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Reduction Technique for Braking Distance of Railway Vehicles via Dry Air Jetting

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Abstract

This paper describes that the technique for temporarily improving the friction force by jetting dry air with less than 30% humidity on the contact surface, and results of the fundamental measurement experiment of the tangential contact force using the small two-disk rolling machine. In the fundamental experiment, the tangential contact force coefficient increased simultaneously with dry-air injection and remained stable during dry-air injection under dry and high-humidity conditions. It was also confirmed that tangential contact force improvement effect of dry-air injection depended on the surface properties of the contact surface of the specimens. Furthermore, as an example of a dry-air injection system application, we proposed the technique of shortening the braking distance of the rail vehicles based on the results of the fundamental experiment, and its validity of the proposed technique was confirmed using a vehicle dynamics analysis.

Keywords: railway vehicle, wheel/rail, low adhesion, high-humidity conditions, friction coefficient, braking distance, dry-air injection.

1 Introduction

The braking distance of railway vehicles increases because wheel slip when large brakes are utilized under low adhesion wheel/rail conditions. As a countermeasure to this problem, re-adhesion technology has been developed to quickly detect and correct wheel slippage, and it is considered that the wheel slip is clearly reduced. However, because re-adhesion control maximizes the utilization of the frictional force between the wheels and rails, its effect is insufficient when the braking force is larger than the frictional force between the wheel and rails. In the case, increasing the friction coefficient between the wheels and rails is effective.

For a long time, in railways, sand has been sprinkled onto the rail top surface from vehicles when the wheels are sticking, and it is known the wedge effect of sand improves the frictional force. Recently, a technique for injecting alumina between wheels and rails has been developed to increase the coefficient of friction between wheels and rails and is now utilized in some vehicles [1]. In contrast, if solid objects are interposed between wheels and rails, it may negatively affect equipment that utilizes track circuits, such as signals and railroad crossings; therefore, it is necessary to thoroughly consider running safety in practical utilization. From this perspective, it is necessary to consider techniques to improve the friction coefficient of wheel/rail without solid objectives to shorten the braking distance.

On the other hand, in our previous studies, it was experimentally clarified that under dry conditions with humidity of less than 30%, the lubrication effect of atmospheric moisture was reduced, and the tangential contact force between the wheel and rail increased [2] (see Figure 1).

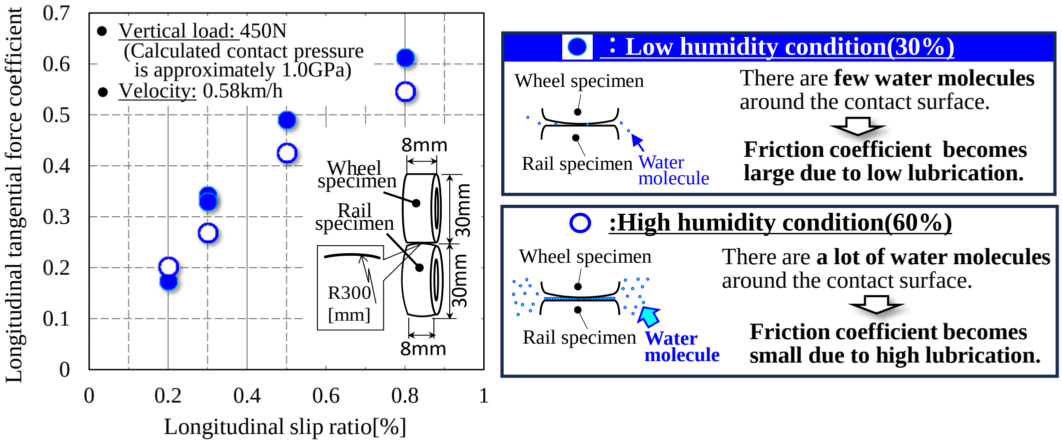


Figure 1: Tangential contact force characteristics under different humidity conditions.

Furthermore, under water lubrication conditions on the contact surface, even at the minimum condition of approximately 2.4mL/min, the tangential contact force coefficient rapidly decreased from 0.2 -0.45. As the watering flow rate increased the tangential contact force coefficient decreased from the blue to the yellow mark, to the light blue, and then to the green mark. In addition, when the water flow rate exceeded 18mL/min, the tangential contact force coefficient became saturated at approximately 0.1(see Figure 2).

From these experimental results, it was found that the tangential contact force characteristics were similar to those under dry conditions by reducing the water lubrication state between the wheel and rail.

By applying this knowledge, injecting dry air onto the contact surface the longitudinal tangential contact force coefficient can be increased by changing the lubrication state of the contact surface to a low-humidity stage of 30%. And the tangential contact force can be also improved even under water lubrication conditions, because the water on the contact surface can be removed by air injection.

In this paper, we proposed a technique for temporarily improving the friction force between a wheel and rail by jetting dry air with less than 30% humidity on the contact surface. Second, the effectiveness of the proposed dry-air injection technique was verified with a twin-disk rolling sliding machines. Finally, as an example of a dry-air injection system application, the results of shortening the braking distance of the rail vehicles with vehicle dynamics analysis to verify the proposed technique are described.

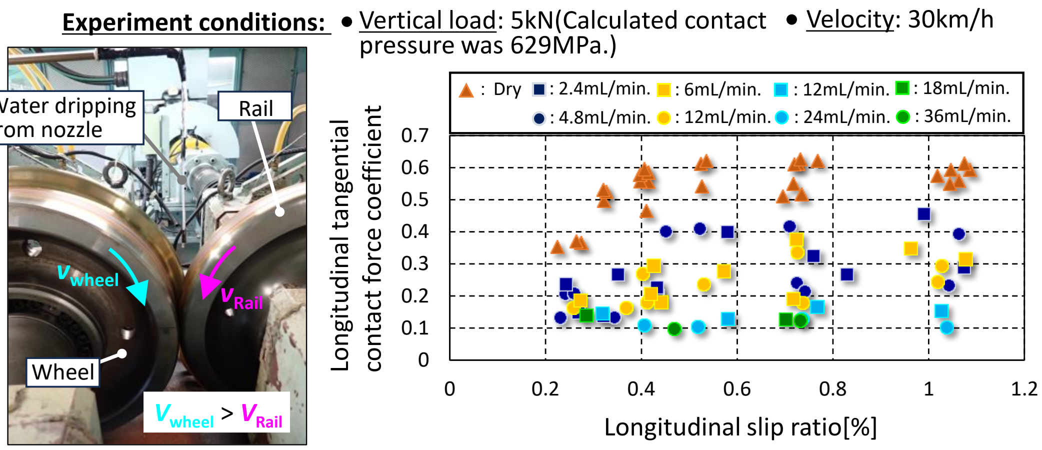


Figure 2: Measurement experiment of tangential contact force under conditions of very small amount of water.

2 Proposal for improvement of tangential contact force temporarily

We proposed a technique for injecting dry air onto the contact surface, aiming to achieve a temporary improvement in its friction coefficient. Based on the fundamental experiment results described in Section 1.

The effect of improving the tangential contact force coefficient by injecting dry air onto the contact surface was investigated under dry conditions, and the ratio of the tangential contact force coefficient before and after dry-air injection was evaluated.

2.1 Experimental apparatus

To investigate the tangential contact force characteristics under steady-slip conditions, experiments were conducted with cylindrical specimens to measure the tangential contact force. The experimental apparatus called “Twin-disk sliding-frictional rolling machine equipped with environmental device” installed in RTRI, which is the same machine described in Section 1, was utilized. This experimental machine can measure the tangential contact force by maintaining an accurate longitudinal slip ratio acting on the contact surfaces and environmental conditions (i.e., temperature and humidity), around the specimens.

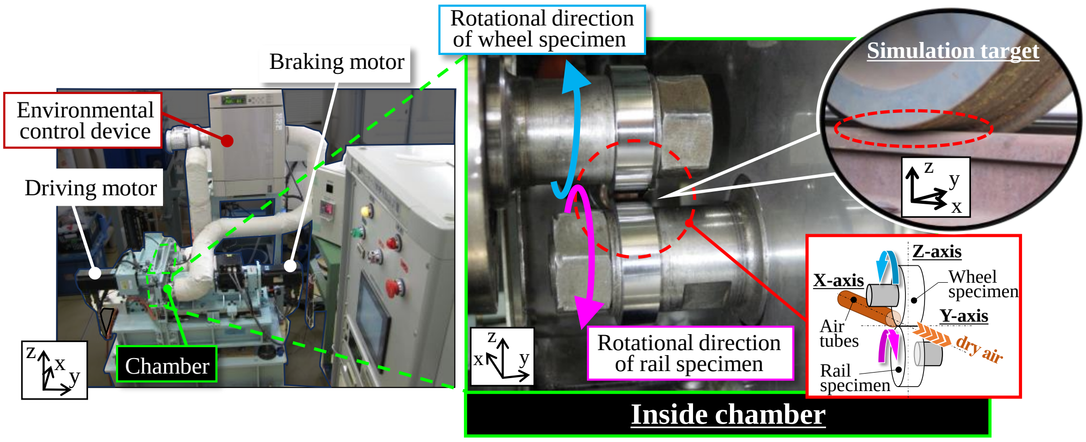


Figure 3: Experimental apparatus and its inside chamber

2.2 Experimental conditions

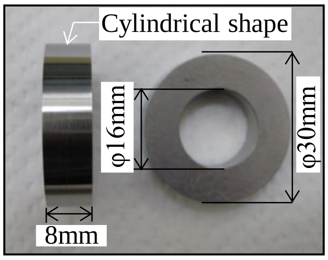
The experimental conditions are as follows: number of revolutions is 100rpm and 1000rpm (rotational velocity is approximately 0.58km/h and 5.65km/h, respectively), vertical load is 450N (The calculated value is approximately 1.0GPa, which is equivalent to the contact surface pressure between actual wheel and rail), longitudinal slip ratio is 0.3% and 0.8%, attack angle between specimens is zero, temperature and humidity around specimens are approximately 20℃ and approximately 80%, respectively.

These experiments were conducted with novel specimens under the experimental conditions described above.

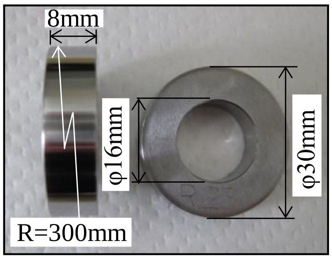
2.3 Test specimens

The wheel and rail specimens were cylindrical specimens 30mm in diameter made from and actual wheel and rail, respectively. To make the contact patch between the specimens elliptical, the shape of the contact surface of the rail specimens was made with an arc with a radius of 300mm. The cross-sectional shapes of the specimens are illustrated in Figure4.

Dirt and oil on the surfaces of all the test specimens were removed with petroleum ether, and the specimens were completely dried before the tangential contact force measurement experiment.



(a) Wheel specimen



(b) Rail specimen

Figure 4: Specifications of wheel and rail test specimens.

3 Validity of our proposed technique and its application

3.1 Effect of dry-air injection on tangential contact force characteristics

The results of the dry-air injection experiments are presented in Figure 5. The experimental conditions were as follows: a vertical load of 450N (calculated contact pressure is approximately 1.0GPa), longitudinal slip ratio of 0.8%, humidity around the test specimen of 80%, and drying air injection pressure of 0.8MPa.

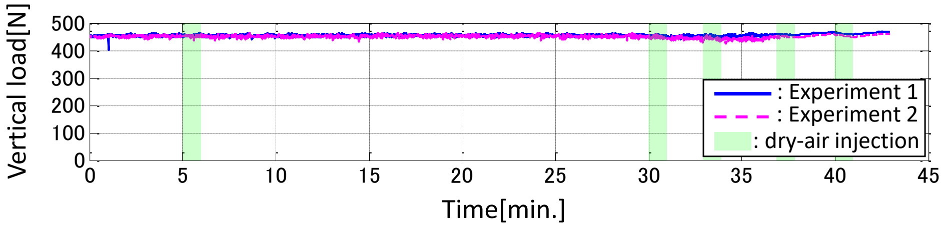
As presented in Figure 5, the surface properties of the contact surface changed approximately 3 min after the start of the experiment; thus, the tangential contact force coefficient reached its maximum value and maintained that state for a while. In addition, approximately 8 min after the start of the experiment, the tangential contact force coefficient decreased from its maximum value to approximately 0.6 to 0.4 because the real contact area of the contact surface decreased owing to wear. Such tangential contact force characteristics have been reported in many experimental studies [3][4].

Under these tangential contact force characteristics, the tangential contact force improvement effect of dry-air injection was implemented in the following two ranges. First, a dry-air injection experiment was conducted at Point A, where the contact surface was smooth, and the coefficient of friction was high. When dry air was injected at 0.8MPa for 1min, starting 5 minutes into the experiment, the tangential contact force coefficient increased by approximately 4.6-11.8% compared to before the injection.

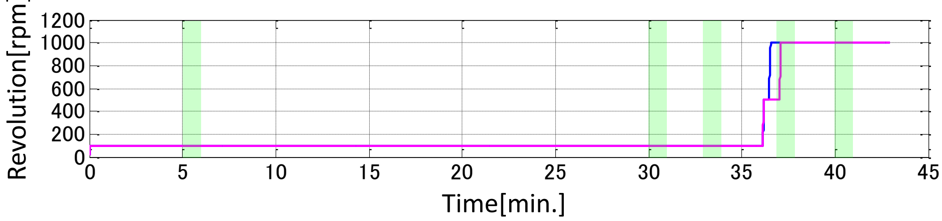
Next, we conducted a dry-air injection experiment in the same manner at Point B, where the contact surface was in a worn state. When dry air was injected 30 and 33 after the experiment, the tangential contact force coefficients were approximately 17.9-26.7% and 38.4-41.2% larger than before the injection. Furthermore, even when the rotation speed of the wheel specimens was set to 1000rpm, the rate of increase of the tangential contact force coefficient 37 min and 40 min after beginning the experiment was high at approximately 21.7-22.8% and 17.5-22.0%, respectively. Here, the tangential contact force improvement effect at Point A was lower than at

Point B. This was due to the influence of the surface properties of the contact surfaces. That is, it is considered that the improvement effect of the tangential contact force by jetting dry air is small because the wear of the contact surface is small, and the friction coefficient is originally large at Point A.

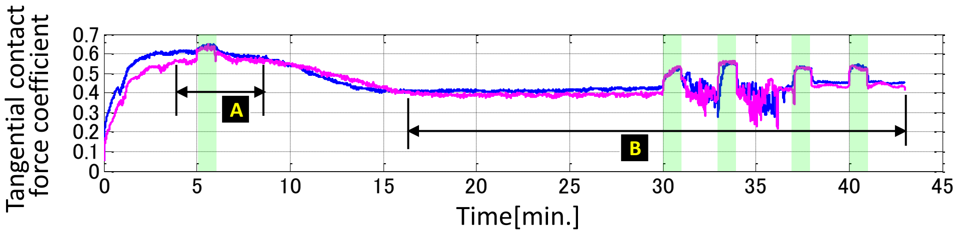
From these experimental results, it was confirmed that the tangential contact force coefficient increased simultaneously with dry-air injection and remained stable during dry-air injection under dry and high-humidity conditions. Furthermore, it was found that the tangential contact force improvement effect of dry-air injection depended on the surface properties of the contact surface of the specimen.



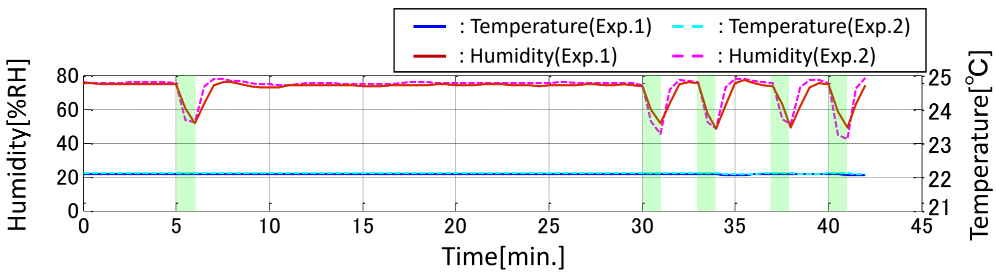
(a) Vertical load



(b) Revolution of wheel specimen



(c) Longitudinal tangential contact force coefficient



(d) Temperature and humidity around test specimens

Figure 5: Experimental results under 0.8% longitudinal slip ratio conditions.

3.2 Relationship between humidity around test specimens and tangential contact force improvement effect

The relationship between the contact surface's longitudinal slip ratio and the tangential contact force improvement during dry-air injection was investigated. The experimental results are presented in Figure 6.

It is confirmed that the higher the humidity around the test specimens, the higher the improvement effect of the tangential contact force by injecting dry air. When the humidity around the contact surface was high, the area around the contact surface was lubricated with moisture in the atmosphere, which was removed by dry-air injection. This is thought to increase the tangential contact force improvement effect. In addition, the tangential contact force improvement effect tended to differ depending on the longitudinal slip ratio, and this effect was particularly noticeable under conditions where the humidity around the test specimens was high. This is because a larger longitudinal slip ratio results in a larger range where the tangential contact force acting within the contact patch between wheel test specimens increases, and the tangential contact force coefficient increases when evaluated over the entire contact surface.

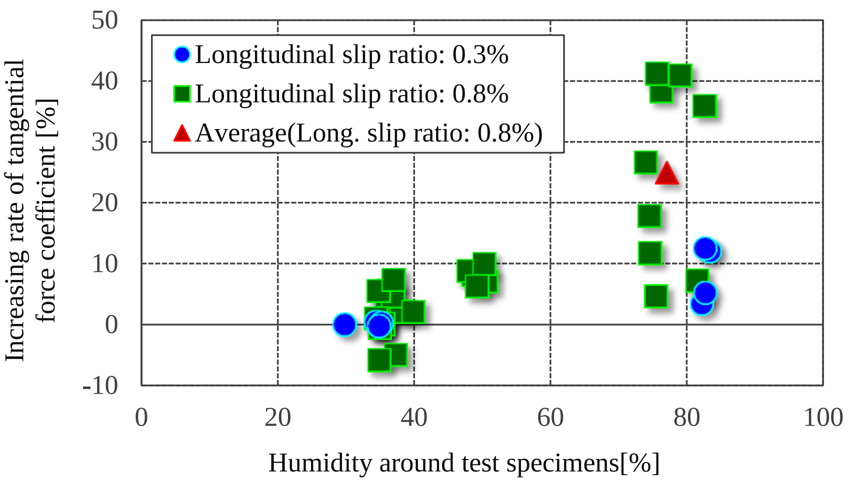


Figure 6: Effect of longitudinal slip ratio between test specimens on increasing rate of friction coefficient.

These experimental results indicate that the tangential contact force improvement effect of dry-air injection increases when the longitudinal slip ratio between the test specimens increases.

However, a large variation in the tangential contact force improvement effect was confirmed, particularly at a longitudinal slip ratio of 0.8%. Because this is thought to be due to differences in the surface properties of the contact surfaces, the data for the 0.8% longitudinal slip ratio conditions in Figure 6 are distinguished in Figure 8 for each contact surface condition.

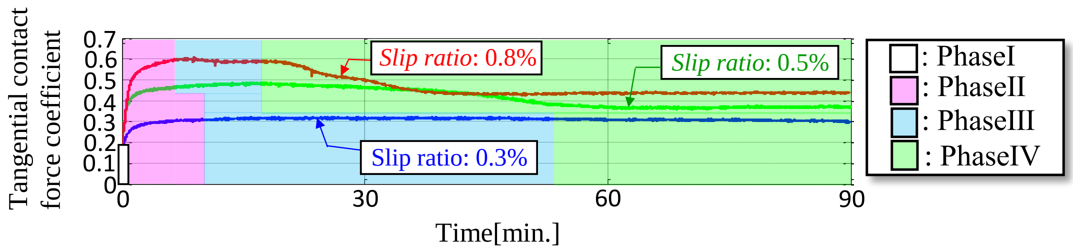
The relationship between the tangential contact force characteristics and contact surface properties from previous experiments [5] utilizing a novel test specimen are illustrated in Figure 7(a) and Figure 7(b).

Phase I: The condition of the contact surface of the specimens before the experiment is the same as new specimens shown in Figure 7(b) in terms of its shape and color (silver).

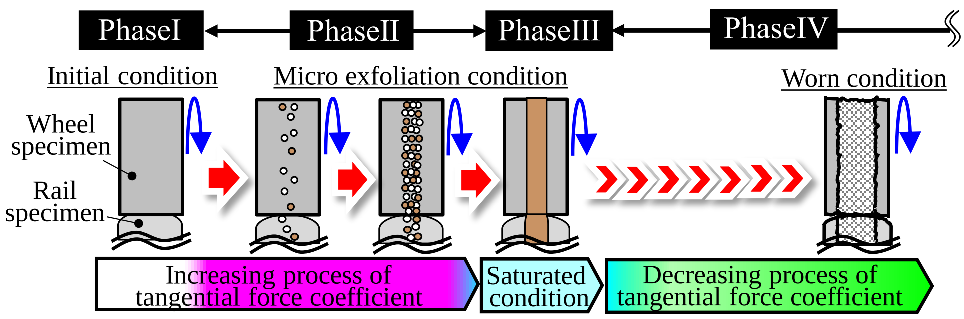
Phase II: When rolling-sliding frictional force is applied to the contact surface of the specimens, the contact surface changes its color to dark brown slowly, and accordingly the longitudinal tangential force increases.

Phase III: The dark brown on the contact surface becomes deeper, and the change in color becomes stable for a while. The longitudinal tangential force coefficient reaches a maximum value too and is stable for a while. At this time, the contact surface is measured by the surface roughness measuring device, and the contact surface swelled approximately 1μm. The larger the slip ratio is, the shorter the length of time the longitudinal tangential force coefficient is kept stable.

Phase IV: The contact surface changes from dark brown to silver slowly. At this time, the longitudinal tangential force coefficient is a little small due to wear progression on the contact surface.



(a) Time history of experiment results



(b) Time history of change in contact surface

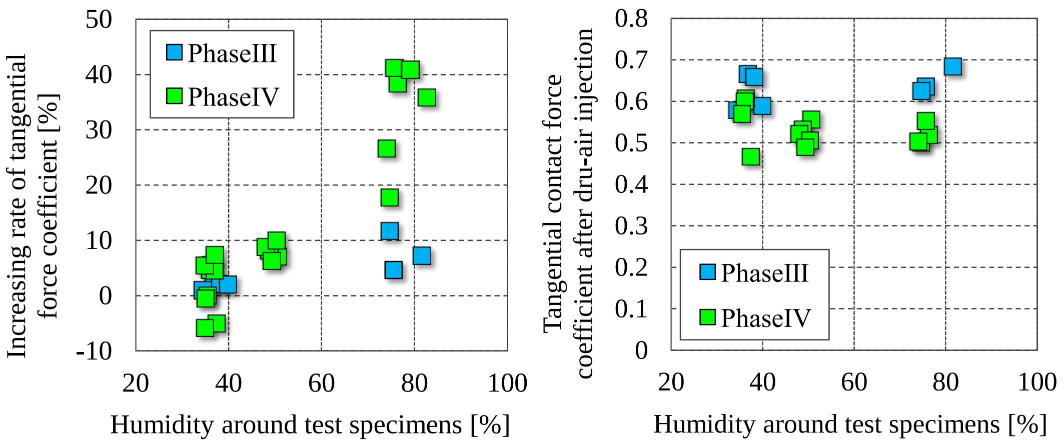
Figure 7: Relationship between surface properties and tangential contact force characteristics.

When evaluating the data, it was observed that under a 0.8% longitudinal slip ratio condition, most data indicating a high rate of increase in the tangential contact force coefficient corresponded to the phase IV contact surface state (see Figure 8(a)).

However, the tangential contact force coefficient of Phase IV are smaller than that of Phase III from Figure 8(b). This is because the tangential contact force characteristics are greatly influenced by two factors, i.e. the contact area (contact patch) and the surface properties.

As shown in Figure 7, the friction coefficient on the contact surface becomes large because rolling-sliding frictional force is applied to the contact surface repeatedly, damage is done to the contact surface and the oxidation layer is formed on the contact surface. And the tangential contact force coefficient is saturated to the friction coefficient on the contact surface. In that time, when comparing Phase III with Phase IV, the tangential contact force coefficient of Phase IV is smaller than that of Phase III due to large wear on the contact surface. On the other hand, the friction coefficient becomes large under less than 30% humidity conditions as described in Section1, and especially, the increase of friction coefficient tends to be greater in the damaged area of the contact surface. Therefore, the increasing rate of tangential contact force coefficient of Phase IV is greater than that of Phase III. In other words, the proposed technique implies that the frictional force on the contact surface does not increase infinitely but can increase within a range that does not exceed Phase III.

The experimental results show that injecting dry air with less than 30% into the contact surface under high humidity conditions increases the tangential contact force. Especially, it was confirmed that the increasing rate of the tangential contact force coefficient tends to large under the conditions of the damaged contact surface due to wear. It was also found that under such conditions, as the longitudinal slip ratio increased, the improvement effect of the tangential contact force increased.



(a) Increasing rate after/before dry-air injection.

(b) Comparison between tangential contact force coefficients after dry-air injection.

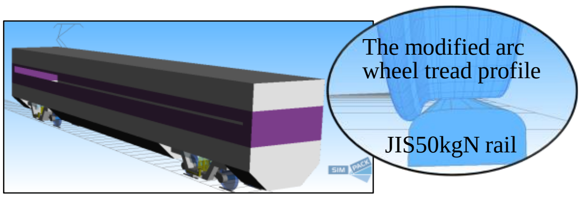
Figure 8: Evaluation focusing on contact properties of contact surface under 0.8% longitudinal slip ratio condition in Figure 6.

3.3 Effect of reducing braking distance on real vehicles utilizing vehicle dynamics analysis

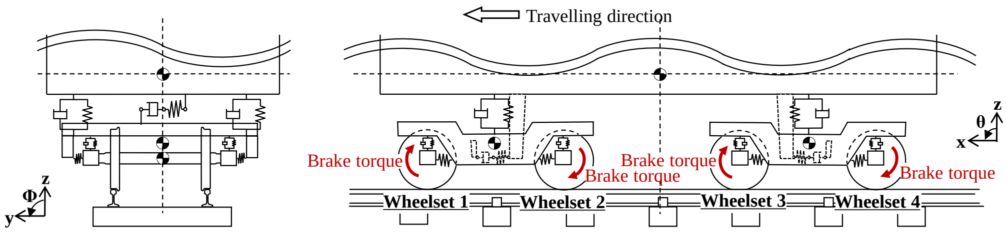
The proposed technique is expected to temporarily increase the coefficient of friction between the wheels and rails during acceleration and deceleration under dry with high humidity and water lubrication conditions (see Figure 9(a)). This study evaluated the effect of shortening the vehicle braking distance with vehicle dynamics analysis, which is commercial multibody dynamics software "SIMPACK", under a scenario where dry air was injected between all eight wheels/rails when a typical commuter vehicle brakes on a straight section (see Figure 9 (b), (c)).

The coefficient of friction between the wheels and rails during dry-air injection was modelled to increase uniformly, considering the variation in the laboratory experiment results. The numerical analysis conditions are as follows: static wheel load is 35.5kN, braking torque is 2500Nm, and braking initial velocity is 100km/h.

(a) Application image of the proposed technique.



(b) Railway vehicle model based on multibody dynamics software SIMPACK (ver.2019.1-build97)



(c) A railway vehicle model using spring and mass model

Figure 9: Application image of the proposed technique and description of the numerical analysis model.

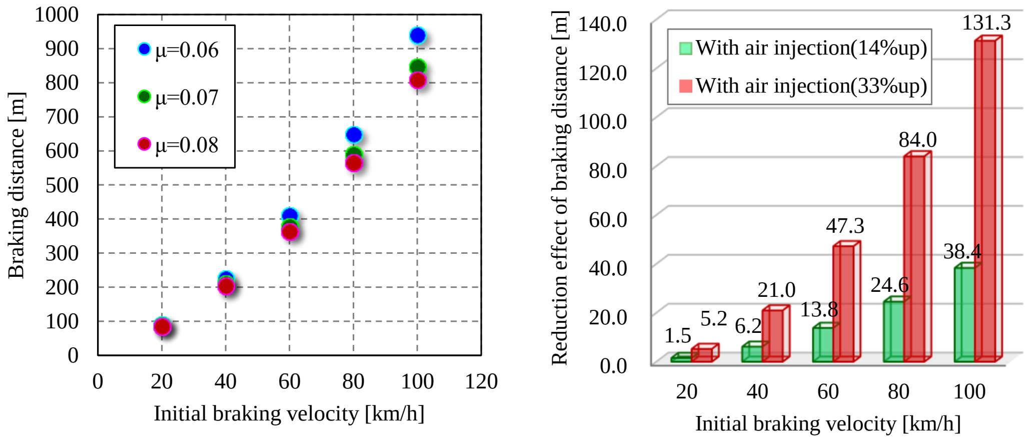
The effect of dry-air injection on the improvement of the friction coefficient was explained with the results of multiple conditions for the friction coefficient between the wheels and rails. Figure 10(a) shows the relationship between the friction coefficient of the wheel/rail and the braking distance, whereas Figure 10(b) illustrates the effect of dry-air injection on reducing this distance.

In Figure 10(a), the higher the initial braking speed, the longer the braking distance. Based on the case in which the friction coefficient of the wheel-rail was 0.06, the braking distance when the initial braking velocity was 100km/h was approximately 940m. As the wheels slid under all velocity conditions, it was confirmed that the braking distance tended to increase.

Next, assuming that the dry-air injection system application is used, when the friction coefficient of the wheel-rail became 0.07, the braking distance decreased because the tangential contact force of the wheel-rail increased. When the friction coefficient was greater than 0.08, the braking distance was shortened to 808m without large sliding between the wheel and rail.

Figure 10(b) illustrates the relationship between the ratio of the increase in the friction coefficient of the wheel-rail and the braking distance based on Figure 10(a). If the friction coefficient of the wheel-rail increases by even just 14% (friction coefficient from 0.06 to 0.07), the braking distance can be shortened by a maximum of 40m. If the friction coefficient of the wheel-rail increases by 33% (from 0.06 to 0.08), the braking distance can be reduced by a maximum of 131m. In the fundamental experiments in Figure 6, the dry-air injection was confirmed to improve the tangential contact force by an average of approximately 25%. In other words, our proposed technique can potentially shorten the braking distance of actual vehicles under the condition that the friction force of the wheel-rail is slightly smaller than the braking force.

From the evaluation results above, we can confirm that the proposed technique effectively reduces the braking distance of actual vehicles.



(a) Relationship between braking distance and friction coefficient

(b) Reduction effect of braking distance

Figure 10: Numerical analysis results under 2500Nm braking torque conditions.

4 Conclusions

To develop a technology to improve the friction coefficient of wheels and rails without solid materials, we proposed a novel technique for injecting dry air with a humidity of less than 30% on to the contact surface. Measurement experiments of the tangential contact force were conducted to verify its effectiveness. Consequently, we experimentally confirmed that the proposed technique is effective under high environmental humidity condition and high slip ratio on the contact surface. We then considered applying the proposed technique to shorten the braking distance of railway vehicles and confirmed its validity through vehicle dynamics analysis. It was found that the braking distance could be shortened by up to 40m even if the friction coefficient between the wheels and rails was improved by approximately 14%, indicating that the proposed technique is applicable.

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