STUDY ON THE MECHANISM OF DISCONTINUOUS SUPPORT STIFFNESS ON THE DEVELOPMENT OF RAIL CORRUGATION

Anbin Wang¹, Zhiqiang Wang¹, Pan Zhang¹, Ning Xu¹, Zheyu Zhang¹, Kuang He²
¹Luoyang Ship Material Research Institute, Luoyang, China, 471003
e-mail: wangab725@163.com
²Zhengzhou Metrol Transportation Company Limited, Zhengzhou, China, 450002

To minimum the adverse influence of rail corrugation on train operations and track maintenance, and to take effective measures for prevention and control, it is important to understand the cause of generation and development of rail corrugation, and analyze the influence factors on the corrugation. In the process of analysis, observation and tracking on the system for rail corrugation should be carried out to grasp the characteristics of rail corrugation. This paper describes the study of the fastener assemblies with different values of rail supporting stiffness using on-site tests with an impact excitation. The rail dynamic frequency response functions in both vertical and lateral directions were measured at positions which were directly over the fastener and also in the middle span of two fasteners along the rail. Through a large number of experimental data and analysis, it was found that the transfer functions clearly show opposite trends when the wheels running over on the fastener and on the middle span between two fasteners. This demonstrated that the discontinuous support is a main cause of rail corrugation. According to the experimental results, the support space and the rail stiffness should determine the characteristic frequencies of existing rail corrugation. The difference of rail response at the characteristic frequency is affected by the rail support stiffness, which can effectively inhibit the formation and development of rail corrugation.

1. Introduction

Rail corrugation, is a periodic, wave shaped deformity phenomenon appearing on rails along the longitudinal surface, and is a railhead surface defect on the railway tracks. With the increase of curvature of the track, train speed and axle load, and the traffic density growth, and the wide use of new types of locomotives and vehicles, rail corrugation phenomenon has become increasingly serious, which can cause considerable harm to railway transportation and safety. These include: i) increasing the wheel-rail dynamic interaction forces, shortening fatigue and service life of the rail; ii) worsening vibration of the vehicle-track system and hence increase the parts wearing and even damage, and resulting in the increasing of energy consumption and repair costs; iii) causing poor contact and increasing rolling resistance and energy consumption; iv) causing noise and vibration pollution, affecting passenger comfort, and even endangering the traffic safety. In addition, the requirement of regular grinding to the rail surface also added to the operating and maintenance costs [1, 2].

The main points of corrugation formation and development include: a) the periodic variation of wheel-rail interaction dynamic force along the track. This periodic dynamic force causes rail and increase rail wearing. The impact force due to vibration will speed up the development of
corrugation; b) a cyclic process of interaction between vehicle and track dynamic behavior with corrugation; c) quasi-periodic vertical load is the main cause of rail corrugation; d) the space between sleepers affects the "Pinned-Pinned" resonance frequency as well as stiffness of track in certain degree, thus affecting the corrugation. Experiments show that, discontinuous support stiffness has significant effect on the generation and development of the rail corrugation [2].

Rolling noise is an important noise source at lower speed of most metro systems. Rolling noise from trains is radiated from vibrations of the train wheels and the track, driven by dynamic forces arising at the contact between the wheel and the rail. The most important sources of these dynamic excitations are the roughness and the rolling impact force, particularly on the curvature tracks [3, 4].

2. Wave type rail Wear

2.1 Rail Rolling Model

Rail corrugation formation and development process is a cyclic process of the interaction of the vehicle-track dynamic behavior and corrugation, as shown in Figure 1 When the vehicles pass through the irregular track, vehicle and track vibrates, resulting in the rail contact surface uneven wear and plastic deformation. When vehicles go through the lines again, track irregularity and accumulation of uneven wear and plastic deformation on rail contact surface will worsen the vibration of vehicle-track; further increase the uneven wear and plastic deformation. After repeated cycles, the process results in the rail corrugation [5]. The interaction between wheel and rail is very complicated, which is the combination of dynamic behavior, the wheel rail contact effect, friction and mutual interaction mechanism among them. One of explanations is that rail corrugation is generated by the quasi-periodic vertical load which is accompanied with constant tangential traction probably caused by the locomotive traction and braking force, guiding force, or the combination of the both.

![Figure 1. Model of feedback between structural dynamics and damage mechanism](image)

2.2 Rail roughness

Rail corrugation is a typical rail roughness phenomenon. During the operation, wave shape wear marks appeared on the rail surface along the longitudinal direction. These wave makes have fixed wave length. It is easy to notice the wear marks on rail head with evident wave crest and trough [4, 5]. Due to the complicated nature of wheel-rail interactions, which concerned dynamics, contacts and friction mechanics and their cross-disciplines, rail corrugation is considered as the consequence of a quasi-periodic normal load in combination with a considerably constant tangential traction,
which may arise from applied traction and braking, steering forces or a combination of all. The corrugation so-called “wavelength-fixing mechanism” is the resonance of vehicle’s unsuspended mass (“P2 resonance”) or the “pinned-pinned resonance” of the rail [5]. Another theory considered corrugation arises as a result of quasi-periodic tangential traction in combination with a substantially constant normal load. This wavelength-fixing mechanism is a tensional resonance of the wheel set. Two kinds of mechanisms might be main issues for the corrugation occurred on the curved tracks.

The “pinned-pinned resonance” was shown to be the dominant mechanism of wavelength-fixing [6]. This pinned-pinned frequency \( f \) can be calculated as equation below (1) [7]:

\[
f = \frac{\pi}{2f^2} \sqrt{\frac{EI}{m_r}} \left[1 - \frac{1}{2} \left(\frac{pi}{l}\right)^2 \left(1 + \frac{2(1 + \nu)}{K}\right)\right]
\]

Where \( E \) is the modulus of elasticity of rail steel, \( I \) is the moment of inertia of the rail, \( m_r \) is the rail mass per unit length, \( l \) is the fastener spacing, \( r_g \) is the radius of gyration, \( \nu \) is Poisson’s ratio, and \( K \) \((\approx 0.34)\) is the shear constant of the cross section.

The wavelength and its wave amplitude are both important parameters to define the rail corrugation level. Therefore the corrugation excitation frequency to the running train can be calculated if the train speed is known, i.e.

\[
f_c = \frac{s}{\lambda}
\]

where \( f_c \) is frequency, \( s \) is train speed and \( \lambda \) is wavelength of corrugation. This is useful to identify the vibration source on the corrugation track. Changing the train speed may affect the wavelength of corrugation but may not effectively inhibit the rail corrugation formation [12].

### 3. Discontinuous Support impact on rail corrugation

In the Spanish Bilbao Metro, the sleeper spacing was 0.6m with ballasted track originally, and became 1.0m after replaced with the STEDEF ballastless track with damping rubber boots. The rail corrugation depth reached 0.4mm only after 920,000 pairs of wheel sets passed through. When the sleeper spacing was reduced to 0.5m, the rail corrugation disappeared [10]. After that, it was considered that longer sleeper spacing could cause more corrugation. However, the rail corrugation was found on city lines with rail sleeper spacing range from 0.6~1.0m, even on some tracks without sleeper but continuous support [11].

The Sleeper spacing has effect on “pinned-pinned resonance” frequency of rail, and on stiffness to a certain degree. Rails with large sleeper spacing and the small rail section have low first order of “pinned-pinned resonance” vibration frequency. One of the parameters to affect “pinned-pinned resonance” frequency is sleeper spacing. For sleeper spacing of 0.6m, 0.75m, 0.9m, the first order “pinned-pinned resonance” frequency with 60kg rail in the vertical direction are 1070Hz, 748Hz, 560Hz respectively. When the sleeper spacing being too large (say great than 1m), the “pinned-pinned resonance” frequency may coincide with the wheels’ second order torsional frequency. Otherwise, the “pinned-pinned resonance” vibration due to sleeper spacing should not be the main reason to cause corrugation.

When the train goes through a curve track, the uneven lateral rail stiffness due to discrete sleeper support can easily trigger the formation and development of rail corrugation; Due to the lower bending stiffness of the rail in the lateral direction, the “pinned-pinned resonance” frequency should be lower or the wavelength should be longer for the lateral or torsional behavior of the rail.

The wavelength of rail corrugation has a wide range. Some of the long wavelength is almost the same as sleeper spacing, and some is a short wave of 28 ~ 35mm wavelength. The short wave length uneven wear is mainly caused by the high frequency vibration of the wheel-rail interaction or “pinned-pinned resonance”.

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4. Experiments of track frequency response function

4.1 Measurement method

In order to eliminate the effect of the different factors, such as the axle load, vehicle speed, curve radius and the wheel rail surface conditions on measurement results, frequency response functions of the track system can be used. The frequency response function can identify system’s natural characteristics such as track stiffness, resonance frequencies etc. This can be conducted to measure the track response when tracks are excited by an impact force using instrumented hammer. Track vibration propagation decay rate can be also obtained through multi-point transmission response function [14].

Figure 2 shows the diagrammatic drawing of track frequency response function test. The positions of excitation and response located at the middle span of the two fasteners and also over them. Receptance is used here to present the frequency response function as below:

\[ \alpha(\omega) = \frac{D(\omega)}{F(\omega)} \]  

Here \( \alpha(\omega) \) is receptance, \( D(\omega) \) is displacement of response, \( F(\omega) \) is input force. They are all function of frequency, \( \omega \) is angular frequency, \( \omega = 2\pi f \).

![Diagram of track frequency response function test](image)

**Figure 2.** Orbital transfer response function test

4.2 Different trackforms

To compare the different track systems, measurements were carried out at three sites systems on Zhengzhou Metro in China. Frequency response functions in both vertical and lateral directions were measured on both high and low rails with three different trackforms, including steel spring floating slab track, slab mat track and standard track. All tracks tested are on the curve with radius of 400 meters. The track with steel spring floating slab was designed with an isolation frequency of 6~8Hz, and the track with slab mat was designed with an isolation frequency of 10~15Hz. The standard track is solid slab without any vibration isolation effects. The rail fasteners are the same for all three trackforms with dynamic stiffness of 50~100kN/mm.
4.3 "Pinned-Pinned resonance" of different trackforms

1) Standard track

This type of track consists of concrete slab in a tunnel with 60kg/m rail and standard baseplate fasteners. The dynamic stiffness of fastener is about 50~100kN/mm. Rail receptances in both vertical and lateral directions at the middle span of the two fasteners and over them are shown in Figure 3 for the low rail and in Figure 4 for the high rail. Assuming a similar dynamic behavior with the low rail and the high rail, an averaged result from both rails has been used to analyze the peaks of frequencies and values of the amplitude of rail receptance.

For the lateral receptance, the first natural frequency is found at 120Hz which should be the unloaded rail resonance in the lateral direction which depends on the lateral stiffness of the rail fastener; and a rebound at around 540Hz should be the “pinned-pinned resonance” in the lateral direction.

For vertical receptance, the first natural frequency is found at 210Hz which should be the unloaded rail resonance in the vertical direction which depends on the vertical stiffness of the rail fastener; and a rebound at around 1100Hz should be the “pinned-pinned resonance” in the vertical direction.

![Figure 3](image1.png)

![Figure 4](image2.png)

2) Slab mat track

This rubber slab mat has a dynamic area stiffness around 0.015~0.045N/mm\(^3\). It’s natural frequency is about 10Hz to 15Hz. This system has a unique nonlinear stiffness design. It consists of a bottom plate with an elastic unit of multiple layers. The elastic unit is made of rubber materials with specially designed composition. Therefore the stiffness changes with loading, and have the feature of “low stiffness under low loading, and high stiffness under high loading”. In the normal train operation conditions, slab mat track exhibits a linear deformation in order to maintain the smooth operation of the train and the vibration and noise reduction. In the situation of overloading such as an engineering train, nonlinear characteristics of the system affect hence to ensure the safety of running trains.

Rail receptances in both vertical and lateral directions at the middle span of the two fasteners and over them are shown in Figure 5 for the low rail and in Figure 6 for the high rail at Site XS. The similar trackform at Site TT was also tested for comparison as shown in Figure 7 and Figure 8. Both sites have a similar behavior.

For the lateral receptance, the first natural frequency is found at 117Hz which should be the unloaded rail resonance in the lateral direction which depends on the lateral stiffness of the rail fastener; and a rebound at around 570Hz should be the “pinned-pinned resonance” in the lateral direction.

For vertical receptance, the first natural frequency is found at 230Hz which should be the unloaded rail resonance in the vertical direction which depends on the vertical stiffness of the rail fastener; and a rebound at around 1100Hz should be the “pinned-pinned resonance” in the vertical direction.

![Figure 5](image3.png)

![Figure 6](image4.png)
3) The steel spring floating slab track

For steel spring floating slab track bed spiral spring supported floating slab track, its natural frequency is very low at 6Hz to 8Hz. The vibration isolation of this system should be better than the slab mat track. Rail receptances in both vertical and lateral directions at the middle span of the two fasteners and over them are shown in Figure 9 for the low rail and in Figure 10 for the high rail.

For the lateral receptance, the first natural frequency is found at 110Hz which should be the unloaded rail resonance in the lateral direction which depends on the lateral stiffness of the rail fastener; and a rebound at around 500Hz should be the “pinned-pinned resonance” in the lateral direction.

For vertical receptance, the first natural frequency is found at 190Hz which should be the unloaded rail resonance in the vertical direction which depends on the vertical stiffness of the rail fastener; and a rebound at around 1200Hz should be the “pinned-pinned resonance” in the vertical direction.

Comparing the rail receptance in both vertical and lateral directions with three trackforms, it can be found that: i) the rail “pinned-pinned resonance” frequencies are similar for three different trackforms with the same rail and fastener spacing; ii) the rail “pinned-pinned resonance” frequency in lateral direction is about 500~570Hz on unloaded track conditions with 60kg/m rail and sleeper spacing of 0.625m, which is much lower than that in the vertical direction (around 1100~1200Hz); iii) rail receptance at the “pinned-pinned resonance” frequency in the lateral direction is higher than that in the vertical direction. This may explain the main reasons of the rail corrugation often occurred on curvature track due to more lateral excitation under traffic. However, for the loaded
track under normal traffic, the effective mass of the vehicle-track system is higher than the unloaded track, and the loaded “pinned-pinned resonance” frequency is lower than that of the track measured with unloaded conditions.

![Figure 9](image-url) The steel spring floating slab track - Low rail receptance in vertical and lateral directions

![Figure 10](image-url) The steel spring floating slab track - High rail receptance in vertical and lateral directions

5. Rail corrugation control

Based on the experiment findings of different trackforms, several measures may be taken to slow down the progress of the rail corrugation growth.

(1) Reduce the “pinned-pinned resonance” vibration in the lateral direction using tuned rail damper [15].

(2) Minimize the difference of rail receptance at “pinned-pinned resonance” frequencies in way of the fasteners and the middle span of two fasteners using lower stiffness rail fastener [15].

(3) Reduce the track unevenness. It would be beneficial in delay the progress of corrugation by reduce the proportion of the stick-slip vibration and accumulation of rail head surface wear.

(4) Improve the elasticity and damping of the track system. To increase the elasticity of track can effectively reduce the proportion of wheel/track stick-slip vibration, and improve the track damping can significantly reduce the development rate of corrugation growth.

(5) Grind rail is one of the most effective measures to mitigate corrugation. Once corrugation appears, it will further increase the occurrence of the slip-stick vibration and to promote the further development of corrugation, therefore form a vicious circle. This circle is interrupted by grinding, so that slow down the development of rail corrugation.

(6) Improve the material strength and wear resistance of rail. Improve the wear resistance is also one of the most effective measures to control corrugation. The slip-stick vibrations can cause the rail corrugation, but improvement to the material strength and wear resistance will reduce delay the accumulation of surface wear and plastic deformation on rail head.

6. Conclusion

Through the experiment study of rail dynamic frequency response functions for the different trackforms, it was found that the rail “pinned-pinned resonance” frequency in lateral direction is much lower than that in the vertical direction; rail receptance at the “pinned-pinned resonance” frequency in the lateral direction is higher than that in the vertical direction. The loaded “pinned-pinned resonance” frequency is lower than the unloaded track measured. This may explain the main reason of the rail corrugation often occurred on curvature track. Some measures are suggested to slow down the corrugation growth.
REFERENCES