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Analysis of dynamic parameters of rail fastening by Rihaczek transformation

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Summary

For evaluation of response signals obtained by rail fastening analysis a new method using time and frequency related transformations has been developed. In the paper the laboratory measurements and dynamic parameter analyses of flexible fastening of Vossloh SKL14 type have been described. The method can also be used for designing new rail fastening systems and their parts.

KEYWORDS: Rail fastening, dynamic test, time frequency transform

1. INTRODUCTION

The basis for the selection and comparison of new components of rail superstructure are also theoretical analysis (simulation) and static and dynamic tests carried out in the laboratory and in the field (directly on the railway) [9]. It is necessary to mention that theoretical analysis of application of mathematical simulation is often based on idealized assumptions. Hence, when the real conditions on the railway or tramway superstructure are encountered, the model may be inaccurate.

For testing the railway superstructure construction, different methods and different criterions were applied. Dynamic testing [4] often uses the method of exciting the structure by mechanical shock. Exciting by shock is useful for the setting up a given set of frequencies as the shock, according to the theory, stimulates all frequencies, mainly resonant. Mechanical shock is often stimulated by a special hammer, which has an incorporated power sensor in radial direction to the railhead.

The response is measured by accelerometer sensors at different points of the rail structure (rail foot, clip plate, clamp, sleeper etc). This method makes it possible to record frequency components in the range 1 Hz to 10 kHz. Recorded data are often recalculated and presented in the form of the frequency transfer function. This shows important frequency components (mainly resonant) that include information about dynamic properties of particular parts of tested structure.

Often in the experimental investigation of dynamic properties [5] of rail fastening, the measurement and calculation of the transfer function is called accelerance (inverse function of dynamic weight). It is for that reason that the acceleration transducer is the most suitable electromechanical measurement device for the measuring of oscillation. Accelerance is defined by the relation

$$H_{aF}(f)=\frac{S_{aF}(f)}{S_{FF}(f)} \tag{1}$$

where $S_{aF}(f)$ is cross spectrum of response and entry signal, S_{FF} is auto-spectrum of entry signal. From the relation (1) it can be seen that measured acceleration is standardized for power measured during the shock.

In spite of the advantages, it is not possible to localize the time behavior of frequency components included in the signal. Therefore for the evaluation of response signals when analyzing the rails fastenings, the authors supplemented the methods of the measurements by utilizing progressive processes of signal analysis, i.e. by utilizing time frequency transformations.

One possible procedure to analyze time occurrence of frequency components of transfer and non-stationary signals, is the use of the so-called time frequency proceedings (transformations). These can be distributed according to two basic groups [3]:

- linear (including mainly Short Time Fourier Transformation, Wavelet Transformation etc.)
- non-linear (including mainly quadratic Cohen Transformations, Affine and Hyperbolic Transformation, eventually further special proceedings)

2. THEORY OF TIME FREQUENCY ANALYSIS

Given a time series, x(t), it can readily be seen how the “energy” of the signal is distributed in time. By performing a Fourier transform to obtain the spectrum, X (ω), it can also be seen how the “energy” of the signal is distributed in frequency. For a stationary signal, there is usually no need to go beyond the time or frequency domains. However, most real world signals have characteristics that change over time, and the individual domains of time and frequency do not provide a means for extracting this information. The general goal of this contribution is to demonstrate some lesser-known methods for creating functions that represent the energy of the signal simultaneously in time and frequency.

Example of linear time-frequency distributions is the Short Time Fourier Transformation. The main idea of the Short Time Fourier Transform (STFT) is to split a non-stationary signal into fractions within which stationary assumptions apply and to carry out a Fourier transform on each of these fractions. The STFT is defined by equation [3, 4]

$$STFT(\tau, f) = \int_{-\infty}^{\infty} [x(t) \cdot g^*(t-\tau)] \cdot e^{-j \cdot 2 \cdot \pi \cdot f \cdot t} \cdot dt \qquad (2)$$

where '*' denotes the complex conjugate, g is the short time window, $x(t)$ is the signal, τ 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(τ, f) correspond to the Fourier spectra of the windowed signal with the window shifted to given times τ. The main disadvantage of linear time-frequency transform is that the time frequency resolution is limited to the Heisenberg bound. This is due to the imposition of local time window $g(t)$. If this window is more resolved in time, the frequency resolution suffers because the effective width of its Fourier transform $G(f)$ increases, and vice-versa.

Quadratic (non-linear) methods present the second fundamental class of time frequency distributions. Quadratic methods are based upon estimating an instantaneous power (or energy) spectrum using a bilinear operation on the signal $x(t)$ itself. The class of all quadratic time-frequency distributions to time shifts and frequency-shift is called Cohen's class. Similarly, the class of all quadratic time-frequency distributions covariant to time-shift and scales is called the Affine class. The intersection of these two classes contains time-frequency distributions, like the Wigner-Ville distribution, that are covariant to all operators.

Cohen [1] generalized the definition of the time frequency distributions in such a way as to include a wide variety of different distributions. These different distributions can be represented in several ways. Cohen's class definition like the Fourier Transformation, with respect to τ, of the generalized local correlation function is most common. With a two-dimensional kernel, the bilinear time frequency distribution of the Cohen´s class is defined according to equation [2]:

$$C_x(t,f) = \iiint e^{-j \cdot 2\pi \cdot \theta \cdot t' - j \cdot 2\pi \cdot f \cdot \tau \cdot + j \cdot 2\pi \cdot \theta \cdot t} \cdot \psi(\theta,\tau) \cdot x\left(t+\frac{\tau}{2}\right) \cdot x^*\left(t-\frac{\tau}{2}\right) \cdot d\theta \cdot dt \cdot d\tau \quad (3)$$

where x is the signal, t (t') is the time, τ is the time location parameter, ω is angular frequency, θ is shift frequency parameter, $\psi(\theta, \tau)$ is called the kernel of the time frequency distribution. A distribution C_x (t, f) from Cohen's class can be interpreted as the two-dimensional Fourier Transformation of a weighted version of the ambiguity function of the signal

$$C_x(t,f)=\iint A_x(\theta,\tau)\cdot\psi(\theta,\tau)\cdot e^{-j\cdot 2\pi\cdot f\cdot\tau}\cdot e^{-j\cdot 2\pi\cdot\theta\cdot t}\cdot d\tau\cdot d\theta \tag{4}$$

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

$$A(\theta,\tau)=\int x\left(t+\frac{\tau}{2}\right)\cdot x^*\left(t-\frac{\tau}{2}\right)\cdot e^{-j\cdot\theta\cdot t}\cdot dt \tag{5}$$

We note that all integrals run from -∞ 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 make interpretation of the distribution difficult. Therefore, the kernel is often selected to weight the ambiguity function such that the auto-components, which are centered at the origin of the $(\theta,\ \tau)$ ambiguity plane, are passed, while the cross-components, which are located away from origin, are suppressed. This means that the suppression of cross-components might be understood as 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 band-pass region of the kernel is made smaller, the amount of cross-component suppression increases, but at the expense of auto-component concentration. There is definition of the kernel for Rihaczek Transformation in equation 6

$$\psi(\theta,\tau)=e^{\frac{j\cdot\theta\cdot\tau}{2}}. \tag{6}$$

Equation 4 can also be rewritten into the following form [5]

$$C_x(t,f)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Pi(\tau-t,\theta-f)\cdot WVT(\tau,\theta)\cdot d\tau\cdot d\theta \tag{7}$$

where

$$\Pi(t,f)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\psi(\theta,\tau)\cdot e^{-j\cdot 2\cdot\pi\cdot(f\cdot\tau-\theta\cdot t)}\cdot dt\cdot d\omega \tag{8}$$

is the two-dimensional Fourier transform of the kernel ψ and WVT presents Wigner-Ville transform. Cohen's class has a simple interpretation as a smoothed Wigner-Ville distribution [5].

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3. ANALYSIS OF DYNAMIC PARAMETERS

The model used for laboratory measurements and analysis of dynamic parameters of a sample of rail fastening is presented below. The rail grid model was constructed of concrete sleepers B 91, on which there were fastened rails of construction shape UIC 60 by flexible fastening Vossloh SKL14.

For the testing of the dynamic properties of the sample, the method of measuring the response to mechanical shock was used. Mechanical shock was stimulated by a special hammer in the radial direction on the railhead. A part of this hammer is a force detector.

The response was measured by accelerometers at different points of the rail structure, on the rail foot and sleepers (10 cm from fastening). Figure 1 show the location of detectors. From the response time signals frequency transfer functions (accelerance) were calculated in order to obtain standardized responses [5].

Figure 1 General view of the working place

Signals from measurements on the rail and sleepers were used for the presentation of particular analyses in this contribution. The measuring system consisted of a Brüel and Kjaer PULSE modular analyses for recording the vibration parameters together with B&k cubic acceleration detector and a B&k shock stimulation hammer (Figure 1).

ISSN 1582-3024

The accelerometers were fastened to the measured construction by means of bee wax. The results were recorded digitally.

The analysis of the response to mechanical shock was evaluated by means of the following methods and parameters [5]:

- Time records of the duration of impulse response function (in principle standardized acceleration value)
- Frequency analysis with the use of frequency response function (according to equation 1)
- Time-frequency method of spectral analysis (for the transfer from time to time- frequency domain, the algorithm of Short Time Fourier Transformation and Rihaczek Transformation was used)

Time histories of the impulse response function, recorded by accelerometers, located on the rail foot, are depicted on the upper graph of Figure 2. The maximum positive value of acceleration of 300 $m \cdot s^{-2}$ is reached 1 ms from the observed beginning. The maximum negative value of acceleration of -300 $m \cdot s^{-2}$ is reached 2 ms from the beginning. Damping of the signal from the acceleration 300 $m \cdot s^{-2}$ to the acceleration lower than 30 $m \cdot s^{-2}$ took 15 ms.

In the left graph of Figure 2 is depicted the amplitude spectrum of this frequency response function calculated according to equation 1. In the graph, six important frequencies (0.2 kHz, 0.7 kHz, 1.9 kHz, 2.4 kHz, 3.3 kHz and 3.7 kHz), are visible. The important values are taken as those which have the damping up to 20 dB from the maximum value of amplitude spectrum.

Time frequency amplitude spectrum estimated by application of Short Time Fourier Transformation to the impulse response function is depicted in the middle graph in Figure 2. As shown on this graph, the time history of important frequency components essentially differ.

Frequency component 1.9 kHz reaches the highest values for a relatively long time (compared to other frequency components). It appears in the signal nearly in its full history, i.e. approximately 40 ms by damping up to 40 dB. The second most important component is the frequency 3.3 kHz. This appears in signal up to the time of 20 ms from the above. Other notable frequencies 2.4 kHz and 3.7 kHz are in the signal for the time of 5 ms up to 15 ms.

Similar conclusions are visible from the middle graph of Figure 3, which present the analysis of impulse response function on the rail foot by the use of Rihaczek Transformation. This transform belong to the category of non-linear time frequency proceedings from the Cohen class.

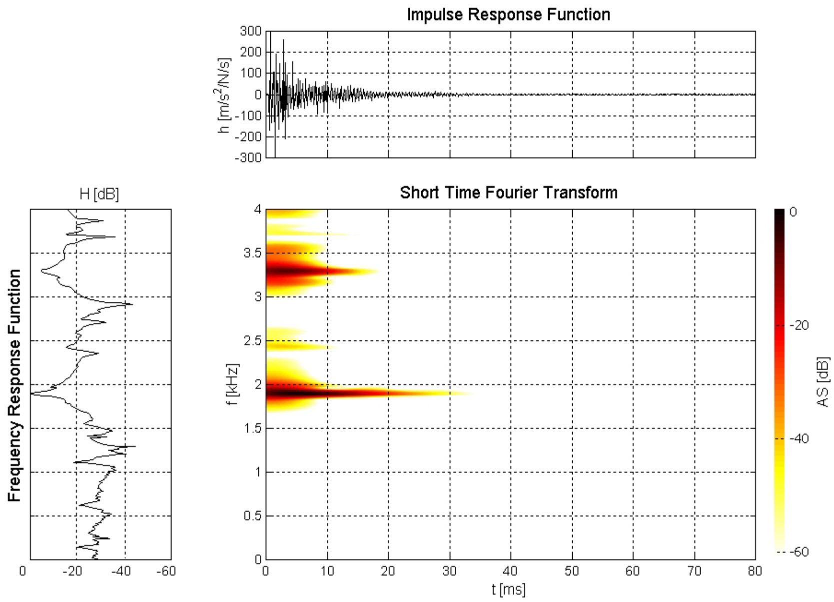

Figure 2 Accelerometric detector located on the rail foot, time frequency analysis by Short Time Fourier Transformation

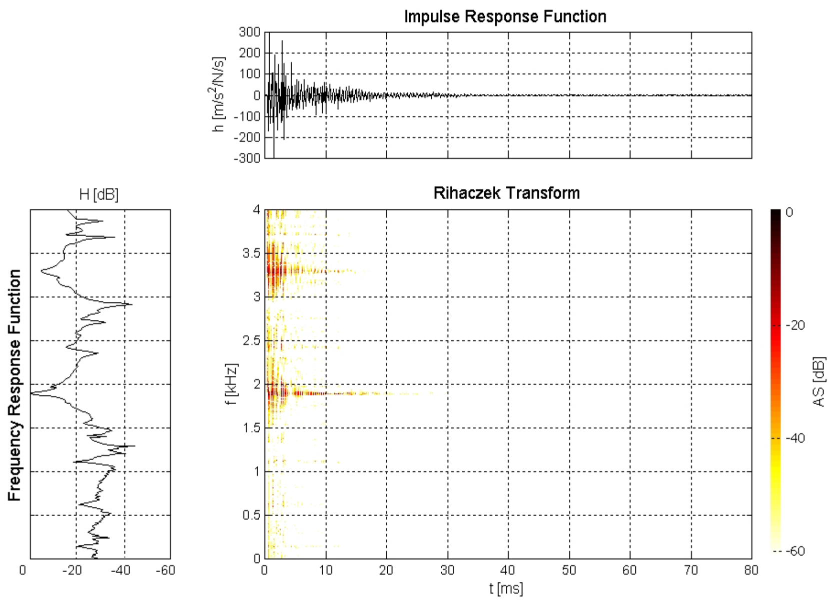

Figure 3 Accelerometric detector located on the rail foot, time frequency analysis by Rihaczek Transformation

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Signals (impulse response function) taken by a second transducer, located on the concrete sleeper, have different character. From the time record (see upper graph of Figure 4) it is apparent that the maximum impulse response function amplitude acquires lower frequency values as a result of the influence of the transformation of the signal through the fastening of rail, clip plate, sleeper to the accelerometer and reaches values of 50 m·s^{-2}. These values were reached 2 ms from the first rise time from "amplitude pack". Values of acceleration are considerably lower than those by the transducer located on the rail foot which was located nearer to the source of mechanical impulse.

In the left graph of Figure 4 is depicted the amplitude spectrum of frequency response function. The form of spectrum considerably differs from the characteristics measured by the first transducer located on the rail foot. The most important components appear in the lower frequencies from the transducer located on the rail foot: in the interval of 0.2 kHz up to 2 kHz, there are also more in number.

Similar conclusions are given by the middle graph of Figure 4 which presents the time frequency amplitude spectrum estimated by the application of the Short Time Fourier Transformation. From this graph it can be seen that time occurrence of significant components included in signal is considerably shorter (the longest is approx. 20 ms from the imaginary beginning) than it is from the signal from transducer located on the rail foot.

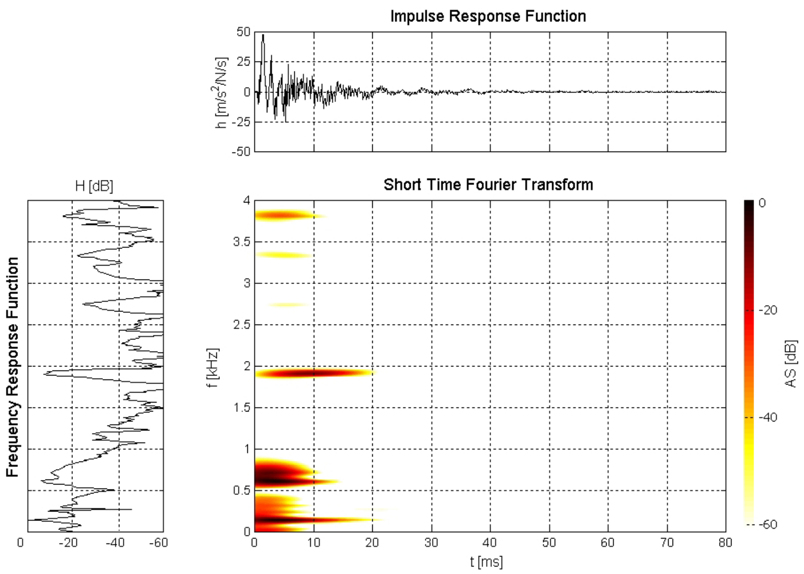

Figure 4 Accelerometric detector located on concrete sleeper, time frequency analysis by Short Time Fourier Transformation

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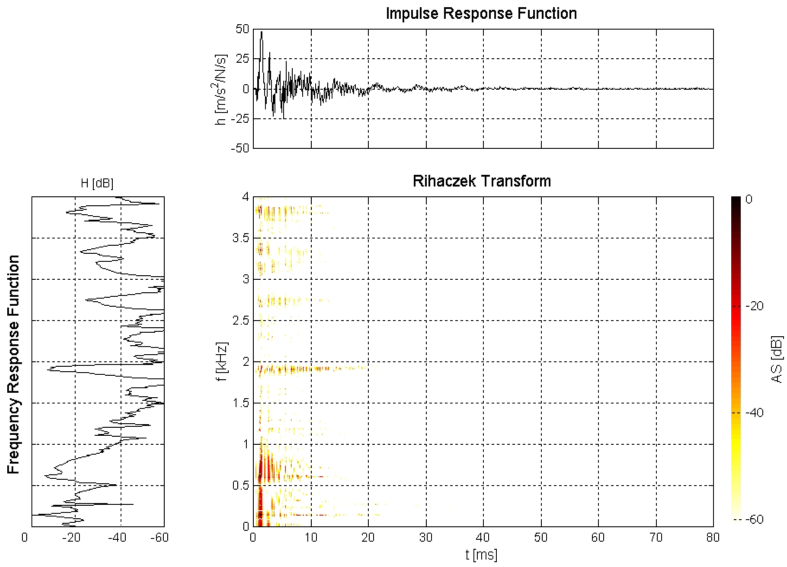

Figure 5 Accelerometric detector located on concrete sleeper, time frequency analysis by Rihaczek Transformation

Similar conclusions apply to the middle graphs of Figure 5 which present the analysis of signals from transducers located on the sleeper by the use of Rihaczek Transformation. The significant frequency components which are calculated by the Rihaczek Transformation (Figure 6) are frequencies of 0.2 kHz, 0.7 kHz, 1.9 kHz, 2.7 kHz, 3.2 kHz, 3.4 kHz and 3.7 kHz. The most significant spectrum component is the frequency component 0.2 kHz which appears within this spectrum for a relatively long time in relation to the activity of other components.

On the whole, it is possible to state from the middle graphs in Figure 2 to Figure 5 that in contrast to linear methods whose ability to resolve the frequency elements in the time region is limited by certain window functions, quadratic methods can achieve this objective. Higher distinguishing makes more favorable localization of significant frequency components in time possible.

The quality of time and frequency achieved by measuring the signal response to mechanical shock and applying by these transformations is a good choice.

4. CONCLUSIONS

Based on measurements and analyses, it is possible to state that the methods presented above are very good for the measurement of dynamic parameters of rail fastenings. The use of these methods enables the testing of new types of rail fastenings and different types of rail washers under rails and the opportunity to optimize the geometric location of damping elements on rail etc. From the mathematical means of signal analysis it is possible to utilize both Short Time Fourier Transformation and Rihaczek Transformation for time-localization of the occurrence of frequency elements of stationary and non-stationary signals.

Based on the experience acquired, it is of great advantage for the analysis of real signals to utilize the properly selected time and frequency sections. This procedure seems to be more suitable than the spatial arrangement. It is possible for more precise localization of time records to separate significant frequency components or to depict all important frequencies. Analysis of signals, acquired by measurement and analysis of response to mechanical shock gives new, more detailed insights to transition characteristics of railway and tramway structures. Hence, it grants valuable knowledge for a thorough analysis of these constructions, which can be important for consequent optimization of construction and operational conditions. Also the fact that by time frequency proceedings analysis of dynamic load of railway and tramway constructions provides real data for consequent formulation of mathematical models. From this point of view, both linear and non-linear time frequency transformations are applicable. These methods give a fast and accurate localization of frequency components included in the measured signal. It is possible to apply the described method successfully not only on samples of several constructions of railway and tramway superstructure but also directly in the field on real tracks.

Acknowledgements

This research has been supported by the research project 103/07/0183 ("The investigation of dynamic effects due to the rail transport by the method of quadratic time and frequency invariant transformations ") and by research project MSM 0021630519 ("Progressive reliable and durable load-bearing structural constructions")

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