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A Proposal of Wheel/Rail Contact Model for Friction Control

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Controlling the friction between wheel and rail is direct and very effective measures to improve the curving performances of railway trucks, because the curving performances depend much on friction characteristics. Authors have proposed a method, "friction control", which utilizes friction modifier (KELTRACK^{TM} HPF) with onboard spraying system. With the method, not only friction coefficient, but also friction characteristics can be controlled as expected. In this study, MBD simulation is very valuable tool to foresee the effect of the control in advance of experiment with real car. And the creep characteristics of wheel/rail contact with the friction modifier takes very important role in the simulation. In this paper, authors propose a theoretical model of wheel/rail contact condition considering the creep characteristics of friction modifier, which is derived the application of principle tribological theories.

Key Words : Friction, Railway, Contact, Creep

1. Introduction

In Japan, because of the social structure that depends greatly on railway, railway network is very developed especially in urban area. It means couple of lines exists in almost the same route. And as the result, transportation with railway in urban area is very convenient for the customer, but the train operation companies of the lines must compete in shortening of running time and transportation fare. On the point of the shortening time, compatibility between high-speed stability and curving performance is the severe task ahead of urban railway that has high-speed section in suburbs and so many tight curves in urban area.

Speed up in curves causes many problems such as increasing lateral force acting between wheel

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and rail which involves the danger of derailment, occurrence of squeal noise and progress of rail/wheel wear or corrugation on the top of rail. Most of the train operation companies have taken a measure that applying grease on the gage corner of high rail in order to prevent the wear of rail/wheel or loud flange noise, and on the top of the low rail for the purpose of decreasing the lateral force or preventing the occurrence of corrugation. Although lubrication between wheel and rail is a traditional method to resolve these problems, it has a restriction of place to apply. For example, in the case that lubricant is applied to a track just before the station, it contains a fear of skid that makes a flat on the contact face of the wheel and gives severe damage to the rail.

In this study, authors have proposed a method "friction control" between wheel and rail with friction modifier to improve curving performances in tight curve. Friction modifier can maintain appropriate friction coefficient between wheel and rail, and has positive characteristics on creep force against creepage as shown in Fig. 1. Although there have been various proposals to improve steering ability without lack of high-speed stability, friction control with friction modifier is very advantageous because most of them has difficulty in application to the existing railway system, i.e. they need major modify of cars or system.

To realize the concept of friction control, authors selected a system with onboard type device of train, in which liquid type friction modifier is sprayed onto the top of low rail as mist from the nozzle behind the last axle of train, and the following train receives the benefit of it (Fig. 2).

The advantages of this onboard friction control system are as follows : the friction modifier can be supplied onto rail uniformly through the curve by control of its amount in proportional to the vehicle's velocity, the train with friction control device can supply the friction modifier immediately to any curve of the service line where wheel/rail contact condition should be improved unexpectedly, and the supply of friction modifier or maintenance of the device could be performed in equipped place of a car depot.

In this system, the balance between supply and consumption of friction modifier is very important. It is natural that to obtain the good effect of friction modifier, some amount of friction modifier is required. But if the amount of supply is excessive or consumption between a spray to next is too little, the friction modifier cannot play an expected role because coefficient of friction is too low and positive characteristics is spoilt. In this report, in order to recognize the phenomenon, authors carried out experiments with two-roller-rig testing machine regarding the initial condition of friction modifier just after the spraying and consumption of friction modifier by contact rolling.

In order to evaluate the effect of friction control, authors have carried out MBD simulations, experiments with 1/10 scaled model equipment, and real car tests with specially equipped bogie for precise measurements of curving performances. On the viewpoint of MBD analysis of railway vehicle, a model for wheel/rail contact is very important, and J. J. Kalker's FASTSIM is very popular mathematical model for such a cal-

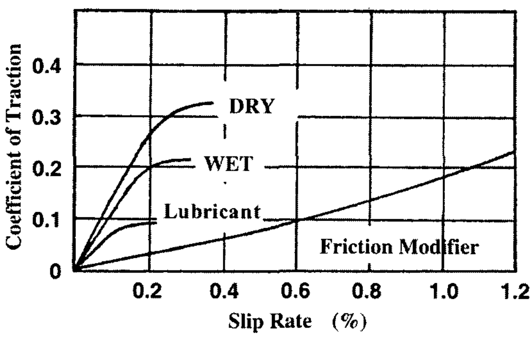

Fig. 1 Creep force characteristics

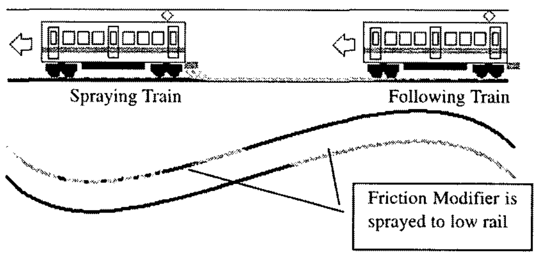

Fig. 2 concept of onboard friction control

culation. In this paper, a wheel/rail contact model, which can express the characteristics of friction modifier and relationship between consumption of friction modifier in contact patch and creep characteristics, is proposed. The contact model was developed by modifying the FASTSIM by the consideration of material characteristics and the state of contact. Authors performed simulations for the evaluation of the contact model. Results of simulations shows the contact model is appropriate for creep characteristics of the friction modifier with the comparison of results of experiments by two-roller rig machine.

2. Friction Modifier

The friction modifier especially for wheel/rail contact, which is utilized in this study, has two remarkable characteristics. One of them is that friction modifier can maintain appropriate traction coefficient between wheel and rail as shown in Fig. 1. In Fig. 1, traction coefficient of friction modifier is moderately smaller than the one of the other contact conditions in the region of less than 0.5% creepage. The other one is that the friction modifier has positive characteristics on creep force against creepage. That is to say, traction coefficient becomes larger with the growth of creepage between wheel and rail even though traction coefficients of the other contact conditions are saturated in small creepage region.

Although it is common that lubricant traditionally used in railway system frequently causes skid phenomena between wheel and rail in braking sections in service lines, owing to the positive characteristics, friction modifier can prevent the skid phenomena. The other hand, because the positive characteristics of friction modifier can prevent the stick-slip phenomena in wheel/rail contact, with the application of friction modifier, squeal noise and corrugation on the top of low rail can be decreased.

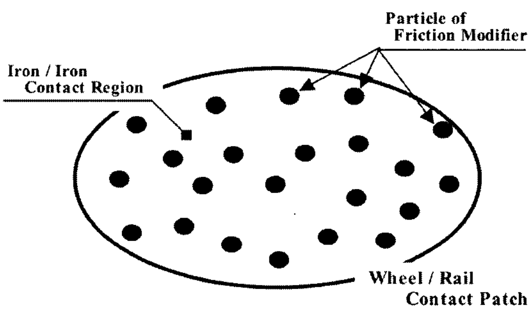

Fig. 3 Model of distributed friction modifier in the contact patch

Even though the friction modifier has very desirable characteristics as mentioned above, in the cases that the amount of friction modifier is applied excessively or sprayed friction modifier has not dried up enough before the approach of train next to the spraying train, expected effects of friction modifier cannot be obtained, as the result, skid phenomena is caused in such cases. As the countermeasure for the situation, authors developed the method to spray small amount of liquid-type friction modifier to the top of rail as the mist. Thanks to the method, the time of drying up of sprayed friction modifier is shortened, and therefore, required traction force can be obtained just after the spraying. Because the mist distributes the friction modifier in the contact patch and as the result divides contact patch into two regions (The region wheel contacts rail directly and the region wheel contacts rail through the layer of friction modifier). The general idea for securing the traction force by dividing contact patch to the two regions is shown in Fig. 3.

3. Fundamental Characteristics of Friction Modifier

In order to identify the model of wheel/rail contact, authors carried out fundamental experiments by two-roller-rig machine (shown in Fig. 4).

3.1 Outline of two-roller-rig machine

The two-roller-rig testing machine (shown in Fig. 4) was developed to evaluate the creep characteristics under various contact conditions between wheel and rail, such as dry, wet and lubricated by conventional grease. Especially, the creep force characteristics of friction modifier applied to the contact region were investigated.

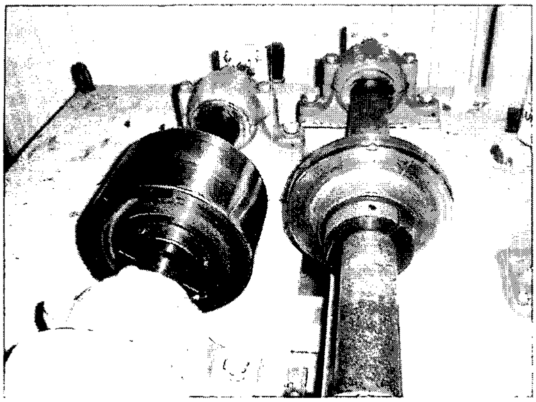

Fig. 4 Two-roller-rig testing machine

The testing machine can produce small slip accurately between two rollers, and measure the creep force generated by the slip. The diameters of both two rollers are 172 mm. Profile of wheel-roller is cylindrical and that of rail-roller has 100 mm convex single arc. These profiles of two rollers are designed considering the contact face ellipse and the contact pressure to model the actual wheel/rail contact.

The procedure to analyze the relationship between creep force and slip-rate was as follows: First, two rollers are driven with given rolling speed and contact pressure. Then, controlling the differential gear mechanically produces required slip. As the result, the torque force of the rail-wheel can be measured in real time, and creep curves are acquired with these measured data.

3.2 Test condition

The spray nozzle, which was used in tests with commercial train in practical, was used to spray friction modifier to rail roller as a mist.

To evaluate the creep force characteristics of friction modifier, the following test procedures were conducted :

(1) A test that creepage between two rollers was gradually enlarged from 0% to 2.0% on un-lubricated condition. (DRY)

(2) A same test procedure to test (1) was conducted with spraying friction modifier to rail roller. (FC)

(3) After the test (2), tests with same procedure to test (2) were conducted repeatedly without spraying friction modifier to the rail roller. (INT)

Table 1 Conditions of experiments

Friction Modifier	KELTRACK™ HPF
Height of Spraying Nozzle	0.4 [m]
Spraying Time	1.35 [sec]
Contact Force	500 [N]
Diameter of Model Wheel	0.168 [m]
Diameter of Rail Wheel	0.168 [m]
Curvature of Rail Wheel Surface	10 [1/m]
Velocity of Contact Patch	3.07 [m/s]
Number of Contact in a Test	350 [1/test]
Definition of DRY Condition	Condition that coefficient of traction was saturated in pre-test (1.0% Slip Rate)
Temperature of Atmosphere	24.0 [℃]
Humidity of Atmosphere	58.0 [%]

The purposes of each test are as follows.

(1) Confirmation of the effects by experimental equipment or environment with the test of dry condition.

(2) Evaluation of initial contact condition of friction modifier that means the original creep characteristics of friction modifier.

(3) Evaluation of contact condition after friction modifier in contact patch was consumed.

3.3 Results of tests

Fig. 5 shows the results of the tests. Followings are clarified by the evaluation of the test results.

With the spraying method proposed in this paper, traction coefficient of friction modifier (FC) is lower than DRY condition in small creepage region and creep characteristics of friction modifier is positive which means traction coefficient is gradually enlarged with the growth of creepage. That is to say, expected characteristics of friction modifier can be realized by the method proposed.

Friction modifier supplied to the contact patch is consumed with the repetition of the tests after the spraying, as the result, the creep characteristics is converged to the one of DRY condition (INT).

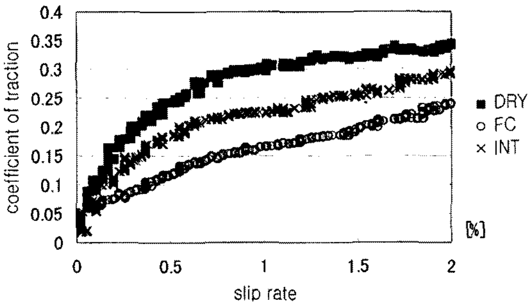

Fig. 5 Results of the tests

4. Identification of Wheel/Rail Contact Model

It was certified by the results of experiments with two-roller-rig machine that positive creep characteristics could be obtained, even just after the spraying, with the method proposed in this paper. At the point of view, positive characteristics in the results of tests are obtained not only by the characteristics of friction modifier but also by the contribution of distribution of friction modifier in contact patch. With consideration of the principle idea of tribology, contact model with friction modifier is constructed by the modifying the FASTSIM of J. J. Kalker in this section.

4.1 Algorithm of FASTSIM

FASTSIM devised by J. J. Kalker is the mathematical contact model that can be created by the properties of materials, friction coefficient and so on, as the result, creep characteristics can be presumed by the software without experimental data. The outline of the FASTSIM algorithm is as follows.

(1) Calculation of diameter of contact ellipse with the consideration of vertical force acts between wheel and rail.

(2) Presumption of linear creep coefficient by properties of wheel/rail materials and shape of contact patch.

(3) Division of contact patch into finite elements.

(4) Calculation of amount and direction of strain in each element by the creepage.

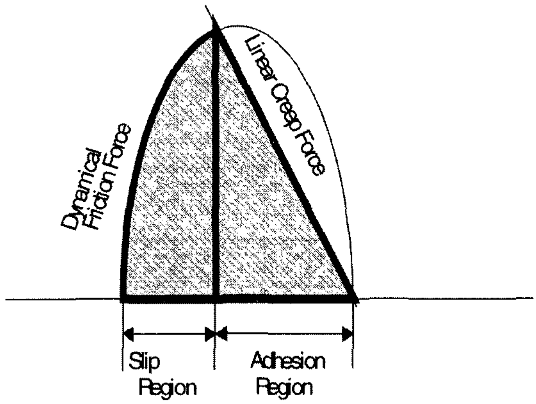

Fig. 6 Concept of Distribution of tangential force

(5) Comparison between linear creep force and maximum static friction force. With the comparison of these forces, smaller force between them is the tangential force of the element. (Shown in Fig. 6)

(6) Repetition of Step (1) to (5) for all the elements.

(7) Integration of whole tangential force to calculate the creep force of the contact patch.

In this paper, in order to represent the characteristics of friction modifier theoretically, ideas of "Thin Film Lubrication Theory" and "Boundary Lubrication Theory" are introduced to the algorithm of FASTSIM.

4.2 Introduction of idea of thin film lubrication theory

Because the "Thin Film Lubrication Theory" is constructed for the characteristics of solid lubricants and the friction modifier is a kind of solid lubricants solved in water based solvent, it is appropriate that the theory is applied to the model of wheel/rail contact through the friction modifier layer.

Generally, adhesion is regarded as the principal factor of sliding friction. Friction coefficient is represented as like Eq. (1)

$$\mu = F/P = (P/p_m) \cdot s_i/P = s_i/p_m \qquad (1)$$

where P: vertical force acting between two objects, p_m: plastic flow pressure, A_r: area of real contact, s_i: shearing strength at the real contact point

In the Eq. (1), both s_i and p_m are properties of each materials, and don't depend on vertical force or contact area. That is to say, decreasing s_i or increasing p_m invites the decrease of friction coefficient. But because these are the properties which depends on stiffness of each material, soft material for the purpose of decreasing s_i invites the decrease of p_m, and hard material for the purpose of increasing p_m invites the increase of s_i. Against the inconsistent of them, making the condition that hard material enveloped by soft material can create the situation that hard material supports the vertical load and shearing occurs in the thin film of soft material easily.

In order to introduce the idea of "Thin Film Lubrication Theory" into FASTSIM algorithm, firstly, properties of wheel/rail materials are applied to Young's Modulus in the procedure of analysis of contact patch in step (1), secondly, property of friction modifier is applied to Young's Modulus in the procedure for calculation of linear creep force in step (2).

4.3 Introduction of idea of boundary lubrication theory

The study of "Boundary Lubrication Theory", which is intermediate condition between dry and lubricated, has been made for long time. In the case that two bodies contacts each other directly in area of αA, where A is area of real contact, the friction force acting between the two bodies can be represented as next formula (2); (See Fig. 7)

$$F = A_r\{\alpha s_m + (1-\alpha) s_i\} \qquad (2)$$

Here, parameter α is just a rate of area of direct contact in area of real contact, and it doesn't correspond to the condition of friction modifier distribution in contact patch.

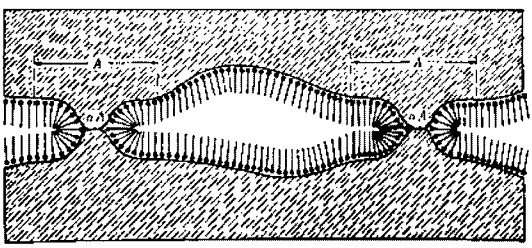

Fig. 7 Bowden's boundary lubrication model

In order to apply this theory into the FASTSIM algorithm, with the definition of the new parameter α called "Direct Contact Rate", creep force with friction modifier can be given with the addition of $(1-\alpha)$ times creep force of the condition just after friction modifier is sprayed and α times creep force of the dry condition.

4.4 Results of simulation

Simulations in order to calculate the creep characteristics considering the effect of distributed friction modifier in contact patch were carried out with reconstructed FASTSIM program by the idea explained in above. Each parameter for the simulation is given in Table 2 and Fig. 8 shows the results of the simulations. For the purpose of simplification, because friction modifier is complex material, the properties of common plain solid lubricants are used for that of friction modifier.

Table 2 Parameters for simulation

Diameter of Model Wheel	0.172 [m]
Diameter of Rail Wheel	0.172 [m]
Curvature of Rail Wheel Surface	10 [1/m]
Velocity of Contact Patch	3.15 [m/s]
Contact Force	200 [N]
Young's Modulus (Steel)	2.0685×1011 [N/m²]
Young's Modulus (Graphite)	0.98×1010 [N/m²]
Coefficient of Friction (Steel)	0.35
Coefficient of Friction (Friction Modifier)	0.35
Division Number of Contact Patch	441

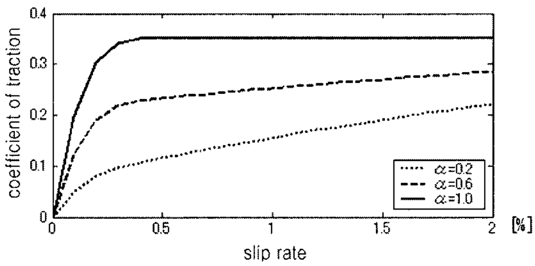

Fig. 8 Results of simulations

With the evaluation of the results shown in Fig. 8, it is confirmed that wheel/rail contact model proposed above can represent the creep characteristics of the condition accurately that friction modifier lies in contact patch. That is to say, adequacy of the model proposed above was verified, and the mechanism of the method proposed by authors was explained qualitatively too.

5. Conclusion

In this report, followings were certified ;

(1) For the purpose of evaluation of Friction Control by MBD simulations, a theoretical wheel/rail contact model was proposed which was derived by application of principle tribological theory, "Thin Film Lubrication Theory" and "Boundary Lubrication Theory".

(2) With the results of experiments with two-roller-rig machine, fundamental creep characteristics of friction modifier were confirmed. And the creep characteristics converged to the one of dry condition with the consumption of friction modifier by repetition of wheel/rail contact.

(3) The mechanism of the method proposed by authors that friction modifier is distributed in contact patch was qualitatively explained with the idea of "Thin Film Lubrication Theory" and "Boundary Lubrication Theory".

(4) The results of simulations with reconstructed FASTSIM program corresponds to the creep characteristics obtained by the experiments with two-roller-rig machine, accurately.

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