Brake System for Shinkansen Speed Increase



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The Shinkansen brake system secures deceleration by controlling braking force according to the adhesion characteristics that vary as speed changes, while preventing wheel slide. But, as speed further increases, braking distance becomes significantly longer due to the effect of the speed increase itself combined with the decrease in transmitted braking force due to the decrease of the adhesion coefficient in the high-speed range. Accordingly, in order to shorten the emergency braking distance at 360 km/h to a level equal to that of 275 km/h —the running speed of E2 series presently in operation—we improved performance of the basic brake equipment, optimized wheel slide readhesive control and developed equipment for increasing air resistance as a supplementary measure.

● Keywords: Shinkansen, FASTECH, Adhesion coefficient, Emergency brake, Air resistance

1 Introduction

The emergency braking distance of the present Shinkansen is just under 4,000 m (E2 series at 275 km/h). If increasing initial braking speed to 360 km/h while leaving the braking performance as-is, the emergency braking distance will extend to as long as approx. 7,000 m. But the analysis of the risk increase in case of earthquake due to Shinkansen speed increases indicates that the most effective way to control that risk is to keep the emergency braking distance from becoming longer as much as possible. Accordingly, we decided to develop a brake system to deal with speed increase in the FASTECH project, aiming for an approx. 4,000 m emergency braking distance at 360 km/h. To achieve that rapid deceleration that the present Shinkansen does not require, we developed basic brake equipment that has the braking force required for that and a brake control method that makes full use of the adhesion between wheels and rails. Apart from brake equipment, we also developed equipment for increasing air resistance that supplements braking devices that does not rely on the adhesion and examined the effect and safety of the new device when used.

2 Measurement of Adhesion in High Speed Range Using Cars Presently in Operation

As mentioned above, braking of rolling stock depends on the adhesion between rails and wheels that transmit braking force (maximum friction). Thus, in order to develop brake equipment that handles high running speeds, it is necessary to know the adhesion coefficient in the speed range in question. The wet standard adhesion value currently applied to the Shinkansen is calculated by the adhesion planning formula used since the start of Shinkansen operation:

Adhesion coefficient = 13.6/(V + 85), V: Velocity (km/h)

We also verified data on adhesion in the high speed running tests of 200-series and STAR21 Shinkansen cars to achieve operational running at 275 km/h. But we did not have sufficient data about adhesion in the over 300 km/h speed range; so, we had to verify whether it is appropriate or not to apply that formula to the future higher-speed Shinkansen.

In this context, we carried out measurement of adhesion in the high-speed range up to 360 km/h using cars actually in operation in advance of the development of FASTECH. As shown in Fig. 1, the adhesion coefficients of the head cars (sprinkler cars) are plotted almost along the extension lines of the past measurement values. Those measurement results proved that the conventional adhesion planning formula could be applied to the over-300 km/h speed range. The results also indicated a tendency for higher adhesion coefficients for the cars in the rear of the train set and the effect of the ceramic particle injection method developed by Railway Technology Research Institute to increase adhesion.

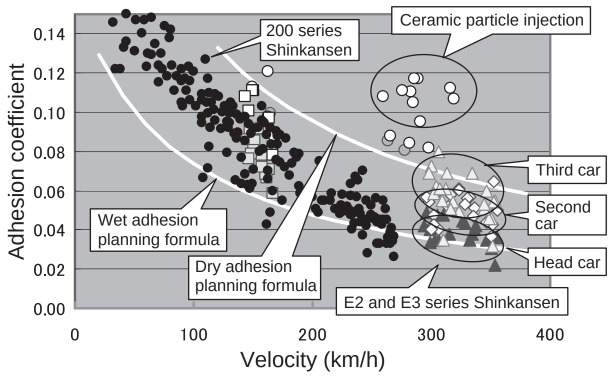

Fig. 1 Adhesion Measurement Results Using Cars in Operation

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3 Setting Deceleration of Braking for FASTECH

As explained above, we have confirmed that the adhesion coefficient between wheels and rails is in line with the traditional formula in over-300 km/h speed range also, as was expected. We therefore planned service braking deceleration for FASTECH under that assumption.

But, stopping at 4,000 m after braking at 360 km/h requires much more deceleration, as mentioned in the introduction. Thus, we introduced "rapid deceleration emergency braking" that ignores the adhesion limit. Since it is impossible to brake at that level of deceleration without sliding the wheels, we developed a brake control method that assumes wheel slide from the start and considered use of equipment for increasing air resistance and ceramic particle injection together with that braking as a supplementary method.

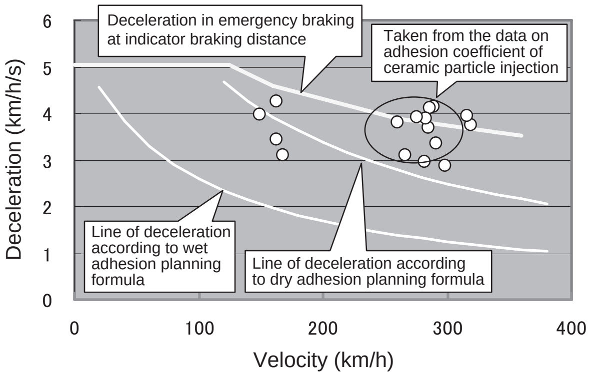

Fig. 2 Rapid Deceleration Emergency Braking of FASTECH

4 Development of Basic Brake Equipment

As the maximum speed increases, the kinetic energy that the brake equipment has to absorb at braking increases too. For example, the heat generation at emergency braking at 360 km/h is 70 to 80% more than heat generation at 275 km/h, and the heat load on the basic brake equipment increases tremendously. Furthermore, decrease of the friction coefficient during braking has to be avoided to achieve the rapid deceleration as mentioned in the above paragraph; hence, higher performance of the basic brake equipment is required. On the other hand, the weight of the basic brake equipment as a part of the unsupended mass cannot be made heavier, since rolling stock should be as light as possible to prevent ground vibration etc.

To meet those requirements, we changed the brake structure by introducing pneumatic calipers, equal-pressure brake lining and center-mounted brake discs; and we developed two types of basic brake equipment based on that concept. As a result of that development, we were able to make basic brake equipment that has stable braking force (rapid deceleration emergency braking) as planned, without increasing the weight.

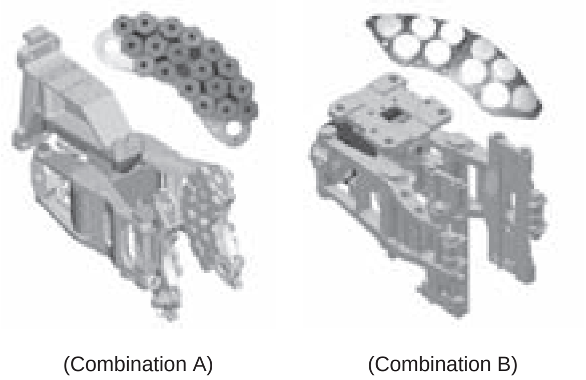

Fig. 3 Appearance of Developed Basic Brakes

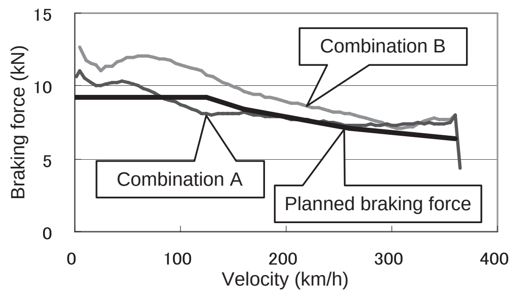

Fig. 4 Braking Force of Developed Basic Brake Equipment

5 Development of Optimal Wheel Slide Readhesive Control

In braking for rolling stock that does not have a very high adhesion coefficient between wheels and rails, mis-control of braking does leads to damaging the tread of wheels on top of being the cause of wheel lock and longer braking distance. So, when wheels might lock, the braking force on the axle involved is eased to re-adhere wheels to rails. We call this wheel slide readhesive control.

As explained above, rapid deceleration emergency braking assumes wheel slide while braking, since the deceleration is set above the adhesion limit between wheels and rails. The points of our development were how to reduce wheel slide, how to prevent over-easing of braking (because loosening of braking for readhesion causes loss of braking force during loosening) and how to readhere wheels to rails quickly; in other words, how to slide wheels appropriately.

The wheel slide readhesive control of present E2 series and E3 series Shinkansen uses detection of deceleration and difference of speed together; and in that control, braking of the sliding axle is immediately eased to facilitate readhesion in case of sliding. The concept behind that is to place importance on how early to detect wheel slide to ease braking. In contrast, the rapid deceleration emergency braking of FASTECH assumes wheel slide will occur; so, if braking is eased as soon as sliding begins, FASTECH cannot secure the required total braking force. Furthermore, repeating brake loosening and re-braking often might cause pitching of the bogie and sliding of the adjacent axle. Therefore, we decided to introduce slip rate control, focusing on the increase of adhesion in the macro slip area[1] when in a lubricated state.

In slip rate control, braking is not eased until the slip rate reaches a fixed value (1 - axle speed/train speed) even if sliding starts, waiting for axle self-readhesion. Of course, if the wheels do not readhere to rails and the slip rate further increases, braking of the axle is eased and readhesion controlled to prevent wheel lock. Therefore, setting of the slip rate is the key to successful control. In order to determine the optimal slip rate, we carried out slip control tests with different slip rates (10 – 25%) using the bogie testing machine. Fig. 5 shows the comparison of 15% slip rate control and conventional 3 km/h speed difference control. The figure indicates that the axle that is sliding can perform self-readhesion with no easing of braking at 15% slip rate control. The test results clarified that a slip rate of around 15% is optimal, that such sliding does not cause damage to tread of wheels, and that slip rate control causes less pitching compared to conventional slip control.

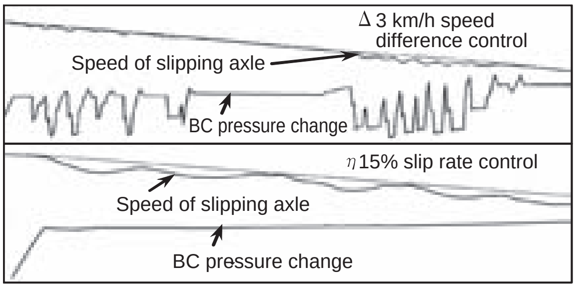

Fig. 5 Comparison of Conventional Control and 15% Slip Rate Control

6 Equipment for Increasing Air Resistance

As explained above, performance of braking using wheels (adhesive braking) is much improved on FASTECH. Still, deceleration at rapid deceleration emergency braking is set much above the adhesion limit; so, we developed equipment for increasing air resistance as a supplementary device to shorten emergency braking distance using air resistance. Since that device had not been previously used for Shinkansen rolling stock, we proceeded with the development considering car structure, running safety, running stability and effects on wayside equipment such as overhead contact lines.

6.1 Calculation of Air Resistance

Equipment for increasing air resistance is a device that opens plates on the car roof and consequently increases air resistance. The braking force (drag) by that can be figured out using the following formula.

$$F = \frac{1}{2} C_d \rho A V^2$$

F: Drag (N),
C_d: Air resistance coefficient (Cd value)
ρ: Air density (kg/m^2)
A: Area of plate that receives wind pressure (m^2)
V: Train speed (m/s)

The resistance is in proportion to the square of the speed; that is, the braking effect increases as the running speed increases.

Fig. 6 Appearance of Equipment for Increasing Air Resistance

6.2 Basic Configuration

The newly developed equipment for increasing air resistance is a rotating push-up type, which pushes up fan-shaped plates while rotating them on the center of the rotational axis. That structure was designed to save storing space, ease adjustment, simplify the structure and achieve the same braking force regardless of the direction. The configuration and structure is shown in Fig. 7.

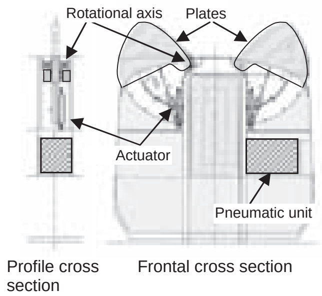

Fig. 7 Equipment for Increasing Air Resistance (Cross Section)

We installed equipment for increasing air resistance at the end of each car, taking into consideration the strength of the car body and the configuration of the passenger cabin. As for placement on the train set as a whole, we decided to install the devices at each end between cars (excluding where the pantograph is installed) and at the both ends of the train to improve the braking effect per location while securing the maximum number installable. In total, seven devices are installed to E954 and five devices to E955 trains.

7 Tests on Actual Cars in FASTECH Project

7.1 Adhesion Measurement

As introduced above, we measured the adhesion coefficient in high speed running using a train actually in operation, but we measured the position of axles of the head car through the third car only and did not consider the effect of temperature; so accordingly, the data taken was insufficient. So, we carried out adhesion measurement in the FASTECH high speed running tests. We measured one of the axles of each car of the train set and took the data on adhesion coefficients by braking with only the axles to be measured. The tests were conducted in February.

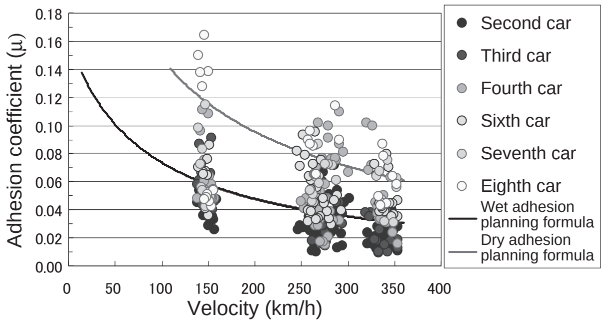

Fig. 8 Adhesion Measurement Results of FASTECH (Water Spray)

The measurement results show that the adhesion coefficients of front cars in the running direction are under the value obtained by the formula and the adhesion coefficients of rear cars are above that value.

The values of the front cars were much lower than the values of adhesion coefficients obtained in past measurements. That could be because of the weather condition such as temperature and snowfall. Based on those results, we concluded that continuous data accumulation is necessary. Adhesion measurement is still underway using FASTECH trains.

7.2 Test Results of Rapid Deceleration Emergency Braking

We carried out rapid deceleration emergency braking tests using pneumatic brakes only under the assumption of failure of regenerative brakes.

As shown in Fig. 9, the emergency braking distance at 360 km/h was almost 4,300 m, and 4,000 m with using equipment for increasing air resistance also used. We confirmed that the train could stop at 4,000 m at around 340 km/h initial braking speed without using the equipment for increasing air resistance. It was raining on both of the test days.

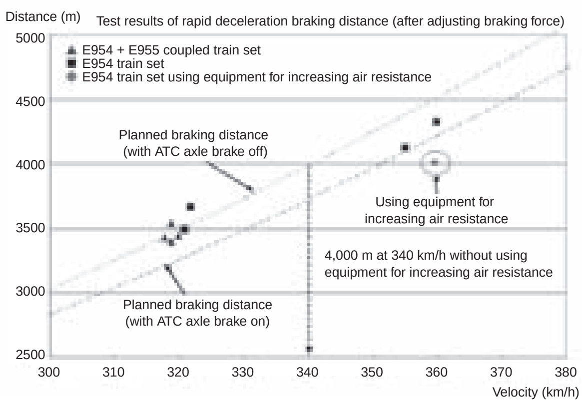

Fig. 9 Braking Distance at Rapid Deceleration Emergency Braking Tests

7.3 Test Results of Equipment for Increasing Air Resistance

The air resistance is obtained by measuring the deceleration of the total train set when deploying the plates of the equipment when coasting.

As shown in Fig. 10, the deceleration effect was larger in tunnels than in open sections, and the deceleration in open sections also was slightly larger than initially planned in the design phase. The effect of equipment for increasing air resistance on shortening braking distance was approx. 300 m when activating rapid deceleration emergency braking at 360 km/h.

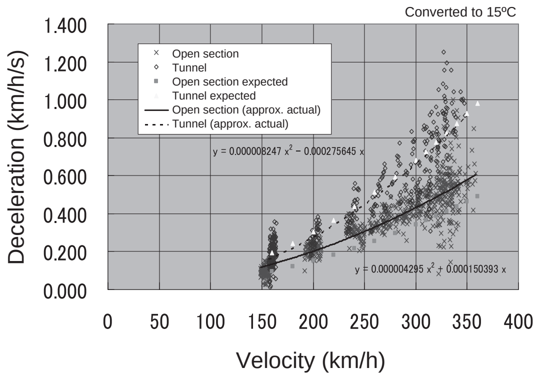

Fig. 10 Effect of Equipment for Increasing Air Resistance

8 Conclusion

In order to control the risk increase in case of earthquake due to speed increases, we improved performance of the basic brake equipment, optimized brake control in case of sliding and developed equipment for increasing air resistance. As the result of those improvements, we could reduce the emergency braking distance at 360 km/h using equipment for increasing air resistance to approx. 4,000 m; thus achieving our target. We also confirmed that the train could stop at 4,000 m at around 340 km/h initial braking speed without using that equipment.

Furthermore, we confirmed that the traditional adhesion coefficient planning formula could be applied to the adhesion coefficient between wheels and rails in the over 300 km/h speed range too.

We are planning to clarify the effect of weather conditions such as low temperature in winter and snowfall, by accumulating further test data.

Reference

1) Seigo Uchida: Shinkansen Brake Systems, 2001