposed method may need to be compensated.

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References


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