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ANALYSIS OF VIBRATION IN GRAVEL BALLAST OF RAILWAY TRACKS

ANALÝZA VIBRACÍ VE ŠTĚRKOVÉM LOŽI ŽELEZNÍČNÍCH TRATÍ

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The article is aimed at the measurement and the analysis of vibrations of gravel ballast of rail tracks. Some dynamical characteristics of the rail track is possible to measure and to analyse easily indirectly with the help of acceleration sensors (eventually sensors of speed or vibration amplitude) placed on different points of the rail, respectively on sleepers or rail holds. For the study of vibration phenomena, which take place in rail, bedding it is necessary to use sensors built-in to ballast layer so that the vibration conduction toward sensors was sufficient and there was not appeared the damage of sensors. The article contains theoretical study of the task, creating the methodology and the real experiment of vibration measurement into gravel ballast is demonstrated there, too. The modern tools of time, frequency and time-frequency analyses are applied there

Příspěvek je zaměřen na měření a analýzu vibrací ve štěrkovém loži železničních tratí. Některé dynamické charakteristiky železničních tratí je možné měřit a vyhodnocovat při využití snímačů zrychlení (případně snímači rychlosti a výchylky) umístěnými v různých místech na kolejnici, pražci nebo upevnění kolejnice. Ke studiu vibračních jevů ve štěrkovém loži je však nutno použít snímač vestavěný přímo štěrkové vrstvy tak, aby nedošlo k jeho poškození. Příspěvek se zabývá teoretickými problémy, tvorbou metodiky měření pomocí měřících kamenů a reálným experimentem. Součástí příspěvku je také aplikace moderních metod časové, frekvenční a časově frekvenční analýzy.

Keywords *Vibration, Gravel Ballast, Measuring Stone, Short Time Fourier Transform, Page Transform .*

Klíčová slova *Vibrace, štěrkové pole, měřící kámen, STFT*

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INTRODUCTION

Vibration of railway's superstructure is influenced by its qualities, service building conditions, climatic phenomena and especially afterwards dynamic loading from wheel set of railway rolling stock. So there it is reduced railway's superstructure stress and thus also service costs, it is necessary to realise laboratory and traffic load measurements, which provide enough information about influence pertinent of design modification of single section track and points (rail, fixation, ladders, sleepers, dilatation devices an so on). It suits to point out, that knowledge of the quantities characterising dynamic process should be progress in construction of the track enables full analyses, which can be important for successive optimisation of building and service conditions. It is also important for making-up and specification of mathematical models, eventually for further activities leading to increases of reliability of railway's and tramway traffic transport. Some dynamic characteristics of railway's and tramway's superstructures is possibly easy to measure indirectly by acceleration sensors (eventually velocity, or vibration amplitude) placed in different places on rail, sleepers and rail fixations. Piezoelectric acceleration sensors are often applied to these measurements for their exquisite characteristics (precious linearity, large dynamic range). Some dynamic characteristics of railway's and tramway's superstructures is simplify to indirectly measured by acceleration sensors (eventually velocity, or vibration amplitude) placed in different places on rail, sleepers and rail fixations. Piezoelectric acceleration sensors are often applied to these measurements for their exquisite characteristics (precious linearity, large dynamic range). Sometime other situation is at measuring some shock waves and some propagation vibrations from superstructure into gravely layer. At study of vibration events it is necessary to the acceleration sensors mount directly into gravely layer spaces so that transmission of vibrations from superstructure to sensors was sufficient and the sensor was not damaged.

DESCRIPTION OF MEASURING STONE

In [4] there was designed and created so-called measuring stone, which is comparable by shape as well as by size with stones of gravely bedding. The acceleration sensor has been stacked into it. Then the measuring stone is possible to fit into gravely layer safe damage the sensor. At installation of the measuring stone it is necessary to respect so that the structure of the gravely layer was disturbed as least as possible it is. So it is possible to respect the measuring stone was well wedged among surrounded grains of the gravely bedding. After consummating trial tests the kind rock wacko was chosen for production of the measuring stone. That appears as optimal with respect to material properties. It is sedimentary rock dark grey till black colour, psamitic fraction creation by grains crystal, spar and fragment rock with as much as 20 per cent rate of clayey-silt matrix. It is rock used relatively often in building practice. By its property it is applicable for preparation of crushed aggregate required faction and suitable formative index for aggregate used in construction of railway's gravely bedding. In required cases it is possible for productions of measuring stone to use also further rock kinds e.g. granule, basalt, eventually other. After selection of acceptable specimens and its subsequent forming, it was bored into specimens a hole such as diameter, so as the accelerometer sensor has been possible insert and wedge into its. Three-axis accelerometer type 4506 of firm Bruel & Kjear was installed there. The hole was enclosure by aluminise bungs with bushing on bring out measuring cable. The measuring cable is protected at installation into gravely measures before damage of steel protector (so-called steel "gooseneck").

ANALYSES OF MEASURED SIGNALS

For transposition of the time domain into the frequency one then there is mostly used Fourier Transform (FT) [3], which is defined for a continuous function by the integrate equation as direct and inverse transformation. Because there is elaborated on the discrete sequence thus it is necessary to modify the integrating equations into the following relations

$$X_k = \frac{1}{N}\sum_{n=0}^{N-1} x_n \cdot e^{-j(\frac{2\pi kn}{N})} \quad \text{and} \quad x_n = \sum_{k=0}^{N-1} X_k \cdot e^{j(\frac{2\pi kn}{N})}, \tag{1}$$

where x_n is the value of the n^{th} element of the discrete sequence (time $t = n\cdot\Delta t$), X_k is the k^{th} frequency element of the signal, N is the number of the elements of the analysed sequence and j is the imaginary value. The evaluation of signals is carried out by the way of computing the power spectral density (PSD) $S(f)$. There is mostly used FT to determination of PSD.

$$S(f_n) = k\frac{2\Delta t}{N}\left|X(f_n)\right|^2 \quad \text{for} \quad n = 0,1,\ldots,\frac{N}{2}, \tag{2}$$

where t is the time step, N is the length of the sequence, f_n is the n^{th} frequency, $\left(f_n = \frac{n}{N\Delta t}\right)$, k is the coefficient for recalculation of physical values, the coefficients of apparatus and et cetera. According to the FT there was derived Short Time Fourier Transform (STFT), which can localise the frequency elements within constant (linear) difference of time. This transformation behoves into big class of linear methods.

The idea of the STFT it is to split non-stationary signal into fractions within them stationary assumptions are applied and on each of these fractions is carried out FT. The STFT is defined by equation (2) [4, 5]:

$$STFT_X^{(\omega)}(t', f) = \int_{-\infty}^{\infty}[x(t)\cdot g^*(t-t')]\cdot e^{-j2\pi f(t-t')}\cdot dt, \tag{3}$$

where '*' denotes the complex conjugate, g is the short time window, $x(t)$ is the signal, t' is the time location parameter, f is frequency and t is time. In the two dimensional time-frequency joint representation, the vertical stripes of the complex valued STFT coefficients $STFT_x^{(\omega)}(t', f)$ correspond to the Fourier spectra of the windowed signal with the window shifted to given times t'.

The next applied method for signal analysis is Page Transform [1, 2] defined as

$$C_x(t,\omega;\psi) = \left(\frac{1}{2\cdot\pi}\right)^2 \cdot \iiint e^{-j\cdot\theta\cdot t - j\cdot\tau\cdot\omega + j\cdot\theta\cdot u} \cdot e^{\frac{j\cdot\theta\cdot|\tau|}{2}} \cdot x\left(t+\frac{\tau}{2}\right)\cdot x^*\left(t-\frac{\tau}{2}\right)\cdot du\cdot d\tau\cdot d\theta \tag{4}$$

where x is the signal, t is the time, τ is the time location parameter, ω is angular frequency, θ is shift frequency parameter, parameter σ controls the cut off frequency of the filter. A distribution $C_x(t,\omega, \psi)$ can be interpreted as the two-dimensional FT of a weighted version of the ambiguity function of the signal

$$C_x(t,\omega) = \frac{1}{2\cdot\pi} \cdot \iint A_x(\theta,\tau) \cdot \psi(\theta,\tau) \cdot e^{-j\cdot\tau\cdot\omega} \cdot e^{j\cdot\theta\cdot t} \cdot d\tau \cdot d\theta \,, \tag{5}$$

where $A_x(\theta, \tau)$ is the ambiguity function of the signal $x(t)$, given by equation

$$A(\theta,\tau) = \int x\left(t + \frac{\tau}{2}\right) \cdot x^*\left(t - \frac{\tau}{2}\right) \cdot e^{j\cdot\theta\cdot t} \,. \tag{6}$$

We note that all integrals run from $-\infty$ to ∞. The weighted function $\psi(\theta, \tau)$ is called the kernel. It determines the specific properties of the distribution. The product $A_x(\theta, \tau)\cdot\psi(\theta, \tau)$ is known as the characteristic function. Since the ambiguity function is a bilinear function of the signal, it exhibits cross components, which, if allowed to pass into time frequency distribution, can reduce auto-component resolution, obscure the true signal feature, and makes interpretation of the distribution difficulties.

Therefore, the kernel is often selected to weight the ambiguity function such that the auto-components, which are centred at the origin of the (θ, τ) ambiguity plane, are passed, while the cross-components, which are located away from origin, are suppressed. That is, in order to suppress cross-components $\psi(\theta, \tau)$ should be the frequency response of a two-dimensional low-pass filter. When a low pass kernel is employed, there is a trade-off between cross-components suppression and auto-component concentration. Generally, as the pass-band region of the kernel is made smaller, the amount of cross-component suppression increases, but at the expense of auto-component concentration [5].

LABORATORY MEASUREMENT

The measured stone was firstly tested in laboratory conditions. A wooden box dimension bases 1 m x 1 m and high 0.8 m was created to this end. That was stiffened in lower part and on side parts by the iron brace rod and wrapping. Gravel ballast about high 0.4 m with specimens of track span grate was simulated in creation box by this way. The Sample track grate was made from part of wooden sleeper. The sample of rail constructional shape S 49 with the help of classical robust fixation with wedge-shaped ribbed turtle S 4 was mounted on its. The test of measuring stone was realised by measuring of responses on a mechanical shock. The shock was generated by 2-Kg weight ball.

This ball was lowered from high 1 m per railhead. The response of mechanical stroke was measured by vibration measuring system. The sampling frequency was chosen 40 Hz. The measuring frequency range was selected from 1 Hz to 20 Hz, because pick-up higher frequency of spectral power density is not important from viewpoints of railway's construction stress. Response analyses on mechanical shock were made by several choice methods as in time and frequency domain so also in time frequency domain. From linear time-frequency procedures there was tested by STFT. From group of non-linear time frequency analysis there was used especially Page Distribution.

In Fig. 1 (upper diagram) there are shown time-bound executions of immediate values of acceleration measured by measuring stone. The frequency spectrum of execution of the acceleration is shown in Fig. 1 (left diagrams). On intermediate diagrams (Fig. 1) it is shown the power spectrum calculated stepwise by the STFT. Accordingly, on intermediate diagrams (Fig. 2) it is shown the power spectrum calculated by the Page Distribution. This method presents a very suitable transformation giving perfect distinction in time and frequency areas.

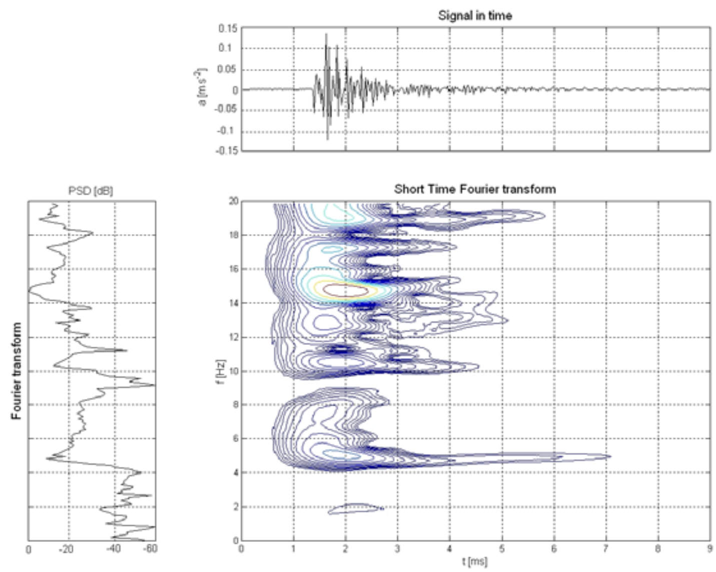

Fig. 1 *Laboratory measurement – time history of signal since measuring stone, frequency spectrum of power spectral density and time-frequency image of Short time Fourier transform*

FIELDWORK

The test measuring was realised in direct track section between Czech towns Cesky Brod and Poricany. On this track there is installed railway's superstructure with rail UIC 60, concrete sleeper type B91 and rail fixation Vossloh SKL 14. During testing procedure the measured stone was set under sleeper at fixation point of rail in depths about 15 cm below bottom border of sleeper. It was find out that acceleration values in vertical direction of a order exceed value in horizontal plane. For these reasons next analysis was restricted only on vertical direction. The analysis of measured signal was realised several chosen methods as in the time and frequency so also in time-frequency domain.

From linear time-frequency procedures there was tested by STFT. From group of non-linear time

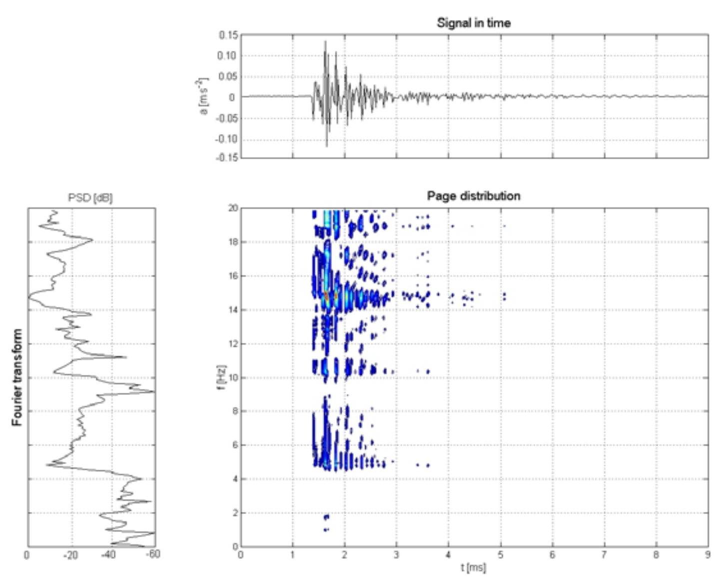

Fig. 2 *Laboratory measurement - time history of signal since measuring stone, frequency spectrum of power spectral density and time-frequency image of Page distribution*

frequency analysis there was used especially Page Distribution. In the next part of the article there are presented the results of measuring and analyses of acquired at the passage train set Eurocity Dvorak at speed 100 km·h^{-1}.

In Fig. 3 (upper diagram) there is shown time-bound executions of immediate values of acceleration measured by the measuring stone. The frequency spectrum of execution of the acceleration in the gravel railway-bed is shown in Fig. 3, left diagram. On intermediate diagram (Fig. 3) it is shown the power spectrum acquired from the time execution according with Fig. 3 (upper diagram) using the Page Distribution.

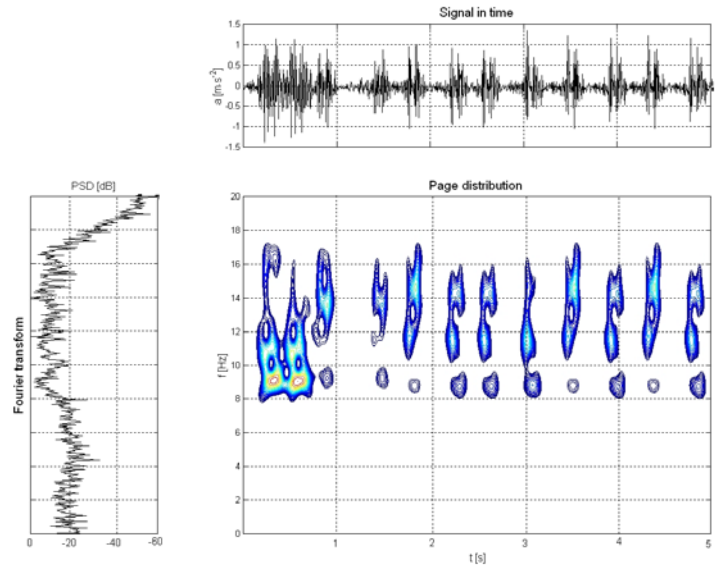

Fig. 3 *Fieldwork - time history of signal since measuring stone, frequency spectrum of power spectral density and time-frequency image of Page distribution*

RESULT

In conclusion of the article it is possible to submit pursuant to ex post measuring and their analyses, the measuring stones well enable location of vibration level in any places in bottoming of railway's or tramway track. They provide the significant tools for acquisition of important information about diffusion of vibration waves in bottoming at passage of track vehicles. Knowledge of the acceleration amplitudes in dependent on frequency and especially knowledge of the time-frequency characteristics of acceleration enable they complete analyses behaviour bottoming of construction track and also railway's superstructure in different traffic load and building conditions. Advantage knowledge is possible further to make especially for composition mathematical models of railway's constructions and for development of new structural designs, which in consequence, make for optimisation track constructions. This fact puts on of meaning namely at development and traffic of high-speed tracks.

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