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METHOD TO SYNTHESIZE THE TRACK VERTICAL IRREGULARITIES

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Abstract

The paper focuses on a method to synthesize the track vertical irregularities, with the possibility of application in the simulation of the dynamics in the railway vehicles. The basic elements of the method are the power spectral density of the track irregularities and the quantities describing the track geometry quality, as they have been adopted in compliance with the ORE B 176 report and UIC 518 leaflet. A major contribution of this method is the extension of the interval specific to the wavelength of the track vertical irregularities, so that this interval be representative for the frequency range of the vertical vibrations in the railway vehicle. The results of the numerical simulations of the dynamic behavior in a vehicle while running on a tangent track with vertical irregularities being synthesized as above demonstrate its efficiency.

Key words: railway vehicle, track irregularities, longitudinal level, track quality, power spectral density

1. Introduction

The numerical simulations represent basic tools in research as they are used since the designing stage in order to estimate the dynamic behavior of the railway vehicle and the optimization of its dynamic performance and in the investigation of the problems arising during exploitation [8, 11]. Similarly, the current regulations in this sector include stipulations regarding the use of the numerical simulation for the homologation process of the railway vehicles in terms of the dynamic behavior as for the issues of safety, track fatigue and ride quality [27]. To know the track geometry is essential for the simulation of the dynamic behavior in the railway vehicles. The track geometry is not perfect, as it is affected by a series of deviations that are mainly due to the building defects, track exploitation, change in the track infrastructure as a result of the action of the environment factors or the soil moving [17]. The track irregularities have an impact on the vehicle's dynamic response and are extremely important when dealing with safety [12, 13, 16], ride quality [4, 12, 25, 26], ride comfort [5, 12, 13], track fatigue [6, 10, 14].

As a matter of fact, certain models of the vehicle-track system underlie the development of the simulation programs, where the typical inputs are represented by the track geometric irregularities, namely the vertical and lateral track irregularities, the deviations in gauge and cross level [9, 10].

In order to include the track irregularities in the simulation programs of the dynamics in the railway vehicles, the review literature features two distinct approaches. One considers the track irregularities as absolute values defined as a function of distance, obtained by measuring the track geometry [10, 16, 17, 21]. As a rule, the track irregularities are measured during the safety and maintenance track controls, by means of certain specialized vehicles called track recording vehicles. Likewise, the monitoring of the track geometry implies other methods that basically rely on the vehicle dynamic response to the track irregularities [3, 22 - 24].

An alternative approach, widely used in the studies on the vehicle dynamics, consists in the introduction of the track irregularities in the numerical model as random data defined by the power spectral density (PSD) [2, 15, 19, 20, 25]. In this case, the track irregularities are not looked at as absolute values defined by distance, but they are represented as functions of wavelength or frequency. PSD can be used either directly, as an input for the power spectral analysis or it can be retransformed into track irregularities as a distance function.

This paper introduces an original method to synthesize the track vertical irregularities based on PSD, as per ORE B176 report [28] and the specifications in the UIC 518 leaflet [27] regarding the track geometric quality. In fact, the method herein considers, on the one hand, the spectrum shape of the track vertical irregularities as in the ORE report and, on the other hand, the values of the standard deviations of longitudinal level and the peak value of isolated track errors. In the UIC 518 leaflet, these errors help describe the track quality levels used for the testing and homologation of the railway vehicles from the perspective of the dynamic behavior. Such values correspond to a wavelength interval of the track vertical irregularities between 3 and 25 m. The method here shows how the limits of this interval can be conveniently changed, so that be representative for the frequency range of the vehicle vibrations in a vertical plan.

A separate section of the paper will feature the results of the numerical simulations concerning the dynamics of a railway vehicle during running on a track with vertical irregularities being synthesized in accordance with this present method. Hence, a model of the vehicle [5, 7] is used, validated by experiments [18]. The results thus obtained demonstrate a series of basic properties of the vertical vibrations nature of the railway vehicles, which ultimately prove the efficiency of the adopted method.

2. Longitudinal level

The track irregularities can be generally defined as the deviations of the track from its design geometry. Thus, the longitudinal level represents the vertical movement of each rail along the track, with respect to its design configuration, as shown in fig. 1.

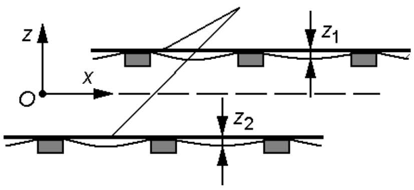

Fig. 1: Longitudinal level [17].

A similar definition of the longitudinal level is to be found in the UIC 518 leaflet. The longitudinal level is there defined as the geometrical error in the vertical plane, represented by the difference between a point of the rail top in the running plane and the ideal mean line of the longitudinal profile [27].

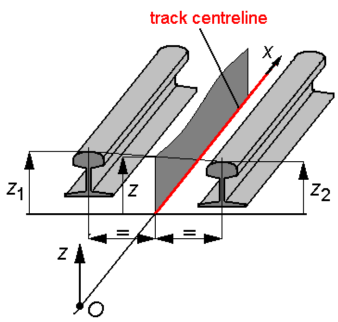

Fig. 2: Longitudinal level.

As in fig 2, some authors [2, 9, 22] define the longitudinal level (z) on the track axis as being the mean value of the longitudinal level of the two rails ($z_{1,2}$),

$$z = \frac{z_1 + z_2}{2} . \tag{1}$$

The longitudinal level mainly affects the vertical dynamics in the vehicle. While running on a track with vertical irregularities, both the rigid modes of vibrations – bounce, pitch and rebound are excited and also the flexible ones (for eg. the carbody bending).

3. The power spectral density (PSD)

A widely used method to have an analytical representation of the track consists in using the PSD of the measured irregularities in the track. PSD is a function of either the wavelength of the track irregularities or of the wave number, or even the space frequency.

While noting with Ω the wave number and with f the space frequency, these quantities are related to the wavelength λ by the equation

$$\Omega = \frac{2\pi}{\lambda} = 2\pi f , \tag{2}$$

where $f = 1/\lambda$, expressed in cycles/m.

The review literature mentions various forms of the PSD function that mainly take the track quality into account. The European countries use the ‚low level' and ‚high level' spectral density, in accordance with the ORE B176 report [28]. For the track vertical profile, the ORE B176 report mentions the following form of PSD

$$S(\Omega) = \frac{A\Omega_c^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)} , \tag{3}$$

considered as representative for the statistic properties of the European railway system.

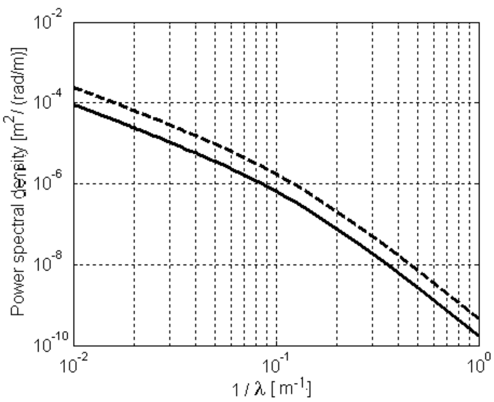

Fig. 3: PSD function of the vertical track irregularity profile. —, $A = 4.032 \cdot 10^{-7}$ radm; – –, $A = 1.080 \cdot 10^{-6}$ radm.

The coefficients Ω_c, Ω_r and A in the PSD equation are derived from experiments. While Ω_c and Ω_r have constant values (Ω_c = 0.8246 rad/m, Ω_r = 0.0206 rad/m), the values of the constant A depend on the track quality. Thus, for a high level track, $A = 4.032 \cdot 10^{-7}$ radm. For a low level track, the value of the constant A is $1.080 \cdot 10^{-6}$ radm. The fig. 3 features ‚low level' PSD and ‚high level' PSD of the vertical track irregularity profile.

4. The track geometric quality as in the UIC 518 leaflet [27]

During the homologation of the railway vehicles in terms of their dynamic behavior, the definition of the track geometric quality is based on three quality levels, namely QN1, QN2 and QN3, included in the UIC 518 leaflet.

In dependence on a certain speed, called the reference speed, the UIC 518 leaflet mentions the quality levels QN1 and QN2, separately defined for the standard deviations for longitudinal level and lateral alignment of the track and, for information, for the peak value of isolated track errors. In the paper herein, the interest is only in the quality levels defined for the standard deviations of the longitudinal level.

The quality level QN3 is a function of QN2, namely

$$QN3 = 1{,}3 \cdot QN2. \quad (4)$$

When the quality of a track section is defined by QN3, then it is excluded from the analysis, as being non-representative from the track standard geometry perspective.

Table 1. Standard deviation for longitudinal level.

The reference speed [km/h]	QN1 [mm]	QN2 [mm]
$V \le 80$	2,3	2,6
$80 < V \le 120$	1,8	2,1
$120 < V \le 160$	1,4	1,7
$160 < V \le 200$	1,2	1,5
$200 < V \le 300$	1,0	1,3

Table 2. The peak value for isolated track errors.

The reference speed [km/h]	QN1 [mm]	QN2 [mm]
$V \le 80$	12	16
$80 < V \le 120$	8	12
$120 < V \le 160$	6	10
$160 < V \le 200$	5	9
$200 < V \le 300$	4	8

The table 1 shows the standard deviations for the longitudinal level and the table 2 features the peak values of the isolated errors, corresponding to the quality levels QN1 and QN2. It is worth mentioning that the values for the standard deviations correlate with an interval of wave length ranging between 3 and 25 m, which corresponds with the usual method of measuring the track geometry.

To use the values in the tables above, the reference speed is considered to be differentially determined, according as whether the track section is tangent or in the curve. Hence, when the track section is tangent or in a large radius curve ($R > 900$ m), the reference speed is the vehicle limit speed itself; for the medium radius curves (600 m $< R \le$ 900 m), V ranges from 160 to 200 km/h; in the small (400 m $\le R \le$ 600 m) and very small radius curves (250 m $\le R <$ 400 m), the speed is of 80 km/h $< V \le$ 120 km/h.

5. Description of the method to synthesize the vertical track irregularities

This section deals with the method to synthesize the vertical track irregularities. The method is developed by means of PSD as in relation (3), mentioned in the ORE B176 report [28], and in the specifications in the UIC 518 leaflet [27] regarding the track geometric quality that is, on the one hand, the value of the standard deviation for the longitudinal level, and on the other hand, the compliance with the maximum values of the isolated errors.

In the PSD equation of the vertical track irregularities, the constant A is replaced with a constant A_A that is calculated as the value of the standard deviation for the longitudinal level coming from the components with a wavelength between Λ_1 = 3 m and Λ_2 = 25 m, corresponding with the stipulations in the UIC 518 leaflet. In other words, the relation (3) becomes

$$S(\Omega) = \frac{A_A \Omega_c^2}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)} . \quad (5)$$

To this purpose, the standard deviation for the longitudinal level between the wave length Λ_1 and Λ_2 needs to be calculated

$$\sigma_u = \sqrt{\frac{1}{\pi} \int_{\Omega_2}^{\Omega_1} S(\Omega) \mathrm{d}\Omega} , \quad (6)$$

where $\Omega_{1,2} = 2\pi/\Lambda_{1,2}$.

From relations (5) and (6), we have

$$\sigma_u = \sqrt{\frac{A_A \Omega_c^2}{\pi} I_0} \quad (7)$$

where

$$I_0 = \int_{\Omega_2}^{\Omega_1} \frac{\mathrm{d}\Omega}{(\Omega^2 + \Omega_r^2)(\Omega^2 + \Omega_c^2)} . \quad (8)$$

Further, the value of the constant A_A, comes from the equation (7), only in compliance with the requirement about the value of the standard deviation for the longitudinal level

$$A_A = \pi \frac{\sigma_u^2}{\Omega_c^2 I_0} . \qquad (9)$$

It is now possible to synthesize the vertical track irregularities, starting from PSD in relation (5). This operation relies on the transformation of the power spectral density of the vertical track irregularities $S(\Omega)$, which is a continuous spectrum, with an infinity of spectral components, within the spectrum of the amplitudes $U(\Omega)$ that is a discrete spectrum with a finite number of spectral components (fig. 4). The condition of transformation consists in keeping the power of the two spectra within the wavelength interval being studied.

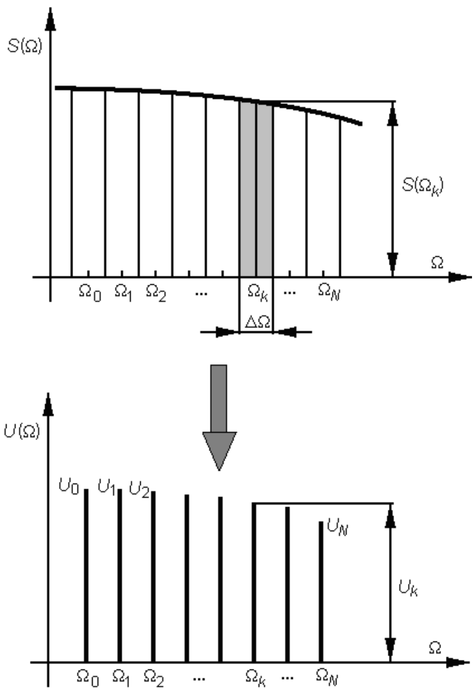

Fig. 4. Digitization of the vertical track irregularities spectrum

A certain wavelength interval of the vertical track irregularities between the minimum wavelength Λ_{min} and the maximum Λ_{max} one will be taken into account, as considered representative for the excitation domain of the vertical vibrations in a railway vehicle. For this interval, a partition with a constant step of the wavelength number, corresponding with the spectral components of interest will be looked at, $\Delta\Omega$,

$$\Omega_k = \Omega_0 + k\Delta\Omega, \quad k = 0, 1, 2, ..., N,$$

where $N + 1$ is the number of spectral components.

The following correlations are being complied with

$$\Omega_0 = \frac{2\pi}{\Lambda_{max}} , \; \Omega_N = \frac{2\pi}{\Lambda_{min}} . \qquad (10)$$

The amplitude of each spectral component is derived by considering the fact that for the interval between $\Omega_k - \Delta\Omega/2$ and $\Omega_k + \Delta\Omega/2$, the standard deviation for the longitudinal level comes from the relation (6) while looking at the constant spectral density in this interval

$$\sigma_u = \sqrt{\frac{1}{\pi} \int_{\Omega_k - \Delta\Omega/2}^{\Omega_k + \Delta\Omega/2} S(\Omega) \mathrm{d}\Omega} = \sqrt{\frac{1}{\pi} S(\Omega_k)\Delta\Omega} . \qquad (11)$$

The amplitude of the spectral component corresponding with the wavelength number Ω_k is as below

$$U_k = \sqrt{\frac{2}{\pi} S(\Omega_k)\Delta\Omega} \text{, with } k = 0, 1, 2, ... N. \qquad (12)$$

An analytical form can now be assigned to the vertical track irregularities, namely

$$u(x) = \sum_{k=0}^{N} U_k \sin(\Omega_k x + \varphi_k) , \qquad (13)$$

where φ_k is the displacement of the spectral component ‚k'. In order to give a random nature to the track irregularities, a uniform random repartition can be chosen for φ_k, with values between $-\pi$ and $+\pi$. This repartition can be practically obtained via Matlab function, rand.m.

The gross synthesis of the track irregularities, which maintained the shape of the spectral density, as in relation (6), and the value of the standard deviation for the longitudinal level as in the UIC 518 leaflet, is followed by the adjustment of the form in relation (13) so that the peak values of the isolated errors fall into the designed limits. This adjustment is done by scaling the amplitudes in the vertical track irregularities with a coefficient derived from the ratio between the value of the admitted isolated error u_{adm} and the maximum absolute value of the vertical track irregularities ($\max|u(x)|$).

$$K_u = \frac{u_{adm}}{\max|u(x)|} . \qquad (14)$$

As a conclusion, the following analytical form of the vertical track irregularities results

$$u(x) = K_u \sum_{k=0}^{N} U_k \cos(\Omega_k x + \varphi_k) . \qquad (15)$$

With the above method, the vertical irregularities have been synthesized on a 2-km distance for a track whose geometry corresponds to the quality level QN1 (fig. 5, diagram (a)) and for a track correlated with the quality level QN2 (fig. 5, diagram (b)). The values of the standard deviations for the longitudinal level corresponding to the reference speed of 200 km/h were selected from table 1, and the peak values of the isolated errors of this type from table 2.

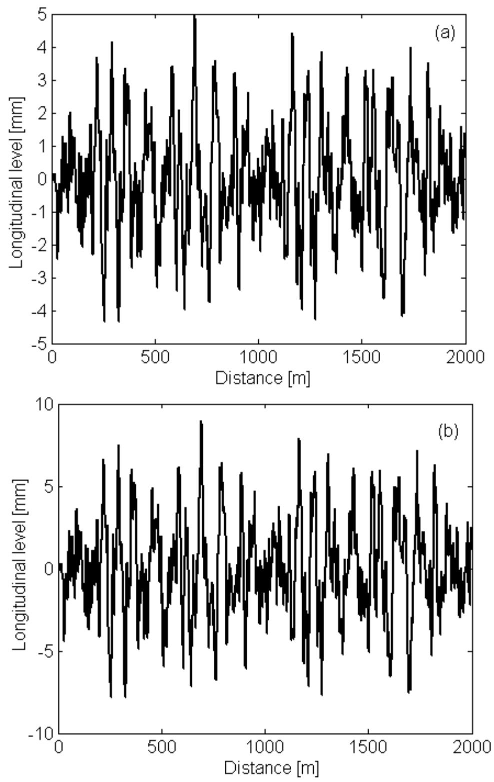

Fig. 5: Synthesis of the vertical track irregularities: (a) quality level QN1; (b) quality level QN2.

For the synthesis of the track geometry, the contribution of 300 spectral components was taken into account (k = 300) with wavelength between 3 and 120 m. The maximum value of the wavelength (120 m) has been established via the fact that the speed of 200 km/h triggers the minimum frequency of the excitation coming from the vertical track irregularities with the value of 0.46 Hz. This frequency is low enough to include the lowest natural frequencies of the vehicle's vertical movements, to be found within the 1...1.5 Hz interval.

The standard deviation value for the longitudinal level is noted to be 1.638 mm for the track with a QN1 quality level and 3.272 mm for a QN2 quality level track.

6. Simulation of the dynamic behavior in a railway vehicle on a track with vertical irregularities

Further on, the results of the numerical simulations regarding the dynamic behavior on the vertical direction of a passenger train are presented during running on a tangent track with vertical irregularities, as per the method in the previous section.

The numerical simulations in Matlab are developed via a complex theoretical model that reproduces the structure of a 4-axle, 2-suspension level passenger vehicle [5, 7], which is validated by the results coming from experiments [18]. Basically, it is about a discrete-continuum model, with 22 degrees of freedom where the vehicle carbody is modeled by an Euler-Bernoulli beam and the suspended masses of the bogies and the four axles are assimilated to rigid bodies. The 7 bodies making up the model are connected among them by Kelvin-Voigt systems that help model the two suspension levels of the vehicle.

Figure 6 features the vertical acceleration in three reference points of the carbody – at the centre and above the two bogies, derived from numerical simulation of the vehicle circulation at speed 200 km/h on a QN2 quality level track (see fig. 5, diagram (b)). At the carbody centre, the acceleration can be noticed to be lower compared to the one above the bogies. Indeed, the mean square deviation of the acceleration shows at the carbody centre with the value of 0.126 m/s^2, of 0.295 m/s^2 above the front bogie and 0.319 m/s^2 above the rear bogie. As for the maximum values of the acceleration, these are as such: 0.486 m/s^2 - at carbody centre; 0.865 m/s^2 - above the front bogie and 0.924 m/s^2 – against the rear bogie.

Figure 7 shows the frequency spectra of the carbody vertical acceleration in all three reference points. A first observation concerns the frequency range. As said earlier, the values of wavelength being discussed are between 3 and 120 m. At the speed of 200 km/h (cca. 55.6 m/s), the frequency range is from 0.46 Hz to 18.52 Hz, where these limits can be easily identified on all three spectra.

The acceleration spectrum calculated at carbody centre is dominated by the influence of the symmetrical movements, focusing on the one due to the resonance of the low bounce with a frequency of 1.17 Hz (fig. 7, diagram (a)). Similarly, the component from the resonance of the first carbody bending natural mode can be identified, starting with 8.2 Hz.

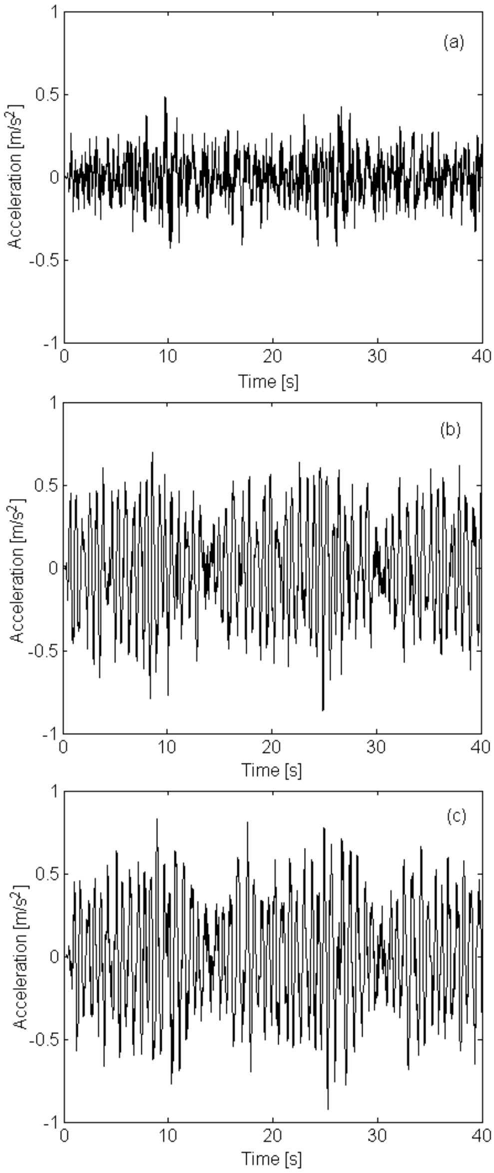

Fig. 6: Carbody acceleration at speed 200 km/h on a track with QN2 quality level: (a) at carbody centre; (b) above the front bogie; (c) above the rear bogie.

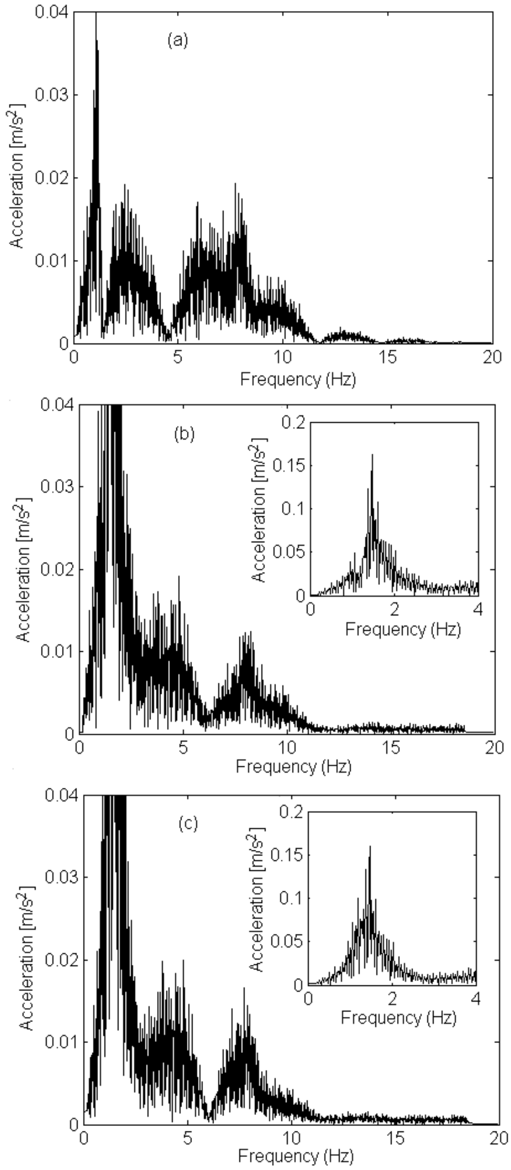

Fig. 7. Carbody vertical acceleration spectra: (a) at carbody centre; (b) above the front bogie; (c) above the rear bogie.

Important contributions also bring the rebound movement of the bogies in the area of frequencies 2...4 Hz and the high bounce from 6.61 Hz. On the other hand, the anti-resonance frequencies are well-defined, thanks to the geometric filtering [1]. Thus, the first anti-resonance coming from the filtering effect of the carbody wheelbase shows at 1.46 Hz, while the following one is at cca. 4.4 Hz.

In terms of the acceleration spectra calculated over the bogies, these are very similar among them, as seen in diagrams (b) and (c) in Figure 7. Above the bogies, the vibration behavior is the result of the overlap of the symmetrical and anti-symmetrical vibration modes, where the latter hold a higher percentage. And the acceleration spectra diagrams above the bogies prove the strong influence of the carbody pitch movement with a natural frequency at 1.46 Hz.

A certain contribution of the low bounce is also visible, mainly against the front bogie (fig. 7, diagram (b)), and the presence of the first natural bending mode of the carbody. The geometric filtering effect is less significant, even though the anti-resonance at circa 6.2 Hz is more evident and comes from the filtering of the bogie's wheelbase.

7. Conclusions

The paper herein has focused on a method to synthesize the vertical track irregularities, applicable in the simulation programs of the railway vehicles dynamics. The aim was to obtain an analytical relation to help reproduce the vertical track irregularities in the virtual environment as a distance function. To this purpose, the starting point was the power spectral density function in the ORE B176 report, where the track quality parameter was changed so as to comply with the specifications in the UIC 518 leaflet regarding the value of the standard deviations at the longitudinal level and the maximum values of the isolated errors.

A significant advantage of this method is that it allows the convenient determination of the limits of the domain specific to the wave length of the vertical track irregularities so that it will be representative for the frequency range of the vertical vibrations in the railway vehicles.

The efficiency of this method has been verified via the results coming from the simulation of the dynamic behavior of a passenger vehicle. To this purpose, the vertical track irregularities, synthesized as herein, have been implemented into a program of numerical simulation developed on a complex model of the vehicle, validated by experiments.

The results such derived have marked out a series of properties specific to the nature of vertical vibrations in the railway vehicle. Thus, based on the analysis of the time evolution of the vertical acceleration, the level of vibrations has proved lower at carbody centre than above the bogies. On the other hand, the analysis of the carbody frequency spectra helps identify the resonance frequencies of the vehicle vertical movements, namely 1.17 Hz – frequency of the low bounce; 6.61 Hz – frequency of the high bounce; 8.2 Hz – frequency of the resonance in the first natural bending mode of the carbody (the symmetrical bending); 1.46 Hz – frequency of the carbody pitch movement. Likewise, the anti-resonance frequencies from the geometric filtering in the vehicle wheelbase have been highlighted.

The corresponding change of the PSD function and of the parameters describing the track quality makes this method applicable in the synthesization of the lateral track irregularities.

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