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Wheel slip rate control using synchronized speed pulse computing

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Abstract

Anti-skid brake control systems for wheel slide protection have been installed on recent rolling stocks. In such systems, it is essential to avoid increasing of braking distance and causing wheel flats under wet condition. In order to improve air braking pressure control and to keep wheel slip rates small in micro-slip wheel rotation, an anti-skidding brake control system named the slip rate control and a new pressure intensifier cylinder which had wheel slide control valves were developed for the Shinkansen brake. The measures processing speed pulses achieved shorter calculation time of each wheel speed/deceleration and rapid wheel slip detection. We obtained a good result that the extension of emergency braking distance was under only 4.5% compared with about 20% extension of braking distance using conventional anti-skid systems under wet conditions. This system was adopted into the brake of Shinkansen series E2,E3,E4 more than 200 vehicles.

1 Introduction

In the event of earthquake and other abnormalities, it is vital to decelerate and stop the Shinkansen trains safely, rapidly, and surely, to minimize the damage.
Slip protection devices ware installed on the Shinkansen, for preventing an elliptical wear called wheel flat [1] in the wheel tread, that was caused by wheel slips under excessively large braking force. Frequent slips activate the slip protection device, but, since the braking force decreases, the braking distance is

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substantially extended.

In order to overcome this problem, two measures were conceived to improve the slip protection device of the Shinkansen. One is to apply the slip rate control system [2] to the Shinkansen, which was put into practical use for narrow-gauge high-speed vehicles, so as to reduce substantially the speed computing time. The other is to use slip protection by reducing the air pressure in stead of the conventional technique by reducing the brake hydraulic pressure. On the basis of these concepts, we developed a higher speed computing system for the slip rate control device (SRC) and a small-sized, lightweight brake intensifier cylinder (BIC) necessary for modifying the pressure control method.

2 Necessity of the slip rate control system

2.1 Loss of braking force during slip control

Figure 1 shows a wheel speed mode from the beginning of slip to the re-adhesion and pressure reduction. On wet rails, wheel slip occurs when the braking force exceeds the adhesive force between rail and wheel. The slip protection device reduces the air pressure of brake cylinder (BC) to induce re-adhesion of wheels. Conventionally, the BC pressure was reduced more than necessary, then returned to the original pressure. In this case, it often happed that the required braking force could not be achieved in spite of re-adhesion, because of delayed activation of valves and time lag in rise of compressed air pressure. Since this causes loss of the train deceleration, it is essential not to lower the BC pressure excessively.

Slip is detected referring to the wheel speed, speed difference between wheel and vehicle, slip rate, and wheel deceleration. These are called slip detection factors, and the proper threshold (limit) is set to enable detection of the slip starting point, slip holding point, and re-adhesion point.

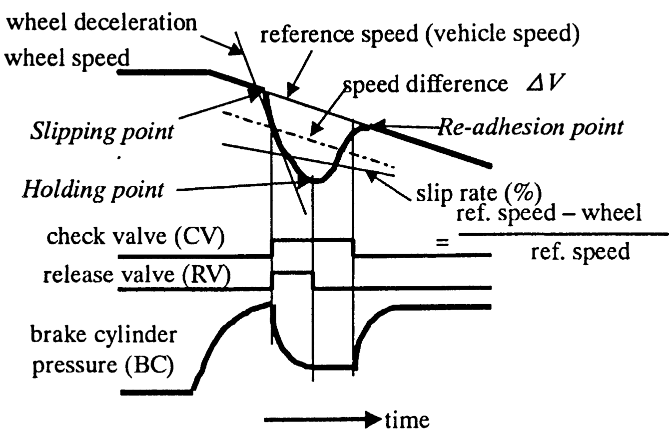

Figure 1 : Wheel slip detection and pressure control for re-adhesion

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2.2 Effective utilization of adhesive force in slip rate control

The slip rate is the value obtained by dividing the difference between train and wheel speeds by the train speed, which represents the magnitude of wheel slip. Within the micro slip range where the slip rate is about 0.2%, the tangential force coefficient increases approximately in proportion to the slip rate. Within the macro slip range beyond the above range, it is known that the tangential force coefficient shows various behaviors [3].

Generally, the tangential force coefficient tends to decrease as the slip rate increases. Therefore, if the slip rate is controlled below 5% through slip control with high-response slip detection, the adhesive force between rail and wheel can be effectively utilized [4]. Taking this into consideration, the following targets were set up for slip rate control:

(1) The braking force is immediately decreased when slip is detected;

(2) During slip, the braking force is increased and decreased, avoiding excessive decrease, while monitoring the slip magnitude of each wheel ;

(3) During slip, the slip rate is kept within a range of 0 to about 5% (Figure 2) ;

(4) When any re-adhesion trend is observed, the adhesion is expected to improve in the next instant ; thus, the braking force is raised immediately.

Even if slip occurs again, it is possible to utilize effectively the adhesion force, by limiting the slip rate to a small level. To achieve the targets, rapid detections of slip and re-adhesion are essential.

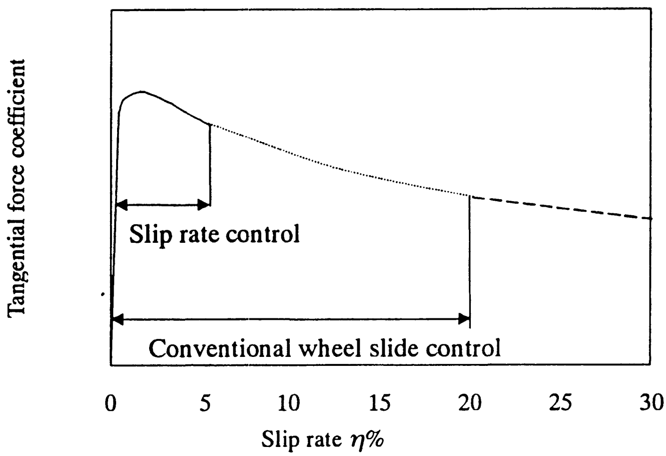

Figure 2 : Range of the slip rate control

2.3 Pressure control during slip control

2.3.1 Mechanical brake of the Shinkansen

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The Shinkansen uses mainly the electric brake, while using the mechanical brake for emergency purpose and stop at stations. In the case of abnormalities such as earthquake, the electric brake cannot be used because power feed through the overhead line is stopped, so the mechanical brake alone works.

Figure 3 is the diagram of the mechanical brake control and the slip rate control system. The slip control system detects the wheel speed by means of a pulse generator installed on the axle and controls the pressure to maintain the wheel slip rate using two valves, that is, release and check valve.

The air pressure is converted to the hydraulic pressure in the brake intensifier cylinder (BIC), activating the disk brake. CPU boards for control are integrated in the brake control unit.

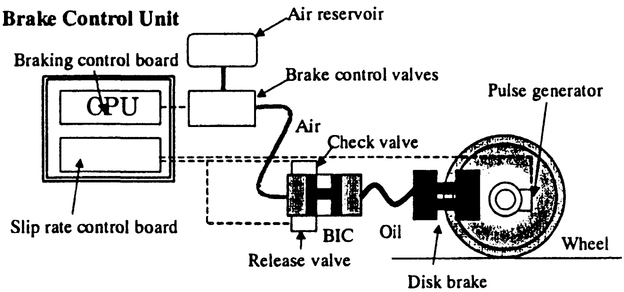

Figure 3 : Mechanical brake and anti-skid devices of Shinkansen

BCU computes the wheel speed by integrating the number of pulses output from the pulse generator within the basic time span. This generator, installed on the axle, generates 60 pulses per rotation.

2.3.2 Pressure control

Conventionally, detection of slip activates the slip prevention valve mounted on the hydraulic pressure side outlet of the pressure intensifier cylinder, to decrease the BC hydraulic pressure to nearly zero as shown in Figure 4.

The new slip rate control for the Shinkansen enables effective utilization of the adhesion coefficient, by reducing the BIC pressure in response to the degree of wheel slip. In the control algorithm, for the initial stage of slip, pressure decreases during time t_1 of CV while pressure holds during time t_2 of. When no re-adhesion occurs in low adhesion state, the BIC pressure is decreased further for a time period twice t_1. Subsequently, the slip rate is monitored while maintaining the pressure for the time t_2 and the next operation is determined.
As described above, the control software incorporates the measures for low adhesion and those to prevent continuation of small slip for a long period.

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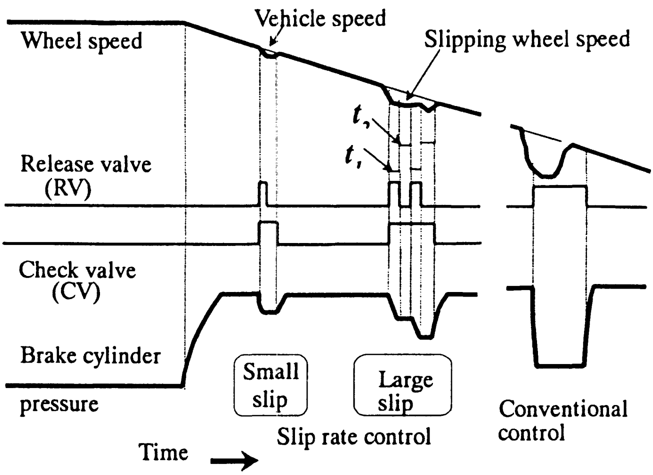

Figure 4: Pressure reduction modes on the slip rate control

2.4 High speed computing of wheel speed and deceleration

The speed is a basic value for detection of wheel slip. Since, by the conventional method, the speed pulse duration is relatively long, the pulse count had an error equivalent to maximum one pulse at the start and end of computing

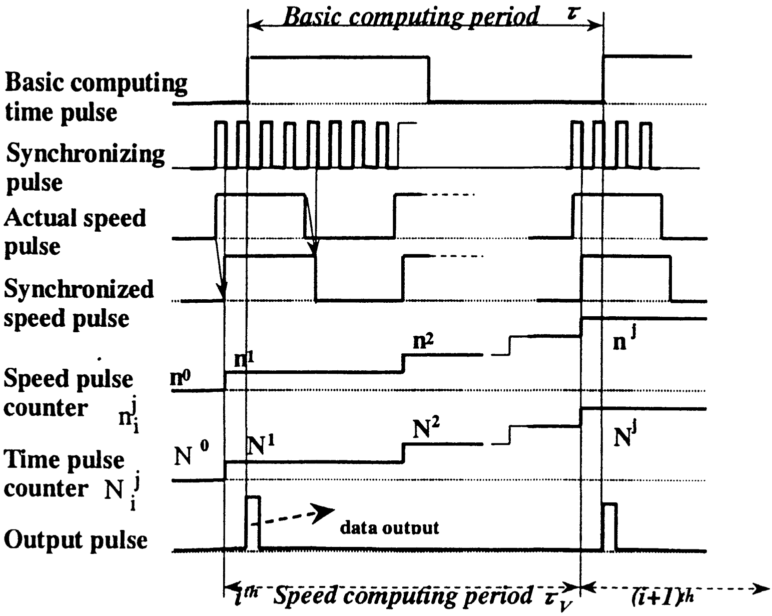

Figure 5: Chart of synchronized pulses for speed computing

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period. Therefore, large errors generated when the computing period τ_v was shortened. For providing a solution for such inconvenience, the new method increases the computing speed and enhances the computing accuracy to minimize the error, resulting in increased accuracy of slip detection. Features are as follows (Figure 5):

(1) Generation of synchronized speed pulse train

The actual speed pulse train is changed to a synchronized speed pulse train with the help of a very high frequency synchronizing pulse train, so that the counting start points can be made coincident between speed and time.

(2) Correct counting of speed pulses

The speed pulses and time just before the end of basic computing period are counted from the speed pulses entered before the start point of the basic computing period by using the time pulses.

(3) Synchronization of output of the speed pulse count result

The data output pulse that triggers outputting of the integrated number of speed and time pulses, is generated at the start of every basic computing period. This enables rapid entering of speed and time data into the CPU.

2.5 Evaluation of accuracy of speed and deceleration

The wheel speed V(km/h) and wheel deceleration β(km/h/s) are represented respectively as follows:

$$V = F_0 n_i / (k N_i) \quad (1)$$

$$\beta = F_0 \{ n_i / N_i - n_{i+1} / N_{i+1} \} / (k \tau_\beta) \quad (2)$$

τ : basic computing time (s)

τ_v : speed computing time (s)

τ_β : decelerati on computing time (s)

F_0 : time countor pulse frequency (Hz)

k : constant related with whee l dia. and pulse generator

n_i : speed pulse summation in ith period

N_i : time pulse summation in ith period

The speed error E_v is a sum of the error by time count pulses and that by synchronizing pulses which related with synchronizing pulse frequency F_1. In order to increase the computing speed, it is necessary to shorten τ_v and τ_β while reducing the error further. For this purpose, F_0 and F_1 were set as high as possible at 192kHz.

Table 1 shows the time necessary for computation of speed, deceleration, and

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Table 1 Comparison of computing times

Slip detection factors	Slip rate control	Conventional control
Speed	42ms	200ms
Deceleration	105ms	350ms
Jerk	210ms	-

jerk in the slip rate control, in comparison with the conventional control. The computing time was reduced to 1/5 of the conventional control for the speed and to 1/3 for the deceleration. In addition, the slip rate control enables jerk detection in 210ms. Though the computation is performed at such speeds, a high accuracy was achieved; the computing error at V=160km/h was 0.04km/h or less for the speed and 0.18(km/h)/s or less for the deceleration.
For this device, an IC using a microcomputer (CPU) was manufactured and incorporated into BCU to compute the wheel speed.

3 Configuration of the new brake intensifier cylinder (BIC)

The brake intensifier cylinder is a device that performs intensified conversion of the pneumatic brake control pressure into hydraulic pressure to activate the hydraulic disk brake device. The slip protection mechanism of conventional BIC is of a type in which the BC hydraulic pressure is released to the outside of circuit in the case of slip. Then the hydraulic piston is pushed in each time slip occurs, which inevitably needs a long cylinder stroke, 180mm.

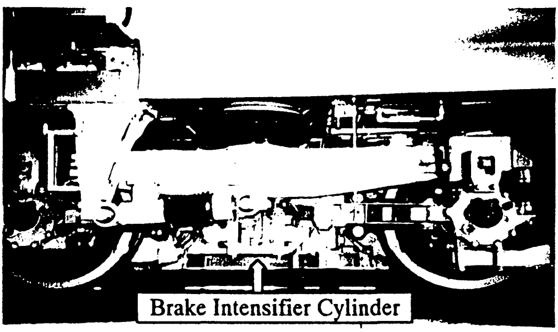

Figure 6 : New BIC installed on the E3 series bogie

In contrast, the new method performs slip control by reducing the air pressure on the primary side of BIC. This substantially reduced the cylinder stroke to 55mm, and removed the hydraulic slip protection valve (Figure 6). Comparing with the conventional cylinder, the new cylinder can achieve substantial downsizing and weight reduction; 61% in mass and 67% in length.

4 Running test results for verifying the control characteristics

4.1 Test method

To confirm the performance of the slip rate control and the new air–pressure-control type BIC for slip control, these systems were installed on E3 series

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Shinkansen of JR East. High-speed test running was made on the commercial line. The braking system of series E3 is requested very hard performance that the train must stop within 600m from 130km/h at over $1.44 m/s^2$. Two train sets of E3 Shinkansen were used as shown in Figure 7.

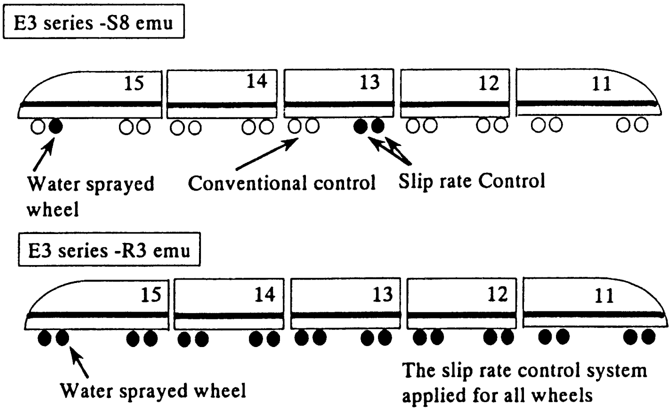

Figure 7 : Running test conditions on the slip rate control

Water was sprayed about 4 liters per minute every nozzle over the rail top from the vehicle to forcibly cause wheel slip. Test running was made in rainy days, so that slip state could be compared between rainfall and water spray conditions.

The maximum value of slip occurrence during one emergency braking (initial braking speed 130km/h) was 17 on the second wheel under rain condition. But the total slip occurrence through a train set was higher during water spray than during rainfall with lower adhesion in water spray.

4.2 Slip rate control condition

The slip rate control device and air-pressure type brake intensifier cylinders were

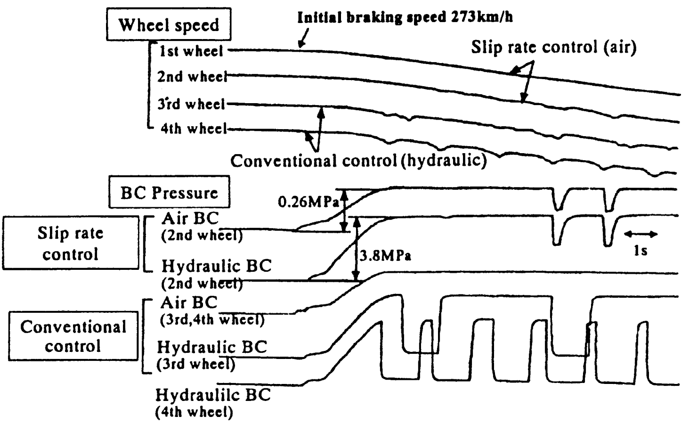

Figure 8 : Advantage of the slip rate control against conventional control

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installed on the first and second wheels of the first bogie of the third vehicle in the first train set. With water spraying that began in the speed range of 270km/h, the emergency brake was applied for comparison with the third and fourth wheels controlled by the conventional method. As shown in Figure 8, the new slip rate control showed less reduction of BC hydraulic pressure and shorter decompression time than the conventional method.

In the case of conventional control, the BC hydraulic pressure dropped to nearly zero, resulting in substantial loss of braking force. Many slips of the fourth wheels is attributed to the fact that these wheels were sprayed with water directly, so there is no relationship between control method and slip frequency. In the brake test on Shinkansen and conventional lines, most of the slip rate controls were of a two-stage pressure control. The speed reduction was 5km/h and the slip rate 4% or less for slip wheels.

4.3 Braking distance

Slip occurrence was less in the brake performance test with the second train set on the Shinkansen line. Accordingly, almost no difference was observed in the braking distance between dry and water spray conditions. This is due to the fact that the braking force is set lower on the Shinkansen line than on the conventional line. The target braking deceleration at 275km/h was about $0.44 m/s^2$. The emergency braking distance with sprayed water was 3500m when the initial brake speed was 270km/h.

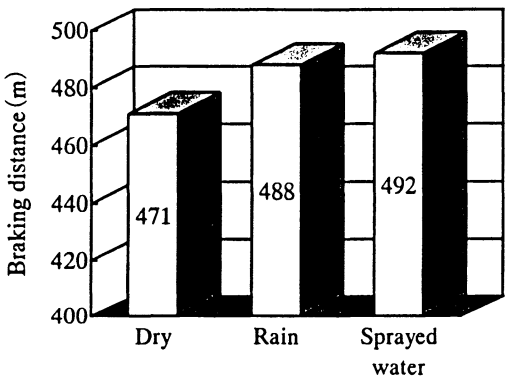

Figure 9 : Emergency braking distance from 130km/h

In the emergency brake test on the conventional line, the initial speed was 130km/h and the target deceleration speed was set at about $1.5 m/s^2$. The emergency braking distance with the initial speed of 130km/h was as shown in Figure 9 under conditions of rainfall and water spray. Though slip caused by decrease of adhesion occurred frequently, the average braking distance increased by 3.6% with rainfall and 4.5% with sprayed water when compared with dry condition. It should be noted that the conventional slip protection occasionally resulted in 10% to 20% elongation of the braking distance though this varies with the number of vehicles of the train set. The test results demonstrated that the new control system can shorten the braking distance significantly.

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5 Summary of the results and conclusions

The slip rate control system and compact lightweight brake intensifier cylinder were developed to ensure safe and rapid deceleration of high-speed running Shinkansen trains even in the case of abnormality. Emergency brake test was made at 275km/h on the Shinkansen line and 130km/h on the conventional line with sprayed water. The following results were obtained.

(1) The method to reduce speed and deceleration errors contributed to substantial shortening of the computing time to detect slip within a time not more than one third of the conventional technique.

(2) When the slip rate control is active, the wheel slip rate is not more than 4% , that is, within the target range.

(3) The elongation of emergency braking distance under water spray condition is not more than 4.5% compared with the dry condition. The braking distance could thus be shortened from the conventional method.

(4) The weight of the new brake intensifier cylinder for air-pressure slip control was reduced to 61% and the length was reduced to 67% of the conventional device.

(5) Because of the above achievements, this system was installed and practically applied to about more than two hundreds vehicles of E2, E3, and E4 series.

Finally, we would like to express our gratitude to those concerned of JR East for their cooperation and guidance during survey and test with actual vehicles in the course of promotion of development. We thank those concerned of NABCO Ltd. and Shinko Electric Co. Ltd. for their efforts on manufacturing the devices.

References

[1] N.Kumagai, K.Nagase, et al. : Factors of wheel flat occurrence and preventive measures, Wear, Elsevier Science Ltd., No.144 (1991) p.277

[2] N.Kumagai, et al. : Brake technologies for higher speeds on Shinkansen and conventional lines, Proceedings of 2nd World Congress on Railway Research, Colorado Springs, AAR, (1996) p.327

[3] ORE Question B164 : Adhesion during braking and anti-skid devices, Report No.2, Office for Research and Experiments of the International Union of Railways, Utrecht, April(1990) p.16

[4] N.Kumagai, T.Obara, I.Hasegawa : A new brake system for speed-up using fine anti-skid brake devices and track brakes, RTRI Report Vol.8, No.3, (1994) p.13 (in Japanese)