Jarosław Bednarz

New methodology for analysis of ground vibrations caused by the railway vehicles

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A methodology for assessing the ground vibrations caused by the movement of rail vehicles is presented in the paper. A description of the results of experimental studies and assessment of the risks associated with the operation of rail vehicles on the road and tram crossing located in Silesia is also presented. The proposed method of assessing risks is based on the time-frequency analysis of signals and the estimation of a histogram of the distribution of amplitude signals.

Keywords: ground vibrations, transport, dynamic loads from railway vehicles.

Wstęp

Today, due to a very high density of built-up areas in cities, residential and industrial buildings are increasingly being located near railways and tramways. This location brings about problems associated with vibration wave propagations in the ground, caused by rail vehicles, which can lead to damages of buildings, and significantly reduce the comfort of their use. There is, therefore, a need to develop a methodology for the evaluation of dynamic threats caused by rail traffic to the existing and planned infrastructure, both residential and industrial [1,2,3,4]. This article presents the use of the author's own methodology concerning vibration wave propagations in the ground, based on an analysis of the results of registration of ground vibration acceleration in terms of time and frequency. Also, a description of experimental tests is shown, the results of which were used to present the developed research methodology with respect to ground vibrations.

1.Description of the methodology assessing ground vibrations

The developed methodology for the evaluation of dynamic threats caused by the movement of rail vehicles is based on the use of PN-B-02170:2016-12 standard [5]. In accordance with section 4.3., of the standard, the influence of vibrations transmitted from the substrate onto residential, and industrial buildings can be neglected in cases where the share of this load is minute, and it can be assumed that the amplitude of the ground motion acceleration at the place of building foundation fulfils the following condition:

$$a_p < 0{,}005[g] = 0{,}05\,\frac{m}{s^2} \qquad (1)$$

Therefore, one of the key elements of the proposed methodology of soil vibration testing is the designation of a histogram showing the distribution of absolute values of ground vibration acceleration amplitudes. The histogram enables the disclosure how often the permissible acceleration values are exceeded.

Additionally, the proposed research methodology determines also the spectrum of registered signals and their spectrograms. Determination of signal spectra, and their spectrograms allows deciding on the application of a vibration-isolating system in the railway, because the application of such a system makes sense only in the case of vibrations at frequencies below 50 Hz.

Figure 1 shows a diagram of the developed methodology for an analysis of ground vibrations induced by railway traffic.

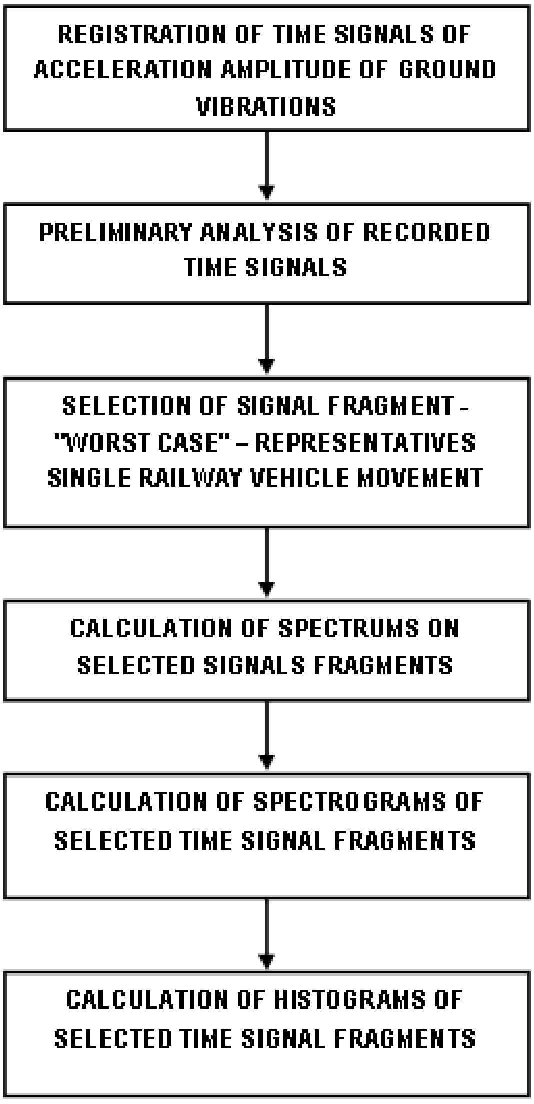

Fig. 1. Diagram of the developed methodology assessing ground vibrations

The first step in the developed methodology testing vibration wave propagation is the registration of time signals of ground vibration acceleration signal registration at several measurement points. The measurement should be made twice:

1. background measurement, in order to check the levels of ground vibration amplitudes caused by the movement of pedestrians, cars and seismic vibrations,

2. measurement of vibrations during railway traffic along the measured section.

The second step is an initial analysis of the registered signals - defining signal spectra, and selecting all the signals corresponding to the movement of a single rail vehicle along the measured section.

The third step is the choice of signal fragments selected in the second step of the analysis, which correspond to the transit of a single rail vehicle along the measured section, for which the values ground vibration acceleration amplitude of are the greatest - when analysing ground vibrations in order to assess the risks, the best choice is a worst-case scenario analysis.

Further steps in the analysis is the determination of spectra and spectrograms of the selected fragment of recorded signals - these analyses allow the evaluation of the option to apply vibroisolation systems [6].

The final step are histograms of the selected fragment from among registered signals. This analysis allows us to define the possibility of dynamic threats, and to take measures aimed at their elimination, if such threats exist.

The application of the proposed methodology of ground vibration assessment for tram passages, along with a description of the experimental research is presented in the following chapters.

2. Description of the experimental tests

2.1. General characteristics of the tests

Analyses presented in the paper relate to the impact of tram passages on ground vibration parameters at a tramway-road intersection located in Upper Silesia (fig. 2.)

Fig. 2. Location of tramway-road intersection

The purpose of the tests was to obtain information on the amplitude and frequency of ground vibrations. The scope of the research included:

1. registration of time distribution of ground vibrations of during the passage of trams
2. determination of the maximum amplitude of ground vibration acceleration for each point and measuring direction
3. defining the spectra of registered signals,
4. processing of research results.

2.2. Description of the conducted research

The research was conducted in a grid of 4 measurement points, whose layout is shown in Figure 3. The adopted coordinate system is shown in Figure 4.

In the course of the tests, the following equipment was used:

1. measuring computer,
2. Teac Gx-01 signal recorder,
3. 4 three-axis piezoelectric accelerometers PCB 356A16 type,
4. 3 uniaxial piezoelectric seismic accelerometers PCB 393A03 type.

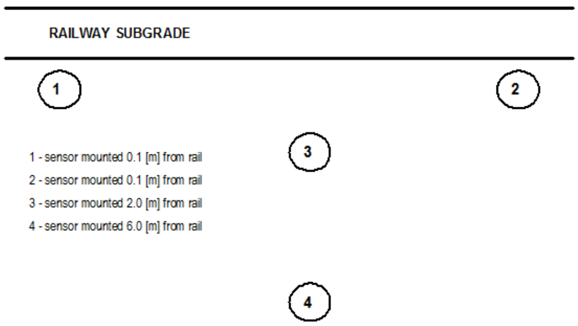

Fig. 3. Measurement point grid

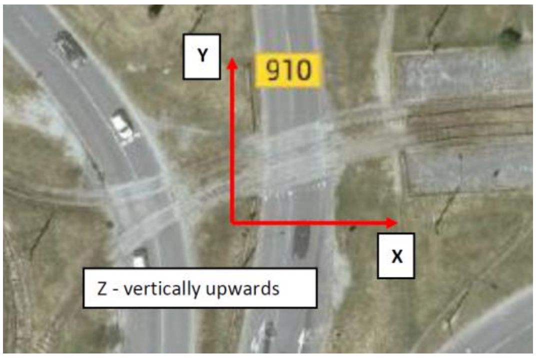

Fig. 4. The adopted coordinate system

At all measurement points, the time distribution of vibrations were recorded using triaxial piezoelectric accelerometers, PCB 356A16 type, mounted on steel discs placed on the ground (fig. 4). In addition, in points 1, 2 and 3, the time distributions of vibrations were recorded using single-axle piezoelectric accelerometers, PCB 393A03 type (fig. 4).

Fig. 5. Attaching the vibration sensors

The following names of the measurement points that are used consistently in the rest of the article have been assumed:

1. PS:(No.): - measurement with the use of a PCB 393A03 accelerometer at the point with number (No.) in direction Z,
2. PP:(No.):(dir.) - measurement with the use of a PCBs 356A16 accelerometer at point with number (No.) in the direction (dir.).

   The following summarizes the key features of the tests conducted:

   1. time distributions of vibration acceleration signal responses in three mutually perpendicular directions were registered, using PCB 356A16 accelerometers at all four measurement points,
   2. time distributions of vibration acceleration signal responses in "Z" direction were registered with the use of PCB 393A03 accelerometers at measurement points 1, 2 and 3,
   3. the sampling rate was established at 500 [Hz]

4. low-pass filtration was used for the registered signals, at a cut-off frequency of 200 Hz,
5. based on the measured measurement signals, maximum amplitudes of vibration acceleration were defined for each point and measuring direction
6. based on the measured measurement signals, spectra of vibration acceleration signals were defined, registered for each point and measuring direction
7. based on the measured measurement signals, histograms of the distribution with respect to absolute values of vibration acceleration amplitude, registered for each point and measuring direction were defined.

3. Application of the proposed methodology of ground vibration analysis

3.1. Initial analysis of the registered time behaviour, and selection of signal fragments for further analysis

The first step in the proposed methodology of research on vibration wave propagation in the ground is the registration and analysis of whole registered time distribution of ground vibrations. This paper focuses only on the analysis of time signals recorded at points 1, 2, and 3 (figure. 2) for "Z" direction (fig. 3), using seismic accelerometers, PCB 393A03 type. Figures 6a to 6 c show the distribution of recorded time signals, and in figures 7a - 7 c - spectra diagrams, established on their basis.

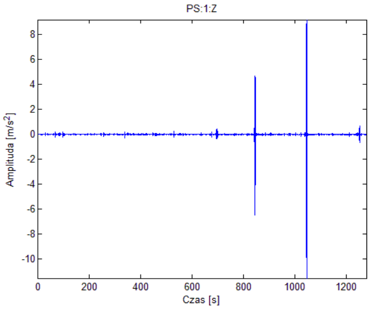

Fig. 6a. Time signal of a vibration acceleration amplitude recorded at PS:1:Z.

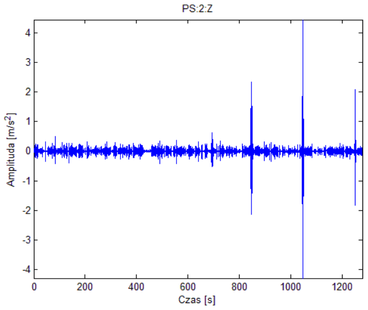

Fig. 6b. Time signal of vibration acceleration amplitude recorded at point PS:2:Z.

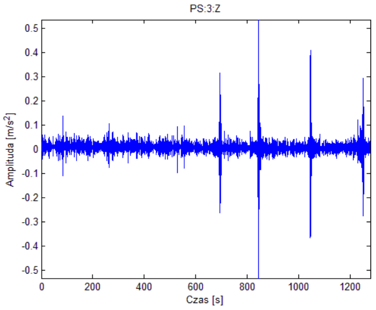

Fig. 6 c. Time signal of a vibration acceleration amplitude recorded at PS:3:Z

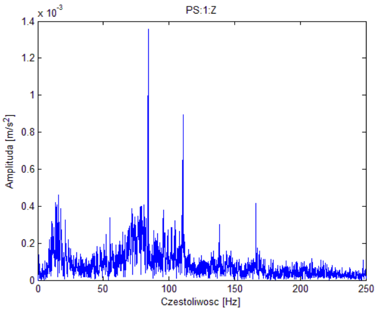

Fig. 7a. Signal spectre of a vibration acceleration amplitude recorded at PS: 1:Z

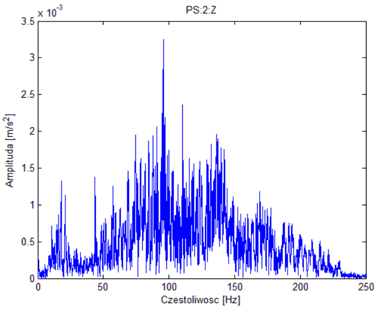

Fig. 7b. Signal spectre of vibration acceleration amplitude recorded at point PS: 2:Z.

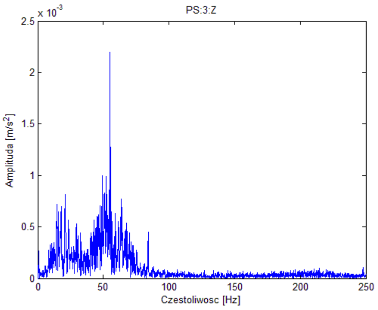

Fig. 7c Signal spectre of a vibration acceleration amplitude recorded at PS: 3:Z

Analysis of charts presented in figures 6a to 6 c and 7a ÷ 7 c is rather difficult - it is hard to determine what the dominant vibration frequencies in the ground are, and how significant are the excesses of the permissible amplitude in respect of ground vibrations ap. Therefore, for a further analysis, a fragment of the signal from 837 to 854 second was selected - for this fragment, the largest values of vibration signal amplitude occur at measurement point PS: 3:Z, which is located at a distance of 2 [m] from the source of enforcement. At the two other points, the amplitude of the excitation source is recorded (movement of a rail vehicle), and these points cannot be taken into account when assessing vibration wave propagation in the ground.

3.2.Determination of spectra of the selected fragment of registered time signals

The next step in the proposed methodology for research on vibration wave propagations in the ground is the definition of the spectra of fragments of time signals recorded in the previous step. Figures 8a-8c show graphs of selected fragments of the registered time signals, and figures 9a to 9c show spectra designated on their basis.

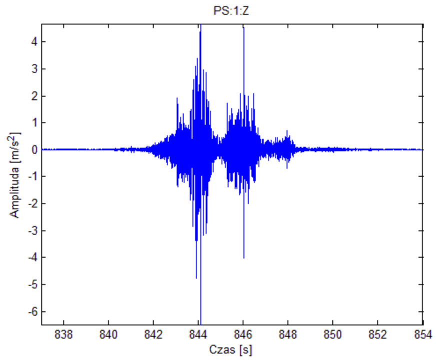

Fig. 8a. A selected fragment of time signal amplitude of vibration acceleration recorded at point PS:1:Z

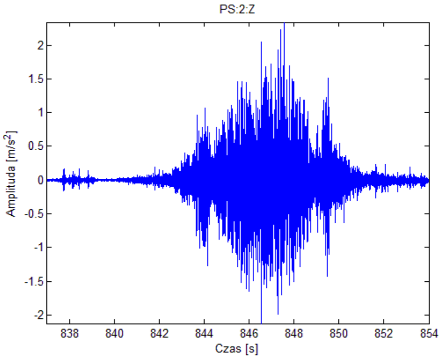

Fig. 8b. A selected fragment of time signal amplitude of vibration acceleration recorded at point PS: 2:Z

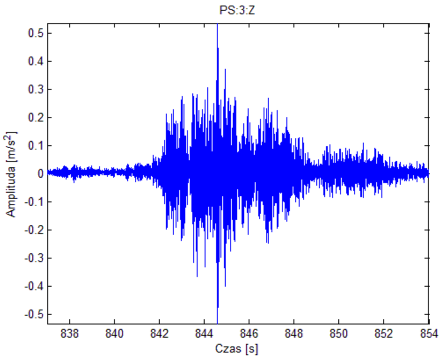

Fig. 8c. A selected fragment of time signal amplitude of vibration acceleration recorded at point PS:3:Z

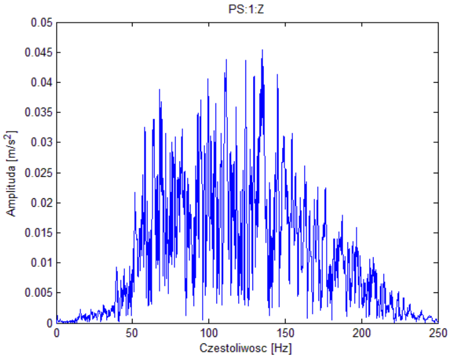

Fig. 9a. Spectre of a selected fragment of vibration acceleration amplitude recorded at point PS:1:Z

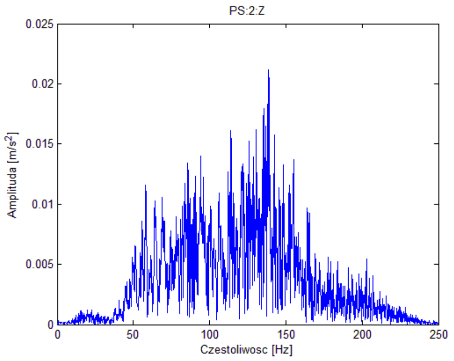

Fig. 9b. Spectre of a selected fragment of vibration acceleration amplitude recorded at point PS:2:Z.

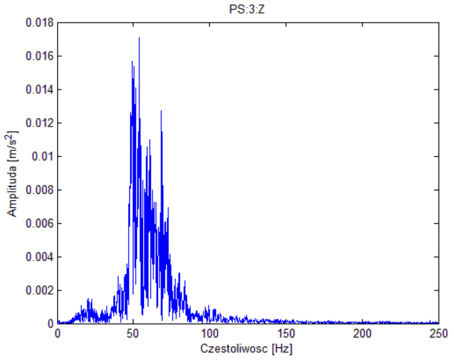

Fig. 9 c. Spectre of a selected fragment of vibration acceleration amplitude recorded at point PS: 3:Z.

3.3. Defining spectrograms of a selected fragment of recorded time signals

The next step in the proposed methodology for research on vibration wave propagations in the ground is the definition of spectrograms of fragments of recorded time signals, selected in the previous step. Figures 10a to 10 c show the spectrograms designated on the basis of selected fragments of time signals, registered during the tests.

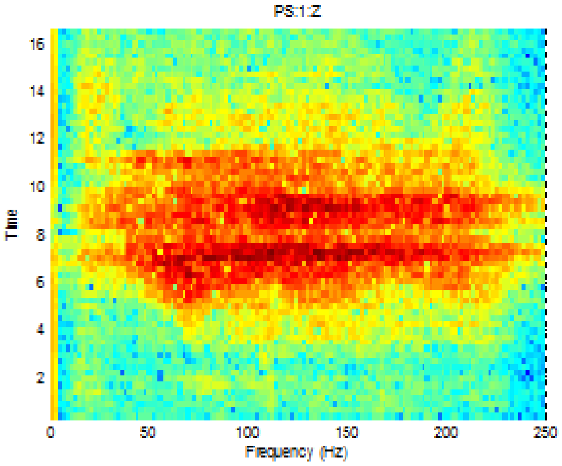

Fig. 10a. Spectrogram designated on the basis of a fragment of time signal vibration acceleration amplitude, recorded at point PS:1:Z

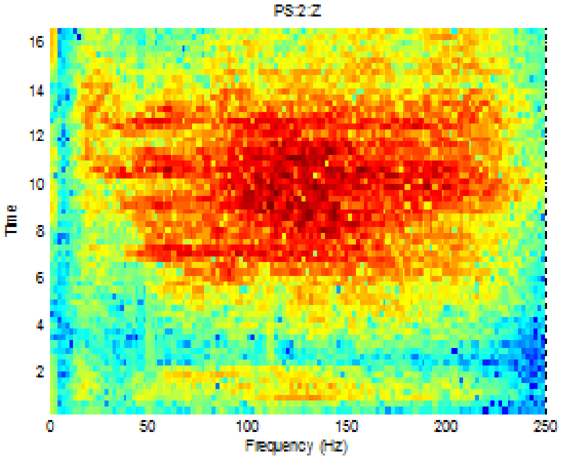

Fig. 10b. Spectrogram designated on the basis of a selected fragment of time signal of vibration acceleration amplitude recorded at point PS:2:Z

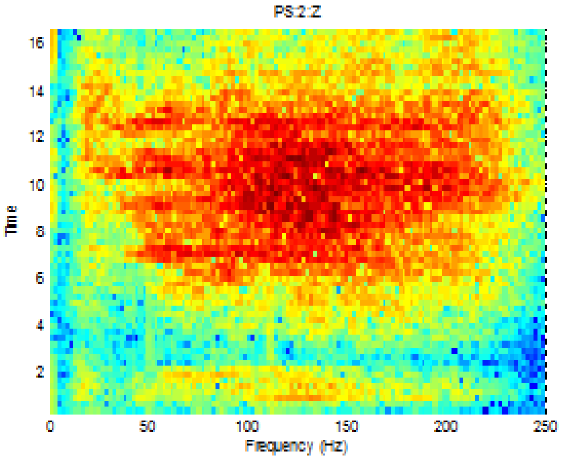

Fig. 10c. Spectrogram designated on the basis of a fragment of time signal vibration acceleration amplitude, recorded at point PS:3:Z

Analysis of spectrograms presented in figures 10a to 10 c allows the conclusion that at the location of the tramway-road intersection, in the ground, substrate vibrations at low frequencies occur, within the range of approximately 0.1 Hz to about 5.0 Hz at all times during the tests. These vibrations can be caused by car traffic in the area. On the basis of the defined spectrograms it can also be observed that the passage of a rail vehicle generates a vibration wave in the ground at higher frequencies, exceeding 10 [Hz]. Directly by the tramway, the resulting vibration wave has frequency components from about 10 Hz to about 220-240 Hz, while the ground parameters and, in particular, its damping factor causes the vibration signal, already 2 [m] from the tramway to have frequencies from the range between 10 and about 100 Hz.

3.4. Defining histograms for a selected fragment of registered time signals

The next step in the proposed methodology for research on vibration wave propagations in the ground is the designation of absolute values of the vibration acceleration amplitude distribution histograms for fragments of recorded signals, selected in the previous step. Figures 11a to 11 c show histograms of the distribution with respect to absolute values of vibration acceleration amplitude, for selected fragments of time signals registered during the tests.

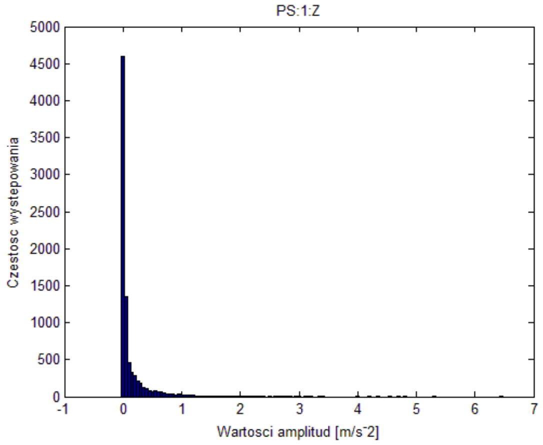

Fig. 11a. Histogram of the distribution of absolute values of the vibration acceleration signal amplitudes, recorded at point PS: 1:Z

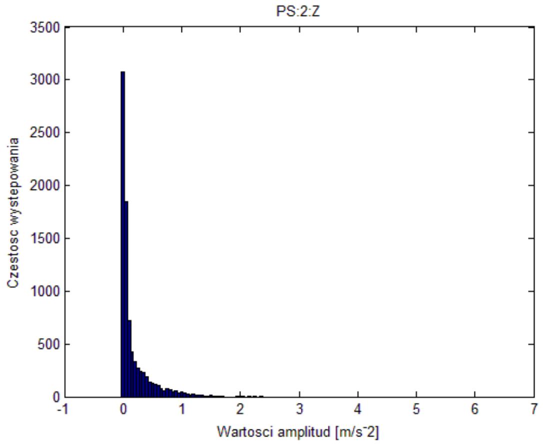

Fig. 11b. Histogram of the distribution of absolute values of the vibration acceleration signal amplitudes, recorded at point PS:2:Z

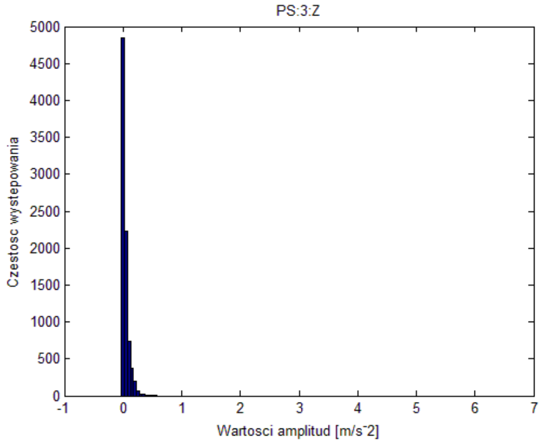

Fig. 11c. Histogram of the distribution of absolute values of the vibration acceleration signal amplitudes, recorded at point PS:3:Z

On the basis of designated histograms, W_H index may be defined, which specifies the ratio between the value of the vibration acceleration amplitude, not exceeding the permissible value ap, and the value of the vibration acceleration amplitude in excess of the permissible value ap, based on the following dependency:

$$W_H = \frac{N_1}{N_2} \qquad (2)$$

where:
N_1 - the value of the vibration acceleration amplitude not exceeding the permissible value,
N_2 - the value of the vibration acceleration amplitude exceeding the permissible value.

The value of W_H index above 1 indicates the occurrence of sporadic excesses of the permissible value of the acceleration amplitude ap during the passage of a rail vehicle. For selected signal fragments, the index values are as follows:

1. for point PS:1:Z - $W_H = 2.33$,
2. for point PS:2:Z - $W_H = 1.37$,
3. for point PS:3:Z - $W_H = 4.96$,

Analysis of W_H index value allows the conclusion that the arrival of the tram for a specific signal fragment took place in the direction from PS:1:Z to PS: 2:Z point - this is indicated by the higher index value for point PS:1:Z. This is associated with the tram acceleration along the measured section - the higher the speed of the vehicle, the larger is the dynamic impact related to the vibration wave in the ground. Additionally, based on the value of WH index at point PS: 3Z, it can be said that the ground at the tramway-road intersection has a high damping factor - the index value of at that point is more than double than at PS: 1:Z and almost three times higher than at PS: 2:Z.

Summary

The methodology of ground vibration testing and dynamic risk assessment for the surrounding of areas with the movement of railway vehicles presented in the article can be successfully applied in the analysis of vibration wave propagation in the ground, and in the assessment of the need to apply vibration-isolating systems in tramways.

The proposed methodology, in an easy and fast manner, allows the assessment of dynamic threats for the environment without having to perform long and complex modelling of the ground, tracks and its immediate surroundings, such as when using the finite element method.

The testing methodology proposed by the author can also be used successfully in the assessment of the need to use vibration-isolating systems, both in existing and newly designed rail transport routes.

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Nowa metodologia analizy drgań gruntu powodowanych przez pojazdy szynowe

W pracy przedstawiono metodologię oceny drgań gruntu wywołanych ruchem pojazdów szynowych. Przedstawiono także opis wyników badań eksperymentalnych i oceny ryzyka związanego z eksploatacją pojazdów szynowych na drogach i przejazdach tramwajowych na Śląsku. Proponowana metoda oceny ryzyka opiera się na analizie czasowo-częstotliwościowej sygnałów i oszacowaniu histogramu rozkładu sygnałów amplitudowych.

Słowa kluczowe: drgania gruntu, transport, obciążenia dynamiczne od pojazdów szynowych.

Author:

dr inż. **Jarosław Bednarz** - AGH University of Science and Technology, Department of Robotics and Mechatronics, al. Mickiewicza 30, 30-059 Kraków, Poland,
e-mail: bednarz@agh.edu.pl