Development of Wheel/Rail Friction Moderating System (FRIMOS)

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Lubrication on sharp curves has been commonly adopted as a method of reducing friction between the wheel flange and rail gauge face to minimize wear and energy consumption. Additionally, lubrication between the running surface of the low rail and wheel tread has recently been recognized as a significant factor in reducing the likelihood of low rail corrugation, squealing noise and rail gage face wear. This paper describes a friction-moderating system (FRIMOS) for the interface between the top of the low rail and the wheel tread, consisting of a solid lubricant known as a friction moderator and a jetting device installed on the vehicle to apply the moderator to the wheel/rail interface.

Keywords: wheel/rail, friction moderator, sharp curve, squeal, FRIMOS, corrugation

1. Introduction

Railway vehicles negotiate sharp curves with large lateral forces interacting between the wheel/rail interface and the angle of attack of the leading axle in a bogie, which depend on its steering performance. In terms of running stability and/or safety, such a large lateral force is one of the main factors contributing to wheel-flange climb derailment at low speeds. In terms of material integrity, it is also a major cause of low-rail corrugation, thin flange wear of the wheel and gauge face wear of the rail, and as an environmental issue it is a particular cause of squealing noise in urban railways as referred to in [1-8].

In the last decade, there has been a focus on lubrication of the interface between the wheel tread and the top of the low rail to reduce large lateral forces and minimize wear to the wheel/rail interface, low-rail corrugation and the squealing noise [9-11]. However, such lubrication involves a certain risk of wheel sliding due to the low traction coefficient it causes, which requires the friction in the interface to be appropriately controlled. A friction modifier is conceivable as one of the promising solutions [12-14]. In addition, the influence of wheel/rail lubrication as one of the main methods of reducing friction in vehicle/track dynamic behavior has been evaluated through vehicle running experiments with track-site and/or on-board measurements as well as vehicle dynamics simulators in [15-20].

This paper describes the development of a friction-moderating system (FRIMOS) that consists of a solid lubricant called a friction moderator and a jetting system installed on the vehicle to apply the friction moderator to the wheel/rail interface as referred to in [15], [19], [21] and [22].

2. Friction-moderating system

2.1 Friction moderator

A friction modifier is conceivable as a promising solution to reduce lateral forces caused by vehicles negotiating sharp curves. The authors have been developing a solid-type lubricant known as a friction modifier whose purpose is the same as the friction modifier referred to in [22]. We selected a number of materials to check their performance specifically in terms of traction characteristics.

As a result, we selected grains of coke whose raw material is artificial graphite crushed to a diameter of 0.2 mm and appropriately arranged about its graphitization. In addition, phenol resin was selected as a coating for the grains of coke from the aspect of preventing them from catching fire and to aid braking (because phenol resin is used for composite brake shoes). Figure 1 shows the friction modifier developed in this study.

We carried out evaluation tests for traction and/or adhesion characteristics using a twin-disc rolling contact test machine as referred to in [2]. Figure 2 shows the traction characteristics of the lubricants listed in the Figure. Lubricant (a) is a friction modifier plated with nickel, termed FM-P. Lubricant (b) is a friction modifier coated with phenol resin, and is termed FM-S. Lubricant (c) is artificial graphite, and (d) is natural graphite. Lubricant (e) is grease with anti-slip additives, while (f) is oil with solid lubricant which is used for the top of low rails.

In the tests, the wheel disc and rail disc were polished to a roughness of \(R_a = 0.12 \mu m\) with angular velocity \(2000 \mathrm{rpm}\) and load \(30 \mathrm{N}\). The traction coefficient was calculated as an average for a sliding length of \(10 \mathrm{~m}\). Table 1 shows the average traction coefficients of the lubricants. Figure 2 shows the traction characteristics of the lubricants listed in the Figure. Lubricant (a) is a friction modifier plated with nickel, termed FM-P. Lubricant (b) is a friction modifier coated with phenol resin, and is termed FM-S. Lubricant (c) is artificial graphite, and (d) is natural graphite. Lubricant (e) is grease with anti-slip additives, while (f) is oil with solid lubricant which is used for the top of low rails.
ished with #80 sandpaper and rotated for five minutes to warm them up. The surface of the wheel disc and rail disc formed by the warming-up operation achieves a root mean square roughness (Rq) of approximately 1 μm. The circumferential speed of the discs was set to 40 km/h with a radial load of 3.5 kN, which gives rise to a maximum Hertzian pressure of approximately 672 MPa. In terms of braking performance, as the top of the low-rail lubricant, it is desirable that traction coefficient increases to more than 10% of the slip ratio to avoid wheel/rail sliding and remains appropriately small within the range of the small slip ratio to help reduce lateral forces.

With these desirable traction characteristics in mind, lubricant (a) performs very well, while (b) does not clearly show an increase in its coefficient in response to the increased slip ratio, although it keeps an almost constant adhesion coefficient and maximum traction coefficient, unlike grease lubricant (e). The tendencies of lubricants (a) and (b) are specifically based on the multi-layer structure of solid lubricants, which give rise to the effect of lubrication with decreasing friction due to the fracturing of their structure and the consequent sliding between two layers. Carbon-based lubricants (a) to (d) thus do not show a decrease in the traction coefficient with a large slip ratio. In addition, the figure shows that lubricants (a) and (b), whose graphitization is lower than that of the artificial-graphite-based (c), display a traction coefficient larger than that of lubricant (c) in the first test (i.e. the first measurement after lubricant was applied to the interface of the wheel/rail discs). However, in the third test (i.e. the third measurement without the addition of lubricant to the interface of the wheel/rail discs), the tendencies of lubricants (a) and (b) are almost the same as that of lubricant (c). This result may suggest that the coating materials of lubricants (a) and (b) have some contribution on the positive or negative slope of the traction coefficient.

2.2 Jetting system for the friction moderator

It is very important to apply the friction moderator to the wheel/rail interface over the whole length of the low rail on sharp curves, and both on-board and track-site lubricators are commonly adopted as systems to achieve this. Focusing on the fact that the friction moderator is a solid-type lubricant, the authors investigated the possibility of applying a jetting system to apply ceramic particles to the wheel/rail interface to increase adhesion between wheel and rail. This is a system known as Cerajet, developed by the RTRI as referred to in [21]. After discussion, it was decided to improve the jetting system to fit a friction-moderating system. Figure 3 shows the schematic structure of such a system. The jetting device was developed with a focus on the arrangement of the nozzle size and air pressure. This device has a function to allow adjustment for optimal jetting timing and volume together with a curve detection system.

![Fig. 1 Appearance of friction moderator](image)

![Fig. 2 Traction characteristics of lubricants](image)

![Fig. 3 Schematic structure of friction moderating system](image)

3. Performance tests for practical function

3.1 Influence of braking performance

We carried out braking tests on a commuter-type vehicle equipped with the jetting friction moderator for the wheel/rail interface on a commercial railway line. The test track was a straight section with an ascending slope of 12.5%. The friction moderator was applied at
0.052 g/m to the wheel/rail interface of one rail side (not both sides) from the location of initial braking to the estimated point of vehicle stop plus an additional distance equivalent to the length of a train set. In the tests, we applied the maximum braking force under normal operation from a speed of around 60 km/h until the train stopped. Figure 4 shows the braking test results under the test conditions of dry, dry with friction moderator, wet and wet with friction moderator. The test results were revised in consideration of the effect of the slope on the braking force. In the figure, some variation of deceleration in each case is evident, but deceleration values (i.e. the velocity decrease rates) in the test cases with the friction moderator were almost the same as those without, so the influence of the friction moderator on the deceleration braking distance cannot be significant. Additionally, the friction moderator is not applied to the wheel/rail interface in rainy conditions with a control system focusing on wiper signals etc., because wet rail surfaces caused by rain are normally anticipated to have a certain lubrication effect.

3.2 Influence on track circuit

The track circuit, which includes right/left rails, wheelsets shunting the two rails and insulation joints, is usually adopted in Japanese railway systems. Shunting malfunction is therefore a very important issue in railway safety, and the materials present on the wheel/rail interface have great influence on the matter. For the friction moderator coated with phenol resin, the raw material (carbon) shows conductivity, but the phenol resin merely shows insulation. In this study, we carried out shunting experiments in test runs of an actual railway vehicle on the test track installed at RTRI’s premises to investigate the influence of friction moderator and sand on the track circuit.

Figure 5 shows the test results of shunting performance. A large amount of sand showed a large impedance, which would represent a problem with shunting. In addition, even a small amount of sand showed a rather large impedance just after being placed on the rail surface, after which its impedance decreased. Friction moderator showed almost the same level of impedance as a clean, dry rail surface. It is therefore apparent that there is no large risk of friction moderator causing shunting problems.

4. Performance tests on a commercial railway line

4.1 Lateral forces and angles of attack

We carried out measurements at the track site to identify the effect of the friction moderator on the lateral forces on a sharp curve with a radius of 197 m (referred to below as curve (A)). Figure 6 shows the lateral forces of the
low rail and high rail as measured at the track site. In the figure, approximately 22 kN of lateral force on the low rail before application of the friction moderator decreased to approximately 7 kN after application to the wheel/rail interface on the low-rail side using the jetting device of the friction-moderating system that was installed on the test vehicle. The lateral force on the low rail thus decreased by 68% due to the effect of the friction moderator. Similarly, approximately 27 kN of lateral force on the high rail before application of the friction moderator decreased to approximately 9 kN after application, representing a reduction of approximately 66% in the lateral force on the high rail. In addition, the effect of the friction moderator on reducing the lateral force continued up to at least 216 axles.

Figure 7 shows the angle of attack measured at the track site. In the figure, the angles before and after application of the friction moderator were about 10 mrad on average, so no significant change was identified.

### 4.2 Squealing noise

A microphone was set up at a location shown in Fig. 8 with trains passing in front of it to measure sound pressure levels. The microphone was placed on a sharp curve with a radius of 165 m (referred to below as curve (B)), and the measured results are shown in Fig. 9. In this figure, the sound pressure level of approximately 87 dB decreased to approximately 77 dB up to 168 passing axles from the first application of the friction moderator. After that, the sound pressure level gradually increased to more than 85 dB with each passing train up, but decreased again from the second application of the friction moderator. The effect of the second application on reducing the sound pressure level was identifiable as approximately 77 dB for 248 passing axles up to finishing the tests and starting the on-board lubrication system.

### 4.3 Discussions

#### 4.3.1 Durability of the function of reducing noise

Figure 9 shows that the effect of the first friction moderator application on reducing noise does not continue compared with that of the second application. It can be thought that the reason for this is that some amount of the first moderator applied remained on the top of the rail when the second application was carried out, because the coefficient of friction (referred to below as COF) did not change significantly even though the sound pressure level increased gradually just before the second application.

The measuring apparatus for the COF, known as a rail tribometer, is shown in Fig. 10. The apparatus was developed by the RTRI to measure the COF of the vehicle running band on a rail at the track site. This figure shows that the structure of the apparatus looks very simple. The measuring mechanism involves two bearing balls fixed to one steel block sliding on rails with a friction force. We measured the friction force using a load cell and estimated the COF as the friction force divided by its own weight. The weight of the steel block, including the two bearings, is designed considering that the contact pressure between a bearing ball and the rail corresponds to the maximum Hertzian pressure of approximately 700 MPa. This value is decided using normal used worn profiles of wheels and rails that are considered to be standard.

Figure 11 shows the method of estimation for the COF averaged from the signal waveforms of measurements. In Fig. 9, the COF of 0.32 - 0.42 before the first application decreased to around 0.2 afterward. The value then increased to 0.24, even with the sound pressure level of 77 dB just after the first application increasing to 87 dB just before the second application.

As shown in Fig. 11, since the COF is estimated as the average of the signal, the average does not change significantly, but the friction condition suggested by the variation in the COF signal may not be the same. Generally in the case of large COF signal variations, the stick/slip phenomenon, which may cause squealing noise, often appears. Figure 12 shows some waveforms of the COF measured signal for the cases of passing axles in Fig. 9. In Fig. 12, the variation in the COF at the passing of 248 axles becomes very large compared with that beforehand.

The relationship between the sound pressure level and $\delta$, which is defined as the average of the COF multiplied by the variation in the COF, is shown in Fig. 13. There is some variation in the figure, but the tendency for the sound pressure level to increase in response to the increase in $\delta$ is significant. Thus, even if the average of the measured waveform of the COF does not change significantly, in cases where the variation increases, the stick/slip phenomenon can be induced to increase the sound pressure level. On the other hand, the reason why the average of the measured waveform of the COF did
not increase significantly in the running tests is thought to be that the amount of friction moderator remaining on the rail surface effectively kept the COF average at the same level, but not enough to reduce the sound pressure level. However, such an amount of leftover friction moderator, although insufficient for noise reduction, may have contributed to improving the durability of the effect on keeping the sound pressure level low combined with the second application of the friction moderator.

Fig. 9  Effect of friction moderator on reduction of sound pressure level and COF of low rail on curve (B)

Fig. 10  Rail Tribometer developed by RTRI

Fig. 11  How to read the waveforms of measured signal of COF

Fig. 12  Waveforms of COF measured at some cases of passing axles in Fig. 9

Fig. 13  Variation of sound pressure level with δ defined as the average of COF multiplied by the variation of COF
4.3.2 Effect of the friction moderator on the reduction of noise caused by rail corrugation

As shown in Fig. 9, the sound pressure level on curve (B) was reduced by about 10 dB after applying the friction moderator. On the other hand, the results of measurement for noise on curve (A) in Fig. 14 show a noise reduction of about 5 dB on average. The results of frequency analysis for the noise before and after application of the friction moderator on curves (A) and (B) are shown in Fig. 15. In the figure, no difference in the sound pressure level around 250 Hz before and after application of the friction moderator on curve (A) is identified. Corrugations formed on the top of the low rail on curve (A), so the longitudinal profile of the surface irregularity on the top of the low rail was measured, and the results are shown in Fig. 16. Considering that the wavelength of corrugations is 34.6 mm on average and the velocity of passing trains averages about 32 km/h, the frequency of noise caused by corrugations is estimated as 257 Hz, which is the same as the above-mentioned frequency of approximately 250 Hz. On the other hand, no corrugation was found on curve (B). Accordingly, the friction-moderating system has an effect on the reduction of squealing noise, but it is not sufficient for the reduction of noise caused by corrugation. However, since preventing corrugation is one of the main purposes of developing a friction-moderating system, the setup will be evaluated for use after removing the corrugations.

5. Conclusions

The effect of lubricating the top of the low rail on reducing lateral forces for vehicles negotiating sharp curves was identified as a result of on-board and trackside measurements [15-18]. The authors developed a friction moderator and a jetting device for its application to the wheel/rail interface, and this is referred to as a friction-moderating system (FRIMOS). In this study, the system was installed on board, and running tests were carried out to investigate the effect of the friction moderator on reducing the coefficient of friction of the top of the low rail and the rolling noise (squealing noise) just beside the track. Although it is not easy to evaluate the performance of a friction moderator from such limited test arrangements, durability of the effect of a small amount of the moderator on reducing the coefficient of friction and rolling noise may be expected. A further study on an automatically controlled system for the jetting friction moderator is expected to provide practical information on optimal jetting timing and moderator volume, and will also identify the potential of the friction moderator to prevent the generation of low-rail corrugation through long-term operational service.
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References


