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The role of high positive friction (HPF) modifier in the control of short pitch corrugations and related phenomena

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Abstract

Vibration and noise from wheel–rail corrugations reduce the life of vehicle and track components and bring great discomfort to passengers and residents living in close proximity to the tracks. Roll–slip (stick–slip) oscillations are involved in a number of corrugation initiation and formation mechanisms, especially in systems that exhibit a high level of friction, and negative friction characteristics. HPF friction modifier has demonstrated the ability to change the negative friction characteristic of the wheel–rail interfacial layer to positive, and reduce and control friction to levels consistent with braking and traction requirements of the system. Depending on the circumstances of the system involved, HPF can always reduce top of rail noise by at least 3–4 dB and in some instances by as much as 25 dB.

1. Introduction

Rail corrugations are a well-studied problem that can be broadly divided into (1) those related to freight and heavy haul, and (2) those usually associated with relatively light axle loads, typically on transit systems. The latter generally involve higher frequency of corrugations, 25–80 mm (short pitch).

In practical terms, corrugations are removed from rail systems by grinding. Three general approaches have been described to reducing the rate of corrugation formation:

1. Making the overall system well-damped. This approach reduced the propensity for vibrational excitation of torsional and flexural bending of wheel sets. Malavasi has established correlations between the frequencies of these and corrugation frequency [1]. Tassilly et al. found that decreasing the vertical stiffness of the track reduced corrugations in the range 50–80 Hz [2]. Although, successful in many instances, this approach is limited by the impracticality of damping the entire system, as well as cost factors.
2. Lubricating by adding grease to the top of the rail. Long wavelength corrugations were reduced, both in severity and extent by lubrication Daniels and Devine [3]. However, lubrication has disadvantages in terms of impact on traction and braking, as well as environmental concerns. Suda et al. also demonstrated the principle in laboratory studies [4].
3. Modifying wheel–rail profiles to distribute the wear across the wheel profile. This has the effect of reducing hollowing, improving traction of wheel sets in curves and tangent track, and reducing slip in the wheel–rail contact patch.

Clarke [5] described a model that showed how short pitch corrugation could be related to roll–slip, and indicated that corrugation formation could be reduced by ensuring that the creepage–force relationship never displayed a negative slope at higher creepage. However, he did not suggest any means by which this could be achieved.

Wu et al. demonstrated in laboratory studies that corrugation patterns agreed well with predictions based on a roll–stick (stick–slip) mechanism, and showed that HPF applied under these conditions could completely suppress the formation of corrugations [6].

High-pitched noise (squeal) is also a significant issue particularly for transit systems. A large proportion of squeal noise originating from the top of rail is associated with roll–stick oscillations [7].

In this paper, we review the underlying phenomenon of negative friction and roll–slip oscillation that relate to both, short pitch corrugation and to noise. We will describe how the mechanisms for noise and corrugations are related, and how knowledge of the frictional characteristics of the wheel–rail interface relates to each issue.

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We will also show how changing the friction characteristics of the 'third body' between the wheel and the rail from negative to positive can reduce the incidence of roll–slip related noise and vibration. From this we draw parallels to the reduction in short pitch corrugations that can be anticipated by control of friction and the type of friction between the wheel and the rail.

2. Origins of short pitch corrugations

Many mechanisms of short pitch corrugations have been identified and described in the literature by Kalousek and Johnson [8], Knothe and Grassie [9], Hempelmann [10], Grassie and Elkins [11], Kalousek and Grassie [12]. As wear is the damage mode for the short pitch corrugation, the primary difference in the corrugation formation mechanism rests in wavelength fixing and initiation mechanisms. The wavelength fixing mechanism is usually related to selected natural frequencies of the wheel/or wheel set and rail and/ rail tie coupling. The initiation mechanism can either be related to the rail–wheel surface irregularities including surface roughness, or the traction–creepage relationship of a particular section of the track. The surface irregularity initiation mechanism is usually based on dynamic excitation of the vertical wheel load. Such irregularities may be present in newly manufactured rail and wheels, or may be introduced by improper grinding of rail. When the depth exceeds 0.01 mm or the wavelength exceeds the dimensions of the contact patch, there is a sufficient dynamic excitation of vertical wheel load. This in turn produces traction force oscillations. This initiation mechanism does not require the creepage at the wheel–rail contact patch to be saturated Fig. 1.

In many sections of the track where creepage saturate, the decreasing friction characteristic of the creepage–traction relationship may result in self-sustained roll–slip oscillations in the wheel–rail system (negative friction).

When the wheel–rail contact patch operates in the vicinity of saturated creepage, the wheel rolls forward while the traction force builds up towards the maximum of the traction–creep curve. Once this maximum is achieved, the force cannot be increased any further because of the negative friction characteristic, and slip occurs. This cycle of events is referred to as roll–slip oscillation of the wheel–rail traction force. Such oscillations precede and can initiate the development of corrugations of rail and wheel surfaces.

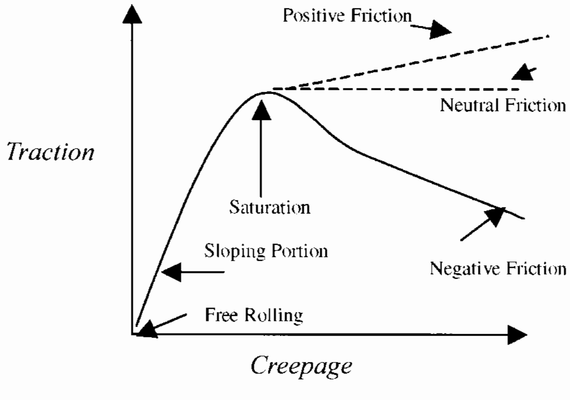
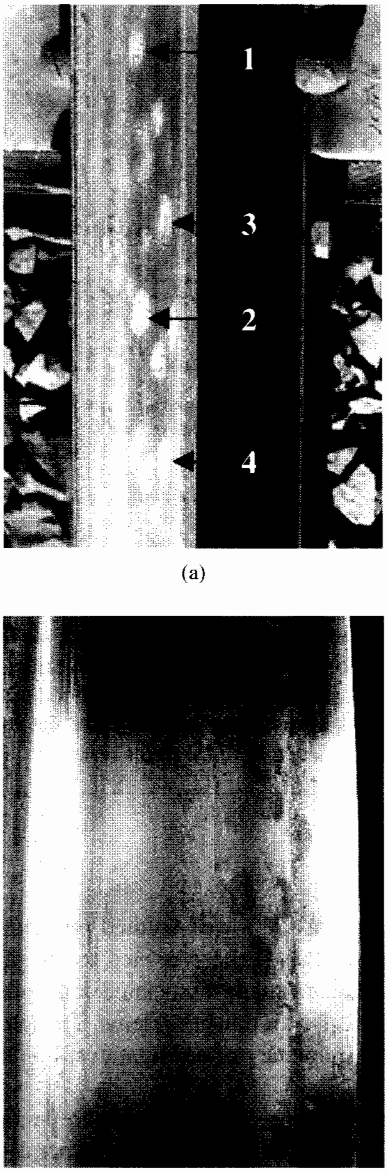


Fig. 1. Traction–creepage relationship.



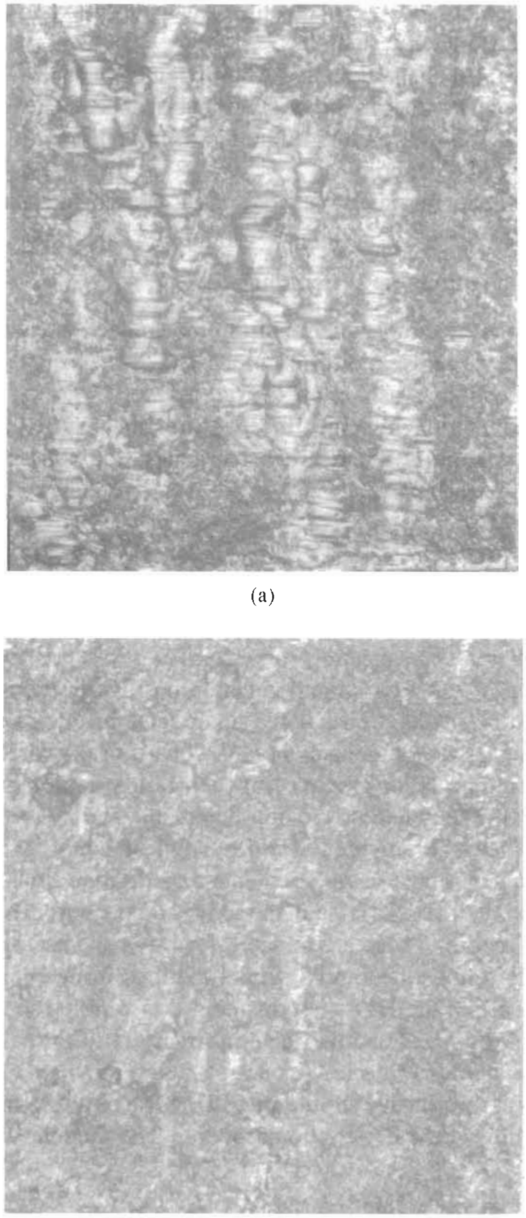
(a)

(b)

Fig. 2. (a) Shiny patches, and (b) darkened patches represent the slip regions of roll–slip oscillations.

Roll–slip can easily be observed on surfaces of rails or wheels of slow moving trains.

The photograph shown in Fig. 2a was taken on low (inner) rail located in a 6° (300 m) curve. Many of the leading wheel sets of bogies had a large angle of attack. The slip regions 1, 2, and 3, 4 are respectively associated with roll–slip cycles for two different wheel sets. The distance between



(a)

(b)

Fig. 3. Observation of oscillatory lateral slip around the wheel circumference. The slip at its maximum is shown in (a), and its minimum in (b).

slip regions 1 and 2 (or 3 and 4) represents the roll portion of roll–slip cycle. At slip region, the lateral traction force is suddenly released leaving slip marks of up to 1.5–2 mm long. Of course, wear rate at the slip regions is much higher than at the neighboring roll regions. Coalescence of several slip regions may form the initiation of the corrugation valley.

The footprints of roll–slip oscillations were also observed on numerous occasions on the non-corrugated wheels of mass transit system operating at maximum speed of 80 km/h. Fig. 3 shows an example of lateral oscillatory slip marks observed in the middle of the band along the circumference of the wheel. The distance between slip (Fig. 3a) and roll (no slip, Fig. 3b) region was about 16 mm. The maximum value of the slip was about 100 μm, repeated along the circumference each 32 mm. Oscillatory roll–slip components have been observed on non-corrugated wheels having slip vectors in longitudinal direction and directions having both lateral and longitudinal components. Notably, wheels with oscillatory roll–slip footprints in the lateral direction were much noisier than wheels with roll–slip footprints in the longitudinal direction. This observation provides another piece of evidence linking the roll–slip mechanism to the generation of top of rail noise. The existence of oscillatory roll–slip on un-corrugated track is a sufficient precursor to the development of short-pitched corrugations.

Roll–slip corrugations may originate in any wheel–rail system where the longitudinal, lateral, and spin creepage reach saturation and the resulting traction force enters the region of negative friction characteristic. The transition occurs at the knee of the traction–creepage curve, typically at 1% of longitudinal creepage or 20 min angle of attack in the case of lateral creepage.

3. Negative friction and the rheological characteristics of the interfacial layer

The rheological behaviour of interfacial layers forming a 'third body' in rolling–sliding contact directly affects the traction–creepage curve. Measurements of the shear stress properties of individual components of the interfacial layer have suggested the following elastic–plastic rheological model [13]:

$$\begin{cases} \tau = G\gamma, & \text{when } \tau \le \tau_c \\ \tau = \tau_c + k(\gamma - \gamma_c), & \text{when } \tau > \tau_c \end{cases}$$

This model establishes a relationship between three rheological parameters: the shear moduli of elasticity (G), plasticity (k), the critical shear stress (τ_c), and shear strain (γ). With increasing creepage, the transition between elastic and plastic moduli moves closer to the inlet of the wheel–rail interface (Fig. 4).

A specially designed pin-on-disk machine is used to measure the rheological properties of a thin powder film between two metal surfaces, under load/shear conditions found at the wheel–rail interface. It can establish the values of rheological parameters G, τ_c, k, and γ. It also acts as a 'microscope' to find a displacement value at which the transition between elastic and plastic moduli occurs.

Fig. 5 shows an example of rheological properties of different components in the interfacial mixture evaluated with the rheometer. At the initial stages, the shear stress generally increases as the slip increases. As the shear stress reaches its critical value, the initial slope of the curves change. Some materials such as molybdenum disulphide have a low shear stress with 'flat' characteristics, meaning that the shear stress no longer varies with increasing slip. For others such as sand,

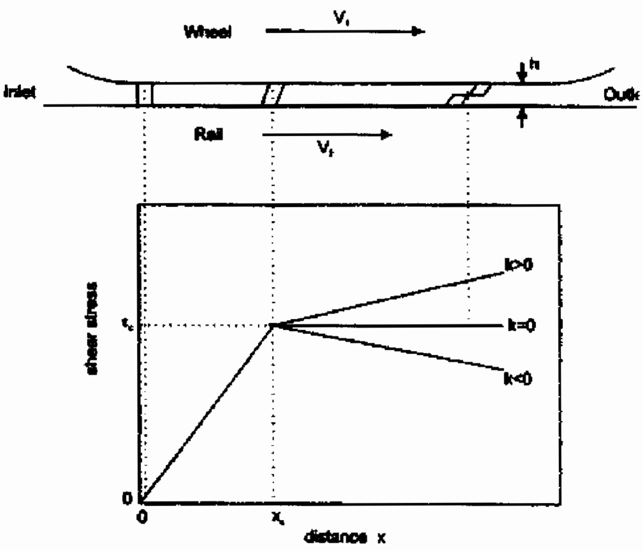


Fig. 4. Rheometer characterization of selected interfacial materials.

the shear stress reaches a critical value at about 100 microns of slip (about 1% creep in an average contact patch), after which the shear stress decreases as slip distance increases.

Materials in the wheel–rail interface have a critical influence on frictional properties and hence on the dynamics of roll–slip oscillations. The 'third body' is comprised of a complex mixture of materials whose composition is influenced by both environmental factors and railroad operating practices [13]. The type of materials being added, the rate at which they are being added, and the means and rates at which they are removed, determines the composition of the interfacial layer.

Inputs to the layer include:

- Iron oxides both from oxidation of rail and from wear mechanisms. These can include Fe_2O_3 (hematite or red iron oxide), Fe_3O_4 (magnetite or black iron oxide) and as well as metallic iron.
- Silica, usually originating from locomotive sand.
- Hydrocarbons from oil or grease lubricants that have been applied to or migrated to the top of the rail.
- Brake shoe debris.
- Contaminants such as: coal, dust, leaves, potash, and others.

Outputs from the system include:

- Displacement of materials from the contact patch.
- Removal by wear attrition processes.
- Removal by washing off the rail by rain.
- Consumption by other mechanisms such as oxidation, evaporation of hydrocarbon lubricants, and other chemical mechanisms.

4. High positive friction (HPF) friction modifiers

HPF refers to a family of materials developed to control top of rail friction and generate positive friction characteristics in the 'third body' interfacial layer [14]. The friction-active components in HPF consist of dry materials. There are no oil or grease components, or volatile organics (VOCs). The materials are non-flammable and non-toxic.

HPF can be provided in either solid or liquid form depending on end use requirements and desired application method. Solid sticks contain the active components in a polymeric matrix. These are suitable for on-board use applied directly to the wheel tread. Under the load from a constant force spring, the HPF stick material transfers to the wheel tread. From the tread the material transfers to the rail; the resin material is selected to burn off under the high temperatures at the wheel–rail interface. This leaves a thin micron scale film of the dry friction modifier. The material fills in

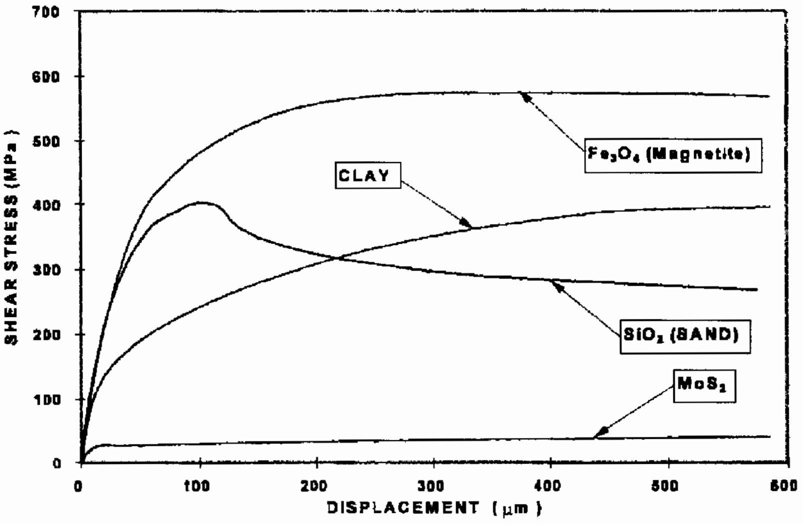


Fig. 5. Wheel–rail interface material composition.

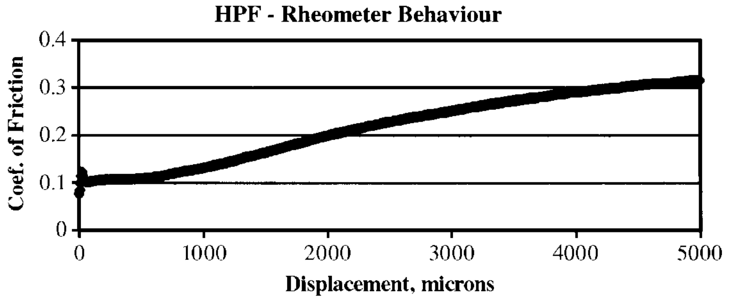


Fig. 6. HPF thin films behavior in the pin on a disc rheometer.

the micro scale asperities in the metal surfaces, providing a surface that is noticeably smoother.

The material is also available as a water-based liquid, which is applied directly to the top of the rail. This may be accomplished by either on-board application from the train, manually, using a trackside applicator, or from a track vehicle such as a 'Hi-Rail' vehicle. The viscosity, flow, and drying rate characteristics of liquid HPF can be adjusted to the required levels depending on the application system.

The behaviour of thin films of HPF in the pin on disc rheometer is shown in Fig. 6. This illustrates the very unusual positive friction behavior of this material, in which friction increases with displacement and creepage over a wide range.

The measured rheometer displacement shown in Fig. 6 can be related to creepage as shown later, assuming a 10 mm circular contact patch.

4.1. Friction control with HPF

Field observations clearly indicate the damage mechanism for short pitch ('roaring rail') corrugation involves wear at high coefficients of friction (0.4–0.6). In addition to positive friction, a key attribute to corrugation control is *control* of the friction level at the top of rail. The requirement is to reduce the friction from a typical dry level of 0.4–0.6 to a controlled lower level that does not impair traction or braking. A value of around 0.35 is believed to be optimal [15]. Coefficient of friction in this case is generally referred to as top of rail friction levels as measured with a push tribometer (sliding friction).

HPF friction modifier provides this ability as illustrated in Fig. 7a. This shows that by contrast, application of a lubricant to the top of rail does not provide control of friction at the intermediate level needed to control corrugations without affecting braking or traction.

This test was carried out at the AAR's Transportation Technology Centre FAST facility [16]. In each case, the material was applied to the top of rail from the last locomotive using an on-board system, on a freight closed loop test circuit, under conditions that were as identical as possible.

Fig. 7b shows the changes in the top of rail (TOR) friction through progression of sequential train laps, starting initially with the TOR systems turned off, and from the dotted line the changes after the systems dispensed the lubricant. The dispensed lubricant had divergent effect of the friction at low and high rails. At the high rail, the friction level was higher than optimum, whereas the low rail friction was lower than optimum. In addition, the low rail friction levels were not stable through the trial period.

By contrast (Fig. 7a), the HPF friction modifier case showed rapid convergence of the high and low rail friction values to the 0.35 level, and that this value was accurately maintained throughout the length of the trial.

4.2. Relationship between HPF and interfacial layer inputs and outputs

The HPF material is one of the inputs that can override the frictional characteristics of the contaminants and change the characteristics of the frictional pair from negative to positive.

HPF is a consumable material in the sense that it will over a time be removed or overcome by the inputs and outputs to the interfacial layer as described. For example, it can be expected that high lateral creep forces will tend to gradually displace the thin film of HPF outside the contact band.

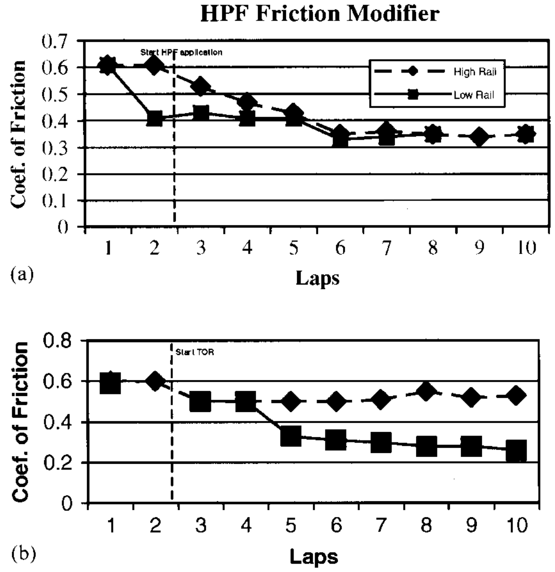


Fig. 7. (a) HPF friction modifier, and (b) TOR lubricant system.

Similarly, accelerated metal oxidation, e.g. rain followed by high temperatures will start to overcome the frictional control provided by HPF. However, practical observations are that sufficient material can easily be maintained by appropriate delivery systems (whether of liquid or solid friction modifier) to overcome these effects.

Numerous studies of stick–slip induced oscillations show that there are three general methods of reducing or eliminating this phenomenon:

1. Making the mechanical system or equipment in which the stick–slip occurs very rigid.
2. Reducing the friction between the moving components to very low levels.
3. Changing the friction characteristics between the moving surfaces from negative to positive.

Provided sufficient HPF material is maintained between the wheel and the rail, two of the three general approaches to reducing roll–slip (stick–slip) oscillation induced corrugations, conditions 2 and 3 are satisfied, namely:

- HPF reduces friction to 0.35, while controlling this at a level that does not detract from braking or traction.
- HPF changes the frictional behaviour of the interfacial layer from positive to negative.

5. Control of wheel–rail noise related to stick–slip/negative friction using friction modifiers

A number of mechanisms exist for generating noise in the wheel–rail system. These include wheel flats, rail joints, excessive surface roughness, and others. Short pitch corrugations themselves produce a form of noise known as roaring rail.

The most critical type of noise in terms of human impact is high frequency squeal. A number of mechanisms of squeal generation have been proposed. As discussed for the corrugation case in sharp curves, lateral creep of the wheel on the rail can initiate stick–slip oscillations when the wheel–rail interface has negative friction characteristics.

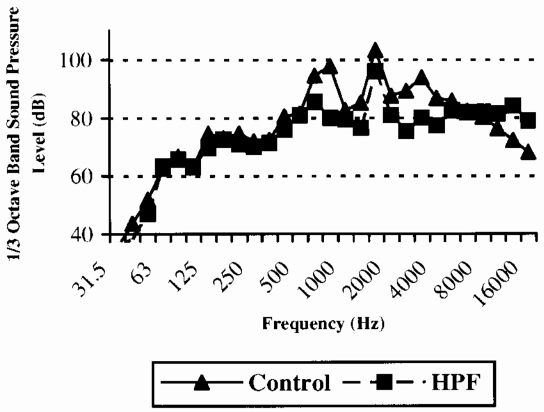


Fig. 8. Sound levels at different frequencies.

The energy dissipated by the stick–slip process, is available to excite squeal in the wheel–rail system. The vibration set up by the stick–slip mechanism causes a diaphragm-type oscillation of the wheel web as the wheel negotiates curves.

Although, flange lubrication with grease is sometimes used as a means to control noise, this approach is relatively ineffective because it does not address the top of rail origin of much squeal noise. Top of low rail application of grease is also commonly used, but results are often inconsistent.

Introducing HPF material in the wheel–rail interface overcomes the negative friction characteristics that lead to stick–slip and wheel squeal. Although, this has been observed many times in field trials, the following example [17] from a transit system is selected as illustrative:

Trackside and on-board noise measurements were recorded for control trains as well as those with solid HPF applied to the wheel tread. The trackside noise measurements were recorded with a microphone positioned 7.62 m radially outwards from the high rail and 1.5 m above grade. The curve was 25 m radius. A weighed noise measurements were taken. Train speed was 16 km/h. Measurements were taken for both East and West bound train directions.

'Peak hold' noise levels representing the peak levels were recorded in one-third octave bands. Trackside 'waterfall'

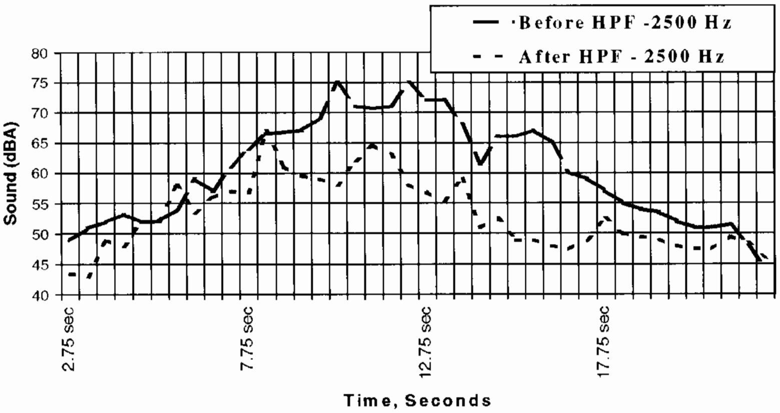


Fig. 9. Sound change with time.

noise data were collected as a series of 0.5 s interval noise measurements. As shown in Figs. 8 and 9, significant sound level reduction occurred in the squeal frequency range of 800–6000 Hz in the eastbound direction. Noise reductions at the predominant squeal frequencies of 800, 1600, 2500 and 3150 Hz were as great as 20 dB and averaged between 5 and 10 dB.

Time slice data of the squeal frequencies of 2500 Hz from 'waterfall' data are shown in Fig. 9. The 'waterfall' data represents noise generation at a particular frequency as a function of time as the train passes the measuring point.

6. Control of corrugations with HPF—practical experience

In the laboratory, clear evidence of corrugation suppression by HPF friction modifier has been published [6]. By the nature of the phenomenon, it is difficult to get good scientific data on corrugation growth rate in practical rail operations. This is even more so in the case of applying HPF friction modifier. In this case, it would be necessary to measure corrugation rates without HPF, outfit the fleet with friction modifier, and then measure corrugation rates again.

There have however been several empirical experiences where solid stick HPF has shown reduction in corrugation rates. In all cases, other variables also changed; nevertheless the experiences are still considered valid.

Kalousek and Johnson [8] have reported the contribution of HPF friction modifier in reducing corrugations on the Vancouver Skytrain. As in many other cases, a number of other variables such as wheel and rail profiles were also changed in an effort to find a solution. Nevertheless, the friction modifier clearly played an important role.

6.1. Case 1

This elevated light rail system located in Asia was experiencing rapid short pitch corrugation growth after startup. In some areas, short pitch corrugations were appearing after 1 week and grinding was carried out at this frequency. A number of changes were made to the system, among which was application of HPF friction modifier to 25% of the wheels. Other changes included wheel profiles, rail profiles, truck primary suspension, and friction between truck and vehicle body.

The modifications reduced the frequency of rail grinding to approximately 6 month intervals. It has observed that when the amount of HPF in the system was reduced (applicators not replenished), the onset of corrugations was accelerated.

6.2. Case 2

This North American light rail system has two separate lines, with similar car types. Line 1 operates underground, and has had HPF friction modifier applied to 25% of the wheel treads since start of operations approximately 10 years ago. This line also uses LCF solid stick flange lubrication. Line 2 operates on elevated track, and has not used friction modifier since the start of operation approximately 4 years ago. Trackside grease lubrication was employed on this system.

No grinding has been carried out on this system. Comparison of corrugations between the two lines showed that Line 2 had significantly more corrugation development after 4 years (no HPF) compared with Line 1 after 10 years operation (HPF). These were typical short pitch corrugations.

Again, although other variables are present, the role of HPF in suppressing corrugation growth on Line 1 is believed to be significant by the system operator.

7. Concluding remarks

We have shown how stick–slip oscillations due to negative friction under saturated creep conditions are a common underlying cause of both wheel squeal and short pitch corrugations. Use of high positive friction modifiers to alter the friction at the wheel–rail interface from negative to positive is an effective means to alleviate the formation of roll–slip corrugations, reduce noise from corrugations and reduce or eliminate wheel squeal.

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