

# Assessment of rail long-pitch corrugation

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**Abstract.** The paper focuses on defects of the running surface of the rail, namely the rail corrugation defect and specifically long-pitch corrugation in curves of small radii. These defects cause a shorter life of the rails, greater maintenance costs and increase the noise and vibration pollution. Therefore, it is very important to understand the formation and development of the imperfection of the rails. In the paper, various sections of railway tracks in the Czech Republic are listed, each of them completed with comparison of defect development, the particular track superstructure, rolling stock, axle load, traffic load etc. Based on performed measurements, defect development has been proved as different on sections with similar (or even same) parameters. The paper assumes that a train velocity is the significant circumstance for defect development rates. Assessment of track section with under sleeper pads, which are expected to be the one of the possible ways to suppress the corrugation defect development, is included in evaluation.

## 1. Introduction

The interaction between wheelset and track in railway applications is a complex issue. Due to the operation on railway infrastructure rail, defects occur. One of those defects is the defect of the running surface of the rail – such as corrugation. All those defects shorten the life length of the rails and increase the maintenance costs and also vibration and noise pollution.

This paper focuses on formation theory of long-pitch corrugation, performed measurements and its evaluation. Long-pitch corrugation occurs mostly in curves of small radii; therefore, such track sections were selected and monitored for over a year in order to be able to understand more thoroughly the long-pitch corrugation development. Then, the aim is to determine the crucial factor, which contributes to the corrugation development.

## 2. Long-pitch corrugation

The determination of the rail corrugation types is rather complicated. Nevertheless, for the purposes of the research is essential to classify this defect, since there are some similar factors affecting the formation and development of the corrugation. Unfortunately, there is no full agreement in this matter; the view of some infrastructure managers is different from others. As an example, the view of Infrastructure manager of the Czech Republic (SZDC) and International Union of Railways were picked. SZDC issued the standard "SZDC S 67 Vady a lomy kolejnic" (Rail Defects and Rail Breaks), in which the long-pitch corrugation is marked with the code 2201 D [8], whereas the International Union of Railways marks the long-pitch corrugation with code 2202 [6]. The reason for inconsistency is the differing opinion on the relations and connections between the formation and occurrence of the



defects. For the purposes of this text, the view of SZDC is adopted, since the author's belief complies more with this approach.

The long-pitch corrugation, sometimes called also as "short waves", is sinuous craggedness of the running surface of the rail. Peak distance of the waves is usually between 8 and 30 cm and the depth of the waves is between 0.1 and 1.2 mm. Typical location, where the long-pitch corrugation could be found, is the lower rail in curves with radii less than 600, sometimes even 700 m [4,5].

Wheel, passing along the rail with corrugations (short-pitch corrugation) or with short wavelets (long-pitch corrugation) gains certain amount of the vertical acceleration. Induced accelerations cause, in contribution with the unsprung mass of the wheelset, additional dynamic forces, which cause vibrations of the track and the vehicle in dependence on periodical changes in acceleration [5].

Negative externalities [5] can be divided into three main categories:

- noise pollution,
- vibration dispersion,
- negative effect on infrastructure.

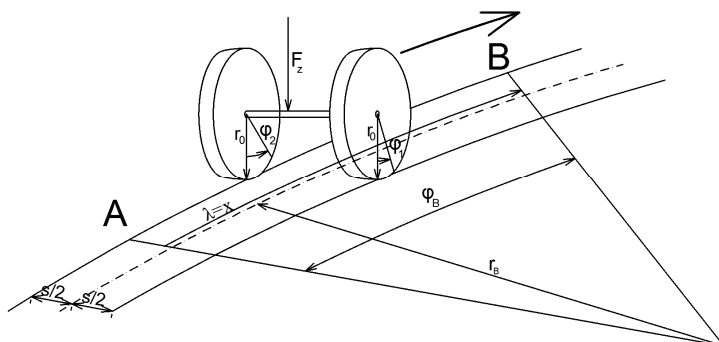
The influence on the track infrastructure is characterized by the defects such as damaged rail pads, broken concrete sleepers, coach screw snap off, abraded aggregate behind the heads of the sleepers and others.



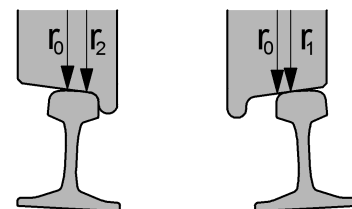
**Figure 1.** Long-pitch corrugation defect.

### 2.1. Corrugation formation theory

The basic principle of movement of wheelset along the curve is shown in Figure 2. In curve with radius  $r_B$ , each of the wheels (with wheel radii  $r_0$ ) travels different length because of the same angular velocity of both wheels.



**Figure 2.** The geometry and forces acting on wheelset altered the basis in [1].



**Figure 3.** Wheelset position in right-hand curves.

This difference in distances  $\Delta\varphi$  corresponds with rotation angles  $\varphi_1$  and  $\varphi_2$ . Distances reached by each wheel ( $x_1$  for inner wheel and  $x_2$  for outer wheel) can be obtained from arc angle  $\varphi_B$ , radius of the curve  $r_B$  and  $s$  is distance of rolling circles 1500 mm.

$$x_1 = \left(r_B - \frac{s}{2}\right)\varphi_B \quad x_2 = \left(r_B + \frac{s}{2}\right)\varphi_B \quad (1) \quad (2)$$

$$x = r_B \varphi_B = \lambda \quad (3)$$

$$\varphi_B = \frac{r_0}{s} \Delta\varphi \quad (4)$$

As both wheels are connected with rigid axle, not allowing one to rotate against the other, the whole wheelset rotates with just one angular velocity. In small radii curves, this forces the inner wheel to slip, since the inner wheel does not have the possibility to dissociate the movement momentum into the actual rotation. The extent of the slip is most likely derived from variables such as rail/wheel friction force depending on relative wheel slip and wheelset attack angle, axel stiffness and others. The length of resulting long-pitch corrugation wave, with vehicle parameters taken into account, can be determined as follows [1]

$$\lambda = \left( \frac{r_0^2 \mu F_Z}{G I_p} \right) r_B \quad (5)$$

where  $\mu$  is friction coefficient,  $F_Z$  is nominal wheel load,  $G$  is shear modulus and  $I_p$  is moment of inertia.

The vehicle influence describes the part of the formula in parentheses, on the other hand the infrastructure influence is represented by curve radius  $r_B$ . Therefore, using this simplified view, from the perspective of infrastructure we could develop a basic idea that a length of the wave  $\lambda$  depends on curve radius.

$$\lambda = f(r_B) \quad (6)$$

The simplified view does not reflect the position of wheelset in curve. To add more complexity to the problem, we need to consider it. Figure 2 explains the implementation of the wheelset lateral position.

The larger the difference between the sizes of the contact circles ( $r_1$  and  $r_2$ ), the smaller the radius, which the wheelset can pass without the relative in-between spin motion and consequent longitudinal slip of the inner wheel [9].

### 3. Monitored locations

In cooperation with SZDC (rail infrastructure manager in the Czech Republic), locations suitable for monitoring of the long-pitch corrugation were chosen, preferably with significant occurrence of this defect. In some of the locations, various precautions with various results were applied before in order to slow down the development of the corrugation. The most accentuated precaution was the asymmetric rail grinding [14], the others were the usage of rail fastening with reduced vertical stiffness and with clamps with enhanced fatigue limit, installation of under sleeper pads or the usage of rail lubricators.

Our chosen locations are in most cases double track and thus allow us to compare both tracks in-between each other. The comparison is not always possible, even in two beside laid tracks some parameters differ. The most often limiting parameter is different composition of trains, and the influence of the slope gradient (for one direction uphill, for other direction downhill; both resulting in the different rate of acceleration or deceleration). Furthermore, it would be optimal to monitor the curves as a whole, yet unfortunately, the curves still will not be the same.

For above-mentioned reasons, just a short track sections not exceeding 50 metres are monitored in every location and with only few exceptions more than one measuring places are observed. This approach allows us to compare also the measuring sections within one track and so the heterogeneity of the train composition is ruled out. Particular measuring sections are chosen based on assumption of influence on long-pitch corrugation formation and development. Together with the track alignment, also substructure and superstructure composition is taken into account. The substructure influences track stiffness (with changes along bridges or bedrock), and so does the superstructure (with changes originating in usage of rail fastenings with high elasticity, special elastic rail fastening, clamps with enhanced fatigue limit or under sleeper pads [11]).

Based on the criteria mentioned in previous text, the searches in the infrastructure manager databases were conducted. The research then follows two main aims:

- monitoring of the development rate of long-pitch corrugation,
- definition of the factors influencing the development of long-pitch corrugation.

### 3.1. Methods of monitoring and evaluating

Corrugation is measured using device “Salamander” (allowing continuous laser scanning of rail running surface). The device evaluates the measured data according to the standard EN 13231-1 [3,9] in these wavelengths ranges:

- 10 ÷ 30 mm: surface defects of rail head, rail joints,
- 30 ÷ 100 mm: surface defects of rail head, rail joints, rail wear caused by braking,
- 100 ÷ 300 mm: long-pitch corrugation (inner rail in curves),
- 300 ÷ 1000 mm: rail defects persisting from the production of rails.

The evaluation is performed using RMS value (RMS stands for Root Mean Square) [9], which is the basic microgeometry quantity reflecting the long-pitch corrugation. It could be described as moving average of effective values. When assessing,  $n$  equidistant samples  $y_i$  of calculated sector with defined length  $L$  for the point on rail with position  $x$  could be obtained from formula

$$RMS(x, L) = \sqrt{\sum_{i=1}^n \frac{y_i^2}{n-1}} \quad (7)$$

The set of RMS values for four wavelength ranges, or wavebands, is computed using this formula. The first and last wavebands are for the purposes of this research expendable, since these wavebands do not reflect the long-pitch corrugation, but other imperfections of the rail. For this reason and on the basis of the chapter 2.1., the only monitored wavebands are 30 ÷ 100 mm and 100 ÷ 300 mm [5,11,13]. The percentage of the samples, which exceed below mentioned limits, can be considered as one of the rail quality indicators.

**Table 1.** RMS limits.

Waveband [mm]	10 ÷ 30	30 ÷ 100	100 ÷ 300	300 ÷ 1000
Limit [ $\mu$ m]	4	4	12	40

Together with microgeometry of the rails, other supportive quantities are measured, such as track geometry parameters and velocity of the passing vehicles. Track geometry parameters are measured using the device “Krab”, which is able to measure a number of track parameters. For the purposes of the research, just cant and track gauge are considered as relevant in this stage.

The velocity of the passing vehicles is measured with the speed radar, to determine the type of rolling stock and its exact speed on measured section, optical recording device is used. The velocity of

the vehicles influences the position of wheelset in curve and it is also strongly believed to be the contributing factor in the corrugation development. In order to describe the expected positions of the wheelsets in curves, the cant excess and the cant deficiency are computed based on the measured speeds, since these quantities allow us to compare the train passages between each other [1]. For this purpose, a weighted average of all speed measurements in a set section was calculated, where the mass of each train was taken into consideration [13].

#### 4. Development rate of long-pitch corrugation

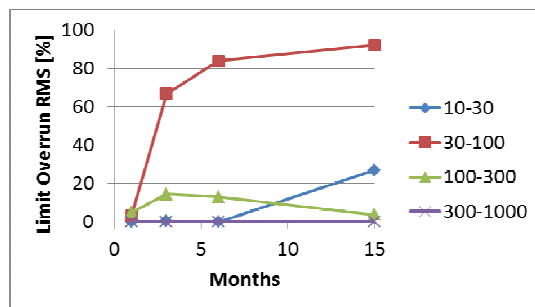
##### 4.1. Initial phase of development

In order to monitor the development rate (formation and development speed) of long-pitch corrugation, it is necessary to start the observation optimally immediately after the renewal of the rails and preventive grinding, or in case of reparative grinding immediately after such grinding. Then it is possible to record the progression from initial condition (e.g. the “flawless” surface of the rails or within maintenance acceptance criteria).

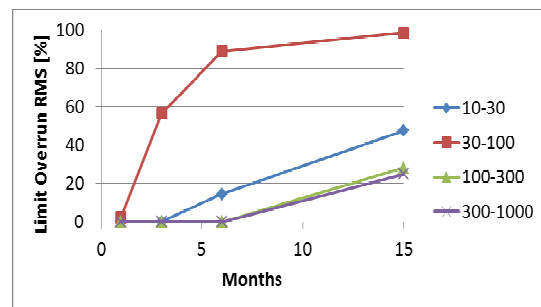
Such measurements were conducted in location Hady, located on the line Brno - Ceska Trebova, between km 161.685 and km 164.485. The first measurement was done before the rails renewal; the second one was performed immediately after the renewal (in order to record the “flawless” state of the rails. Consequently, further measurements were performed with a few months’ headways.

The measuring location consists of two sections containing three measuring places, first measuring place is located in front of the tunnel 1 (curve A), the second one is located in front of the tunnel B (curve B) and the third one is located in tunnel B. For the whole measuring location, only the track No. 1 is monitored. Considering the common structure and geometrical parameters of the track (curve radii 283 m and 261 m, cant 123 mm in both curves, fastening W14, concrete sleepers B 91S etc.) and the railway superstructure, all three measuring places do not exhibit significant differences.

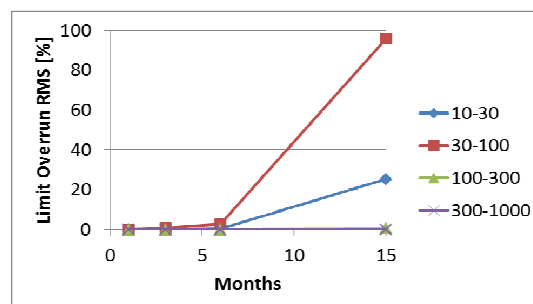
Corrugation development in all wavebands is shown in the Figure 4, Figure 5 and Figure 6.



**Figure 4.** RMS values for measuring point in the tunnel 2.



**Figure 5.** RMS values for measuring point in front of the tunnel 2.



**Figure 6.** RMS values for measuring point in front of the tunnel 1.

As it could be seen in all the Figures, after 15 months the RMS values in waveband  $30 \div 100$  mm are reaching 100%. In case of the curve B (Figures 4 and 5), the progression in this waveband is for both measuring places alike. On the other hand, there is significant rise in RMS values between sixth and fifteenth month after the rail renewal in curve A. This sudden change in development of the defect is not yet satisfactory explained, in the present time we believe the change of previous sleepers B 91S to B 91T could be the factor. Or, to be more precise – not the change of the sleepers type, but the changing process itself (the interference into the superstructure).

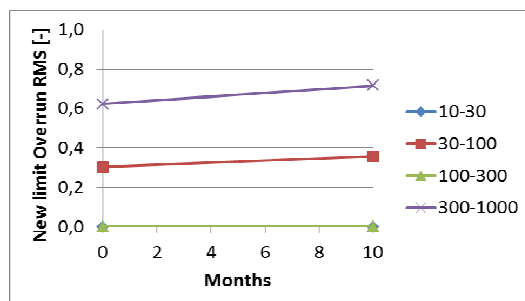
When evaluating only the first six months, the curve B (in front of the tunnel 2) embodies the weighted cant deficiency  $I = 87$  mm. The curve A (in front of the tunnel 1) shows the weighted cant deficiency  $I = 57$  mm.

#### 4.2. Developed defect phase

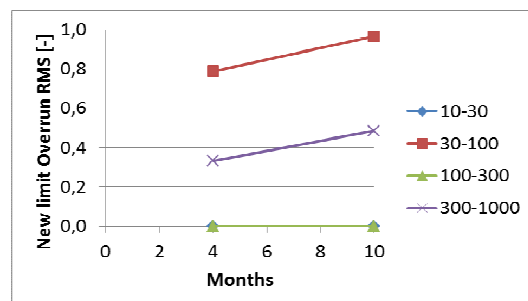
For development rate monitoring in areas, where more developed defect takes place, the location Havlickuv Brod was chosen. Four curves (two in each of the tracks) are monitored in the line No. 324 Havlickuv Brod – Kutna Hora between the km 224.394 and km 225.150 in an approach to the station Havlickuv Brod from the direction Kutna Hora. The location consists of a double track (numbers 1 and 2) with consecutive reverse compound curves (marked A and B). Since all of the curves are in some regards different, it is possible to compare them between each other. For instance, in curve A the cant differs in tracks No. 1 a No. 2, in curve B one of the tracks is equipped with under sleeper pads and the other one is not, also in some curves the trains are passing with the constant speed, and in others the trains are decelerating.

The railway superstructure in the location Havlickuv Brod consists of the rails 49 E1, fastenings E14 with clamps Skl40 and W14 with clamps Skl14, the sleepers B 91S/1 are on both tracks. The difference between used fastening systems could not be considered as a cause of the change in the defects, since the replacement of the fastening system was the result of the development of the defects and should have been the resolution of the problem [13].

Based on conducted measurements, the RMS values ordinarily exceed 100%. For this reason, it is not possible to monitor the development of the defect in time under the terms of above mentioned RMS value calculation. Thus, in following figures the vertical axis does not stand for RMS values in percent, it is transferred to the scale from zero to one in order to be able to compare values magnitudes. Slight alteration was performed to reach this possibility – the limits from table 1 had to be changed, which will allow us to monitor the development furthermore. The downside of this modification is the need for careful examination of the values, otherwise the results could be misrepresented (some of the RMS values could be neglected unintentionally). In addition, the impossibility to compare the results from this location to others could be considered as a disadvantage.

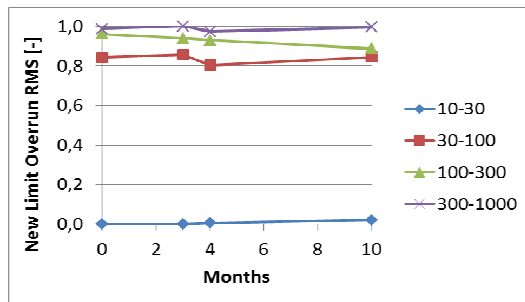


**Figure 7.** RMS values for measuring point in track No.1 in curve A ( $E = 2$  mm).

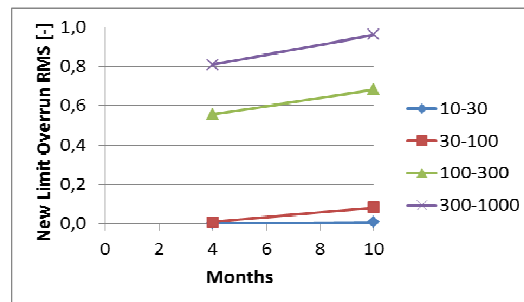


**Figure 8.** RMS values for measuring point in track No.1 in curve B ( $E = 72$  mm).





**Figure 9.** RMS values for measuring point in track No.2 in curve A ( $E = 27$  mm).



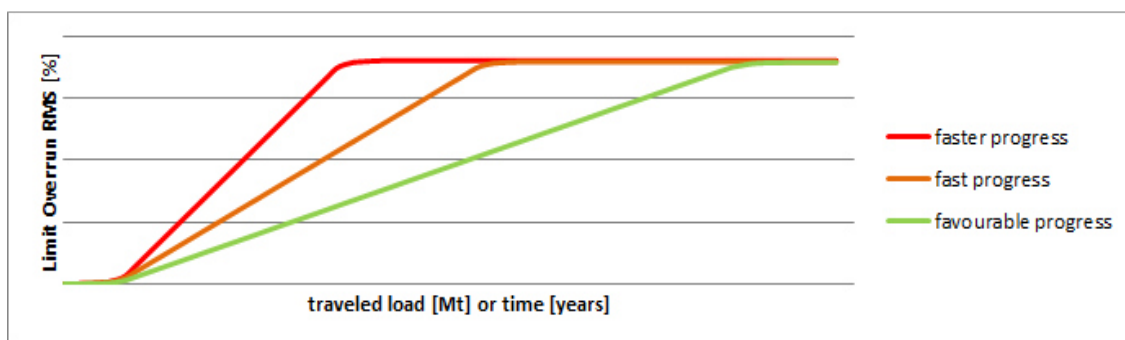
**Figure 10.** RMS values for measuring point in track No.2 in curve B ( $E = 57$  mm).

When evaluating only the wavebands representing the long-pitch corrugation on Figures 7 and 8, then both curves in track No. 1 show significantly lower RMS values than in track No. 2. Higher values in waveband  $30 \div 100$  mm in curve B of a track No. 1 could be the result of the braking effect, which is usually present in this waveband [5]. In comparison of both wavebands in all four curves with cant excess values (specified in figure titles), we could presume that in curve A of the track No. 1 the lower RMS values are the consequence of a cant excess  $E = 2$  mm. In case of the curve B of the same track, where the highest cant excess values ( $E = 72$  mm) were found, the most probable factor is believed to be the influence of the under sleeper pads. According to [7], under sleeper pads reduce the generation of vibrations and noise emissions in these frequencies.

The figure 9 shows, that after the certain state the decrease in development rate is present for some of the wavebands. The reason of this phenomenon has not been explained yet and it is a subject of further investigation.

#### 4.3. Presumed superposition

In order to understand the development process of long-pitch corrugation as a phenomenon, the authors believe, that it is possible to superpose the initial and developed phases of the defect progress. Such combination of the phases will show the whole life cycle of the defect and what is more important – it is able to mirror *the changes* in the development. The author's idea of presumed theoretical development of long-pitch corrugation is shown in Figure 11. Every curve displays different rate of development. The steeper the curve, the more raging the progress is and the less favourable the state of the track is.



**Figure 11.** Presumed theoretical development rate of long-pitch corrugation.

## 5. Conclusion

Longitudinal and lateral motion of the wheelset in curve is a complex issue. Many variables have to be taken into account, and in some cases, negative effects can come up. In curves of small radii, it is

especially corrugation defect on inner rail running surface. This defect is easily recognisable due to increased noise and vibration levels.

The paper aims on the assessment of long-pitch corrugation in curves of small radii. Several locations were determined as suitable track sections for the long-pitch corrugation defect measuring.

The measurements results indicate that cant excess and cant deficiency can be one of the most significant factors supporting the development of long-pitch corrugation. In addition, it is showing that the development rate of the corrugation might be, under right circumstances using preventive measures, decelerated and thus it is possible to extend the life cycle of the rails.

The research will be furthermore focused on investigations and should imply more than development progress of the corrugation. A detailed investigation of the factors and their influence should take place. When done, it would be possible to predict future development of the defect, plan the maintenance works and result in improving the quality of the railway transport.

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