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Interrelation between Wavelengths of Track Geometry Irregularities and Rail Vehicle Dynamic Properties

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Abstract

The paper deals with the problem of railway track irregularities appearance in form of so-called short waves (3-25m). These geometrical irregularities were found in measurements, which were carried out on different railway tracks of Polish Railway Lines. Those tracks can be classified as tracks with good state of maintenance. The article describes the results of the analysis of geometrical irregularities of these railway tracks in frequency domain and demonstrates their statistical characteristics. The studies, in contrast to usually used approach to the analysis of the geometry of the track, are focused on the left and right rail alignment and their longitudinal level. Based on studies of different mathematical models of railway vehicles it was found the relationship between their eigenvalues and wavelengths of track geometrical irregularities. Analysis of the measurements results of car-body acceleration and bogie frame acceleration confirms the thesis that the deterioration of railway track is dependent on the dynamic influences of vehicles on the tracks.

Keywords: short wave irregularities, railway track deterioration, measurements

1. Introduction

The importance of track geometry for studies of railway vehicles dynamic behaviour is undisputable. Geometric irregularities of a track, such as alignment, cant or gauge, generate excitations in the system and are a source of vibrations responsible for dynamic behaviour of the vehicle that moves at high speed on a plain track or an arc of medium or great value of curve radius. For this reason, modern railway tracks designed for high-speed traffic should meet a number of requirements regarding travel comfort and safety.

Requirements relating to classification of railway track from the point of view of geometric irregularities have been the subject of normative acts and a number of scientific

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publications (e.g. [4]). They analyzed methods of defining and describing irregularities for simulation studies and field tests on the real object. We can mention, among others, European Standard series EN 13848 “Railway applications – Track – Track geometry quality” [3], and UIC leaflet 518 [6], [5] or UIC leaflet 714 [7]. They can be treated as basic normative acts.

The series EN 13848 consists of six parts. It covers the wide-ranging problems of classifications irregularities, their recording, measurements and used measuring devices.

Part 1 entitled “Characterisation of track geometry” specifies characteristics of track geometry such as e.g. track gauge, longitudinal level, alignment, cross level and twist.

Parts 2 – 4 entitled “Measuring systems – Track recording vehicles”, “Measuring systems – Track construction and maintenance machines” and “Measuring systems – Manual and lightweight devices” give hints concerning track recording vehicles, track maintenance machines and manual devices.

Part 5 entitled “Geometric quality levels” defines the quality levels of the track geometry. They are called: Alert Limit (AL), Intervention Limit (IL) and Immediate Action Limit (IAL).

UIC standard 518 sets also three quality levels with similar meaning of AL, IL and IAL but with different names: QN1, QN2 and QN3 respectively.

QN1 quality level (AL – Alert Limit), which refers to the value which necessitates monitoring or taking maintenance actions as part of regularly-planned maintenance operations;

QN2 quality level (IL – Intervention Limit), which refers to the value that requires short term maintenance action;

QN3 quality level (IAL – Immediate Action Limit), which refers to the value above which is no longer desirable to maintain the scheduled traffic speed.

These quality levels boundaries base on thresholds connected to standard deviation of longitudinal level defects.

A set of new track quality indices has been developed in USA [2]. In this work and [9], authors sum up characteristics of track irregularities into a track quality index, which is function of the standard deviations of irregularity, and train allowable speed. The considerations shown in that work can be treated as the complement of the tracks classification based on the Federal Track Safety Standards [8]. According to them, there are distinguished nine classes of tracks. For each class is defined the maximum allowable speed for freight and passenger trains. Classification takes into account deviation of track dimension from nominal values and shape of rails rolling surfaces.

It is also worth to notice that there are normative acts, which define the shape and dimension of railway track geometric irregularity, which should be applied in simulation studies [1].

The so-called short wavelength (3 m – 25 m) [3] longitudinal levelling defects are still the crucial parameters for the railway track maintenance and it is pointed in the above-mentioned references. As it is shown in this paper, the problem of such irregularities also exists in the Polish railway infrastructure. There were done several measurements in different sections of railways lines of Polish Railways Lines. These measurements covered the track distance of a length of 500 m each. Basing on them, there were reached the conclusions, which are associated with dominant wavelengths of geometrical irregularities of the track. It was shown that the wavelengths of these irregularities correspond to the allowable velocity of trains in those track sections and they correspond to eigenvalues of wagons, which operate on those lines also. Analysis of the results of acceleration measurements of a carbody and a bogie frame also confirms the thesis that the deterioration of railway track is related to the influences of vehicles on the track within a specific frequency range and therefore the constructional characteristics of the vehicles, which have been operated on the track.

2. Measurement Methods of Railway Track Geometric Irregularities

Analyzed in this paper irregularities were measured with the track geometry measuring trolley and the measuring vehicle.

Track geometry-recording car EM-120 allows to record such track geometric irregularities as longitudinal level and alignment on both sides of the track, twist, gauge and cant. These parameters are registered at 0.25 m.

The track geometry measuring trolley is a portable device designed for collecting and recording information on railway track geometric features in form of a set of readings recorded in digital form.

In both cases the input data are recorded automatically during the passage of the device along the track.

In our case, all measurements are sampled at constant distance based intervals equal to 0.5 m and resolution of measurement is 0.1 m. Measuring range of track gauge is from 1420 up 1485 mm with resolution equal to 0.1 mm. The same resolution is assumed for cant, level and alignment. The range of measurement is equal ± 50 mm. The range of measured irregularity wavelength, i.e. 5 to 25 m (in case of measurements done with measuring trolley), may be approximately estimated as the range of short railway track irregularity (class D1 [3]).

3. Irregularities Statistical Analysis

Track irregularities, which are discussed in detail in this paper, were recorded in sections of line between Warsaw and Poznan (called here measurement 1, measurement 2, measurement 3), in a section of Warsaw-Cracow line (called measurement 4) and in a section of the line between Warsaw and Gdansk (measurement 5). Measurement 1 and measurement 2 were made on the same track in a time interval of around four months.

The first step of the adopted preprocessing was an elimination of abnormal data and then there was done the normalization of recorded data relative to the average, so it is equal to zero.

According to [3] there were done calculations of nominal track gauge peak to peak value, mean to peak value of longitudinal level and alignment, standard deviation of longitudinal level and alignment of measured tracks. We can say, basing on those calculations, although they are not complete, that investigated tracks have more or less track quality AL or QN1 for train speed less than 200 km/h and wavelengths class D1.

Studies on irregularities presented in this paper are focused on left and right rail alignment and their longitudinal level.

The processing of the transformed measurement results concentrated on calculation of the range of the variation of vertical and lateral irregularities of rails, their standard deviations and power spectral densities expressed as functions of irregularity wavelength.

In tables 1 and 2 are presented basic statistical parameters of rails irregularities.

Table 1

Standard deviations of left and right rails in measured track sections

Irregularities Standard Deviations [m]				
Measurement no	Vertical Irregularity		Lateral Irregularity	
	left rail	right rail	left rail	right rail
1	0.00113	0.00120	0.00137	0.00127
2	0.00135	0.00137	0.00199	0.00153
3	0.00109	0.00101	0.00135	0.00153
4	0.00115	0.00120	0.00103	0.00108
5	0.00155	0.00132	0.00168	0.00167

Table 2

Irregularities variation range of left and right rails in measured track sections

Irregularities Range [m]				
Measurement no	Vertical Irregularity		Lateral Irregularity	
	left rail	right rail	left rail	right rail
1	0.0108	0.0111	0.0091	0.0077
2	0.0134	0.0127	0.0123	0.0089
3	0.0089	0.0089	0.0091	0.0112
4	0.0073	0.0073	0.0055	0.0056
5	0.0108	0.0099	0.0113	0.0091

The worst statistical values were obtained for measurement 5, although they are also moderate.

Now we will show examples of results for the power spectral density of irregularities on the tested tracks sections. Examples present results obtained for three different lines. In figures 1 – 3 are presented PSD results for vertical irregularities of rails.

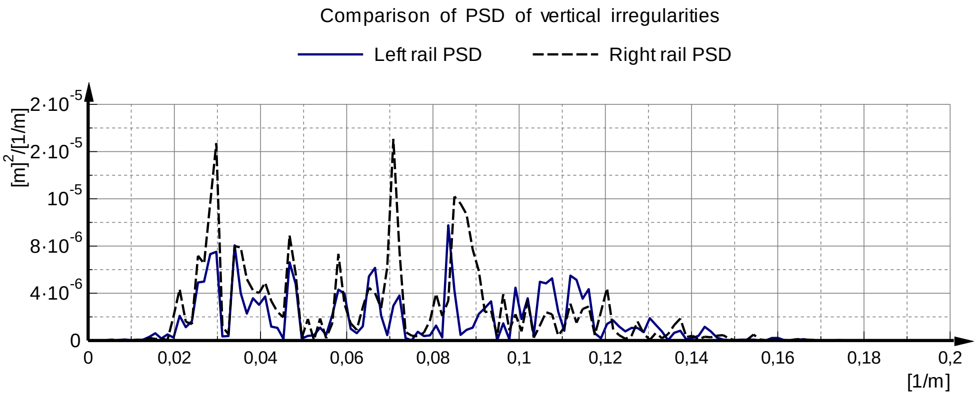

Fig. 1. Power spectral density of vertical irregularities for measurement 1

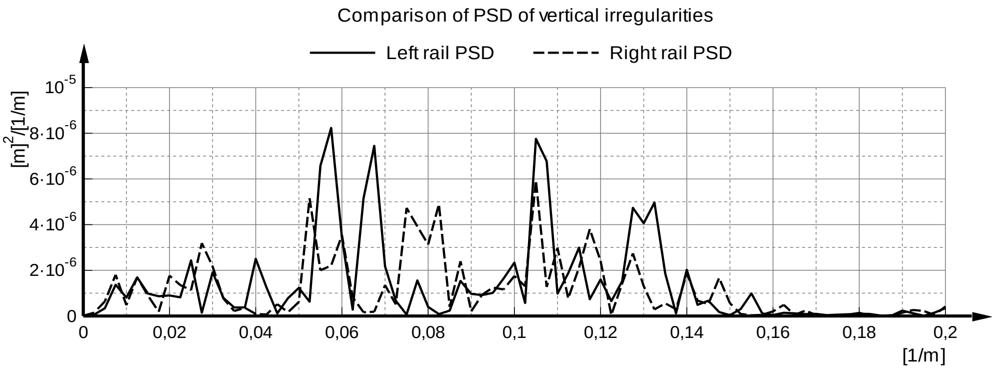

Fig. 2. Power spectral density of vertical irregularities for measurement 4

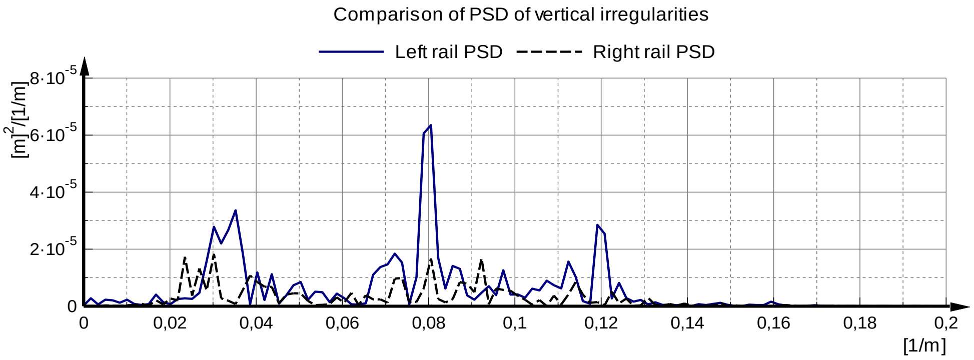

Fig. 3. Power spectral density of vertical irregularities for measurement 5

The analysis of obtained results we will begin with vertical irregularities.

Recorded results for measurement 1 (fig. 1) show that wavelengths of irregularities are included in the range between ~8 and ~50 m. Irregularities for left and right rail are comparable with the high correlation coefficient. Peaks of PSD are located in almost the same position for left and right rail, although they are clearly marked for right rail. Dominant wavelengths are equal to ~33, ~14 and ~12 m.

Wavelengths of irregularities for measurement 2 are analogous, however the third peak splits into three peaks situated closely to each other.

For measurement 3, the irregularities wavelengths are included between ~7 and ~50 m. Peaks are not so clearly marked as in previous case, but we can also select dominant wavelengths approximately equal to 30, 16.5 and 14.5 m for both rails.

The level of PSD for measurement 4 (fig. 2) is smaller than in previously considered examples. Considering this fact, we can say that wavelengths irregularities are included in the range between ~7 and ~25 m. In PSD diagram we can distinguish wavelengths equal to 18, 16 and 9.5 m. Some peaks of PSD for left and right rail have different locations.

In the last measurement (fig. 3), the distinct peak is situated for wavelengths approximately equal to 12.5 m. There are also easy to detect peaks for 25 and 8 m.

In figures 4 – 6 are presented some results for lateral irregularities of rails.

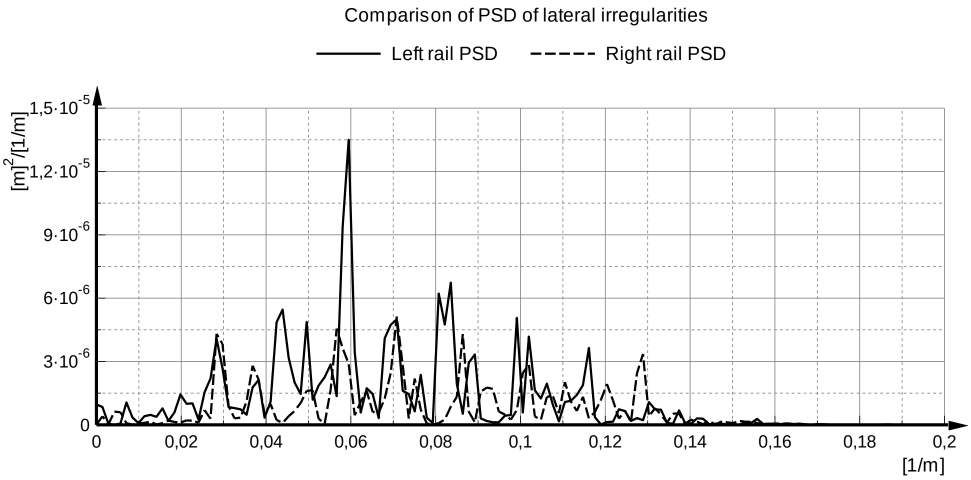

Fig. 4 Power spectral density of lateral irregularities for measurement 1

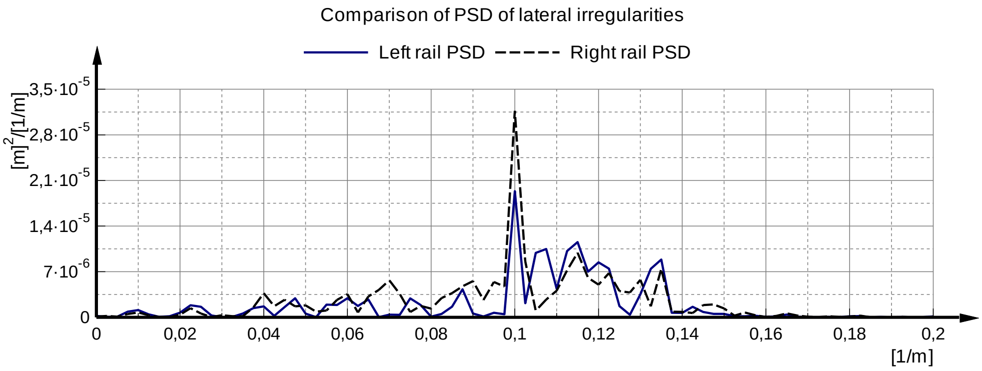

Fig. 5. Power spectral density of lateral irregularities for measurement 4

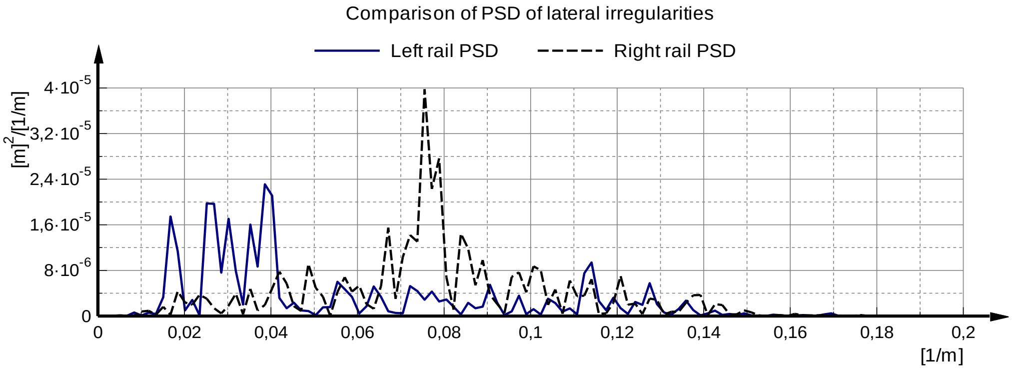

Fig. 6. Power spectral density of lateral irregularities for measurement 5

Having analyzed results presented above (examples on figures 4 – 6) we can conclude that they are easier for the interpretation.

Dominant wave of measurement 1 is ~17 m long (fig.4) and for measurement 2 is 32 m.

Waves, with a length of ~11 and ~18 m, dominate in the third measurement. Single, very well distinguished wave of length equal to ~10 m dominate in the fourth measurement (fig. 5.). We can conclude that the PSD’s of the right and left rails are characterized by a high degree of similarity in the measurement. Such fact is not observed for results found for the fifth measurement. The dominant waves for left rail have lengths in the range from ~25 m to ~55 m. Dominant wave for right rail is ~13 m long.

The range of irregularities wavelengths covers the interval ~7,5 m to ~50 m in all studied cases.

We will deal with the waves with length, which does not exceed 30 m, because of the adopted measurement method.

The fundamental problem in irregularities study is to answer the question if such irregularities can cause derailment of the car or decrease the ride comfort.

Both facts are related to the frequency of excitation. Alignment wavelength, which causes vibrations close to the resonance of lateral motion of a bogie frame or carbody, may be the derailment reason and specific wavelength of the longitudinal level may decrease the ride comfort.

Therefore, the fundamental problem is to determine whether the measured irregularities cause excitations in the railway vehicle – track system that are close to the resonant states of cars.

Passenger trains operate with velocity from 140 km/h to 160 km/h on studied railway lines and freight trains with velocity from 60 km/h to 80 km/h.

These speeds result in excitation frequencies range from ~ 1.3 to 6.4 Hz.

Finally, it is necessary to mention about results, that were obtained for measurements made over the same track section. They show the growth of statistical parameters, very similar power spectral density function and moreover very high Pearson coefficient (equal to 0.94).

4. Description of Rolling Stock Characteristics

In this paragraph are described typical models of wagons, which operate on the Polish railways. There was done analysis of these models eigenvalues. In addition, the frequency analysis of recorded vertical and lateral acceleration of the carbody and the bogie frame was performed.

As mentioned above, passenger and freight wagons operate on measured routes. It is not possible to build their mathematical models because of the diversity of their construction. Therefore, there were used their abstractions which were built for a passenger car, a freight car and a locomotive.

Abstractions of vehicles have been modelled using Virail package.

General assumptions for modelling were that suspension characteristics are linear and the contact between wheel and rail is linear. It is based on equivalent geometric parameters of rail (UIC60) and wheel (S1002) such as wheel equivalent conicity and gravitational stiffness.

Passenger car model is composed of rigid bodies such as car body, two bogie frames and four wheelsets. Elements of primary and secondary suspensions are assumed massless.

Model parameters (geometry, inertia, stiffness and damping) are similar to those used in typical models of passenger railcars of European carriers.

Parameters of locomotive model respond to EP-09 locomotive. It is a discrete model consists of 15 rigid bodies: the body, two bogie frames, four wheelsets and eight axle-boxes. Rigid solids are connected with massless elastic–damping suspensions. The exceptions are connections of wheelsets with axle-boxes. Those elements allow only for the rotations of the wheelsets.

The parameters and the structure of the freight car model have been adopted on the basis of technical data four-axle type Eanos wagon. Bogie parameters specification is based on freight bogie 6RS/N parameters.

Interaction between railway car and track irregularities depends mainly from eigenvalues of the vehicle and the frequencies of excitations i.e. train operation speed and wavelengths of irregularities.

Eigenfrequencies of models are presented in table 3.

Table 3

Eigenfrequencies of railway vehicles mathematical models connected with their carbodies and bogies

Vehicle element	Motion	Passenger car	Locomotive	Loaded freight car
		f [Hz]	*f* [Hz]	*f* [Hz]
carbody	lateral displacement	0.50	0.43	0.44
	bounce	1.09	1.05	0.84
	roll	1.37	1.56	1.26
	pitch	1.44	0.97	0.92
	yaw	0.70	0.66	0.77
bogie	lateral displacement	4.88	6.61	4.63
	bounce	5.25	4.13	4.81
	roll	5.23	4.83	5.11
	pitch	6.48	5.23	5.45
	yaw	7.52	6.25	7.47

The eigenfrequencies of the horizontal movements of the vehicle on the track are in the range from ~0.43 Hz to 0.77 Hz for the carbodies and from ~4.63 to 7.52 Hz for the bogies. The eigenfrequencies of the vertical movements of the vehicle on the track are in the range from ~0.84 Hz to ~1.56 Hz for the carbodies and from ~4.13 to 6.48 Hz for the bogies.

Now we will present the results of measurements of the passenger car equipped with MD bogie type. Measurements were performed with the vehicle velocity equal to 160 km/h on well-maintained track. Results obtained for vertical motions are shown in figures 7 and 8 and for lateral motions in figures 9 and 10.

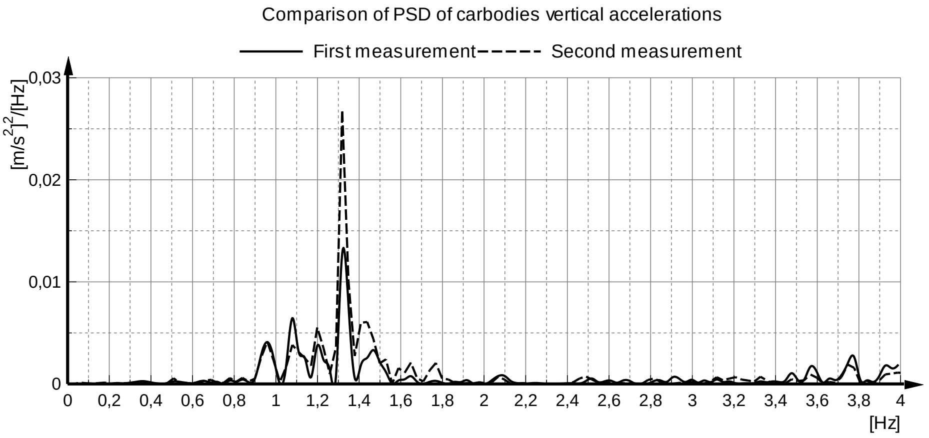

Fig. 7. Power spectral density of vertical carbody acceleration

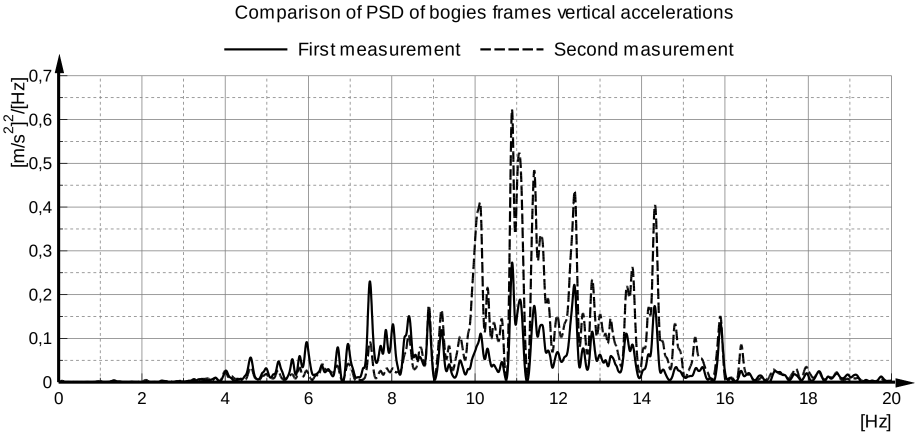

Fig. 8. Power spectral density of vertical bogie frame acceleration

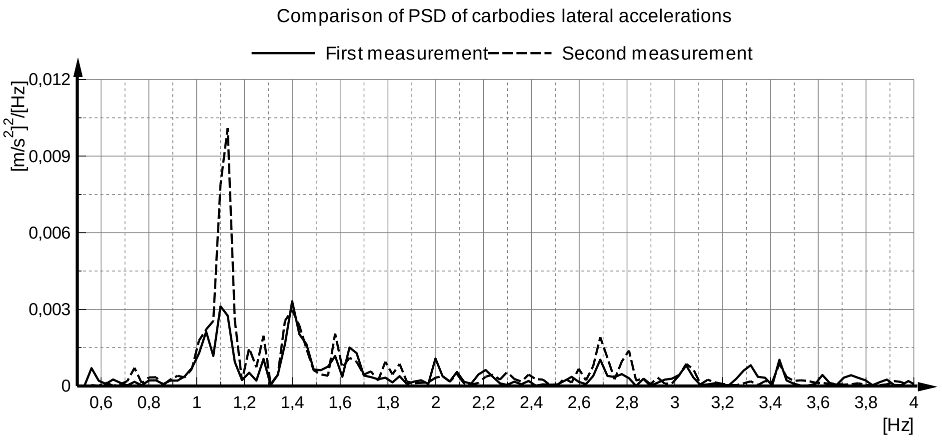

Fig. 9. Power spectral density of lateral carbody acceleration

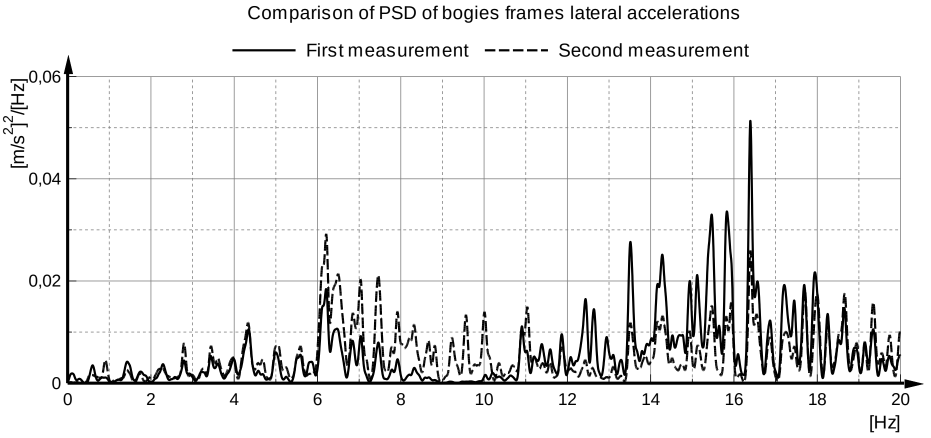

Fig. 10. Power spectral density of lateral bogie frame acceleration

Results obtained from experiments show that maximal vertical carbody accelerations are situated between ~0.9 – 1.7 Hz. It responds, if vehicle speed equals to 160 km/h, the wavelength range from ~27 to 50 m. Frequencies of maximal bogie frame vertical acceleration are included in the interval ~5 – 16 Hz i.e. ~3 – 11 m of wavelength.

These ranges for the lateral vibrations are respectively ~18 – 50 m and ~8 – 15 m.

5. Conclusions

Explanation of appearance of a railway track geometric irregularities and their increase decisively influence the track maintenance optimisation.

The newly built or just after the renovation railway line is theoretically an ideal geometrical straight line or a curve. In practice, track geometry is always imprecise. Every rails joint introduces disturbances of shock type in vehicle vibrations and besides those; there are special track sections like crossings or turnouts where track geometry causes transient vehicle vibration. Resulting forces, acting on the track, vary with the frequencies corresponding to the vehicle eigenfrequencies and affect the different level of track degradation. Finally, the track geometry damages progressively. The appearing irregularities are thus characterized by a short wavelength (class D1 [3]) i.e. between 3 and 25 m whereas the geometry of new tracks is characterized by long wavelengths (class D3 [3]).

This range of irregularities wavelengths depend mainly on the dynamical action of a bogie on the track and speed of vehicles exploited on the railway.

The appearing irregularities may be different for different railway lines depending on the rolling stock being in operation on them. However, it appears that the track irregularities wavelengths depend on the rolling stock initially operated on a railway line. Measurements made on the same track indicate this fact, that the wavelengths of irregularities did not change, but their amplitudes are changed.

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