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The Analysis of Dynamic Effects in the Exchange Part of Turnouts

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Abstract. This paper deals with description and application of the modified Wigner-Villa's transformation for dynamic analysis. The use in the field of railway constructions testing represents a quite interesting application area of the transformation. This paper contains mathematical description of the technique, a case study from area of railway turnout's dynamic analysis and practical experience obtained and recommendations for its practical use. The described analysis is focused on dynamic processes in the exchange area of turnouts and their comparison with dynamic processes in the frog part of the turnouts.

Introduction

The basic claim for the particular parts of the railway track is their functional reliability and the safety of the interconnected railway operation. Although the superstructure has been developed to almost perfection during more than 150 years of the railway history, it is still possible to find new technical solutions. This especially applies to various types of turnout structures, various rail fastenings, various types of rail pads, sleepers etc.

Permanent pressure to increase the transport speed and the operational load on the railway resulted in huge development of new technologies. The decision on modernization of the corridors became the impulse for development of all areas of the railway transport, either in the area of vehicles and infrastructure. In conformity with the above-mentioned trend, application of new experimental processes should continue for evaluation of the quality and suitability of individual constructional solutions [1].

The level of dynamic effects in the railway superstructure are influenced by its quality, operational and technical conditions, and climatic events and, most importantly by dynamic load on the railway vehicle axle. The fact also relates to construction of the railway turnouts representing the key points of the railway roads [2].

The railway turnout structures represent one of the key points of the railway transport. Therefore it is necessary to pay a special attention to these structures. The turnout structure consists of a number of structural components of different properties which in summary must fulfil the required functions. Among the most important properties is especially their reliability and safety within the framework of the railway operation. In accordance to this trend, the development and application of new experimental procedures for assessing the quality and effectiveness of individual design solutions must also proceed.

A classic simple turnout consists of three main parts - a frog part, a middle part and an exchange (Fig. 1). The frog part consists of a frog, a retainer and an outer rail. There is a crossing of rails and separation of rails in two different directions. The frog forms the place where the wheel passes a gap (depression) for the wheel rim of the vehicle, which moves in another direction. In order to avoid an impact or climbing of the flange on the tip of the frog, the second wheel of the same wheelset is guided by a retaining device, which does not allow it to move away from the outer rail.

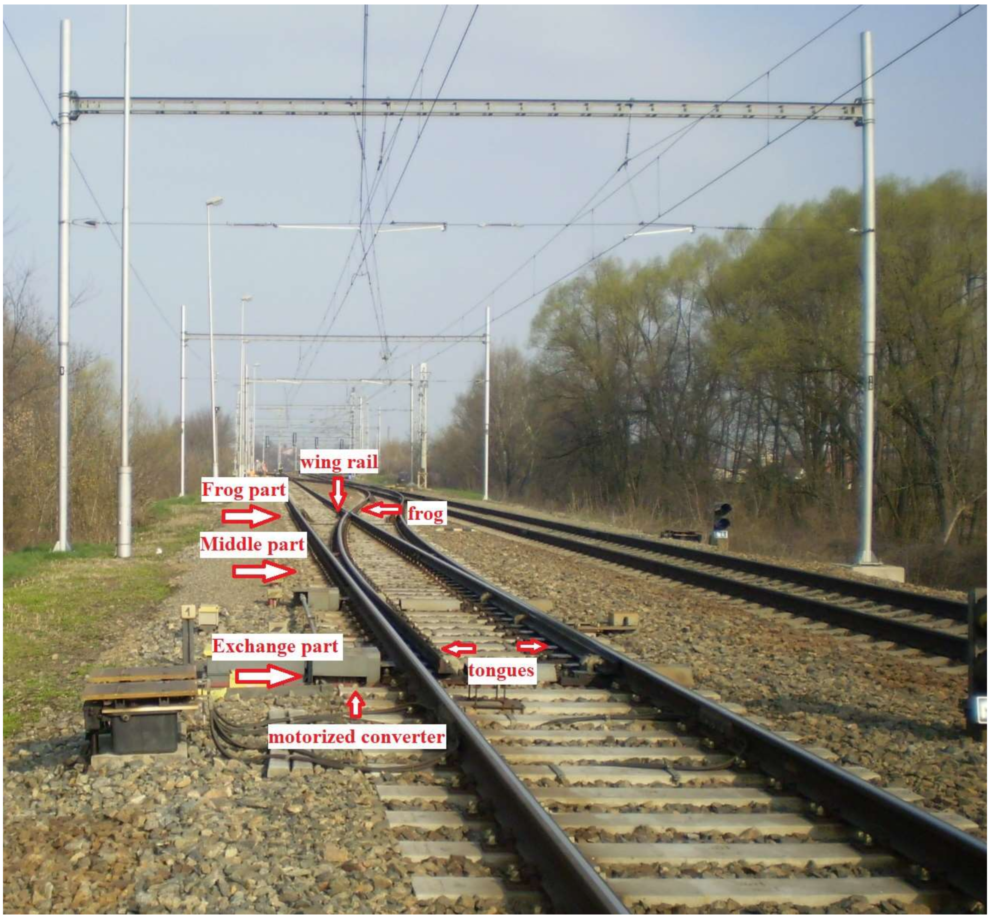

Fig. 1 The picture of a turnout with a description of the most important parts

The middle part of the turnout actually forms a tangle of tracks. It connects the exchange and the frog part. The interchange is a moving part of the turnout, on which the track branches in two directions. The main parts of the exchange consist of tongues, supports and a turnout. The tongue forms the only moving structure of the carriageway. The position of the tongues determines the direction of further movement of the train set while driving. The tongues are usually stored on stool bases. Under normal circumstances, one tongue always rests on the support. A motorized converter is used to adjust the tongues. To secure them in the appropriate position there is an exchange lock. From the above, it is clear that especially the frog and exchange part belong to the key parts of turnouts in terms of dynamic effects. Let us now briefly consider the dynamic processes in both areas.

High dynamic forces can be expected in the area of the transition of the train set wheel from the wing rail to the tip of the heart, where, depending on the quality of the geometry of the transition, a dynamic impact occurs [3].

After the impact of the wheel, vibrational energy propagates downwards from the surface of the heart to the relatively rigid base and sleepers on which the heart is mounted, then the vibrational energy is transferred from the sleeper to the gravel bed. A small part of the energy is captured by the internal damping of the frog itself, another small part is captured by the base and the pad under the tip of the heart, the pad under the base and also the sleeper. Due to the fact that the whole system is relatively rigid, a large part is transferred to the gravel bed and subsoil. Here, the sharp edges of the gravel bed are stressed and they begin to abrade. The resulting fine-grained parts adversely affect the cohesion of the grains and free spaces begin to form under the sleeper. If the turnout is not sufficiently supported, the geometry of the transition from the wing rail to the tip of the heart will collapse and the whole process of degradation will be greatly accelerated.

From theoretical assumptions and computer simulations [4], it is concluded that another area requiring increased attention is the exchange area. The mechanism of vibration transmission in the exchange part is similar to that in the frog area, assuming lower vibration values. This is due to the uninterrupted running surface of the rail, when the ankle gradually approaches and rests on the tongue rail. The intensity of vibrations is damped by the rail grate, when a small part is damped already in the rail and its rubber pad. Further vibration damping occurs in the sleeper. The undamped component of the vibration energy is also transferred to the gravel bed. The question is how much of this energy is compared to the energy propagating in the frog area.

Wigner-Villa's transformation

Wigner´s distribution was proposed in 1932 by Professor Wigner in the field of quantum physics and about 15 years later, it was adapted for the area of signal analysis by the French scientist Ville. Wigner-Villa's transformation is defined for the time-frequency domain by relation [5]

$$WVT_x(t,f) = \int_{-\infty}^{\infty} x\left(t+\frac{\tau}{2}\right) \cdot x^*\left(t-\frac{\tau}{2}\right) \cdot e^{(-j\cdot 2\cdot \pi \cdot f \cdot \tau)} \cdot d\tau \,, \tag{1}$$

where '*' represents a complex conjunction, t is time, f is frequency, τ is shift along the time axis, x is time representation of the signal $x(t)$ and $WVT_x(t,f)$ is a time-frequency representation of the input signal. The equation (1) shows that it is essentially the Fourier transformation of relation $x(t+\tau/2)\cdot x^*(t-\tau/2)$, so the functions $x(\tau/2)$ and the complex conjugate of $x^*(-\tau/2)$ at some point in time t. From the equation (1) it is also apparent that the Wigner-Villa's transformation is a complex function in the time-frequency space. Another interpretation of equation (1) shows that this transformation can be interpreted as a combination of the autocorrelation function [6]

$$C(t,\tau) = x\left(t+\frac{\tau}{2}\right) \cdot x^*\left(t-\frac{\tau}{2}\right) \tag{2}$$

and Fourier transformation

$$WVT_x(t,f) = \int_{-\infty}^{\infty} C(\tau) \cdot e^{(-j\cdot 2\cdot \pi \cdot f \cdot \tau)} \cdot d\tau \,. \tag{3}$$

Unlike for example the Short time Fourier method, in which the resolution is limited by window function, Wigner´s-Villa's spectrum provides good resolution both in frequency and in time domain. The important feature here is that the calculation is not limited by Heisenberg uncertainty principle. Although the calculation of the coefficients of Wigner-Villa's transformation is not limited by Heisenberg's uncertainty principle, certain problems may arise in calculating multicomponent signal, which is generated by the sum of two or more signals [7, 8].

In principle, there are two reasons to modify the basic properties of Wigner-Villa's transformation. The first reason is that in practice it is not possible to integrate from -∞ to +-∞, but the calculation can be carried out only for a limited signals. The second reason is to try to eliminate the effect of cross-components, which often oscillate heavily. Restrictions of both problems can be achieved by calculating the modified of Wigner-Villa's transformation (often called pseudo or smoothed) by equation [9]

$$PWVT_x(t,f)=\int_{-\infty}^{\infty} h(\tau)\cdot x\left(t+\frac{\tau}{2}\right)\cdot x^*\left(t-\frac{\tau}{2}\right)\cdot e^{(-j\cdot 2\cdot\pi\cdot f\cdot\tau)}\cdot d\tau \tag{4}$$

where the function $h(\tau)$ is a window function with maximum at $\tau = 0$. A Gaussian curve is often used as the function $h(\tau)$. Such a solution quite effectively suppresses interference (smoothes), but deteriorates resolution. Smoothed Wigner-Villa's transformation is therefore a certain compromise between smoothing and resolution [10].

Case study

To compare the dynamic effects in the exchange and the heart section, turnout No. 59 (Fig. 2) was selected in the so-called Pardubice head of the Choceň railway station with a left turn direction (turnout designed for a speed of 80 km·h^{-1}). The selected turnout is of type J60-1:14-760-zlp,L,p,ČZP,b,KS,ZPT. Trainsets may pass through this turnout in a straight line at a line speed of 160 km·h^{-1}. The turnout is equipped with a system of railway superstructure UIC 60 with Vossloh Skl 24 fastening and concrete sleepers.

A measurement methodology certified by the Ministry of Transport was used to measure the dynamic effects acting on the turnout [11]. This methodology consists of three parts. The first involves measuring the motion behaviour of a structure. The second area includes the propagation of vibrations around the frog and the exchange of turnouts and especially the effects of vibrations on the gravel bed. In the third one, the measurement of force is performed.

In total, two basic measuring areas with 3 measuring points were set in the measured turnout, to which acceleration sensors were attached (A4 - rail, A7 - sleeper and A0 - gravel ballast). The vibrations in the gravel bed were measured by an acceleration sensor placed on the rod (it served as a waveguide) implemented in the gravel bed. In the exchange part, the sensors were placed on the heel of the support, then on the sleeper in the area of the passage of the ankle from the support to the tongue rail and measuring rod, which was embedded in the gravel bed near the passage of the wheel. Simultaneously with the measurement of vibration characteristics, a large number of other parameters were measured. Their comparison and analysis is not part of this paper.

Fig. 2: The view of frog (left) and exchange (on the right) part of turnout

Autonomous S-Box dataloggers developed at the authors' workplace were used for the measurements. As part of the measurement campaign, the passage of a total of 30 trains was recorded, for which, in addition to the time course of vibration acceleration, their other parameters were also recorded - travel time, running speed, number of cars, and type of locomotive and direction of travel. For their own evaluation, these trains were divided into suitable categories. Note that these characteristics were determined by the measuring system itself. From the measured records, the basic vibration characteristics, ie the effective value of the acceleration a_{ef} and the amplitude spectra for the individual train categories, were calculated for each measured point and each position of the acceleration sensor. A table and basic graphs were created from the calculated data of the effective value of acceleration and these were compared.

Tab. 1: The comparison of the maximum values of vibration acceleration

Train set	Turnout	Effective values of vibration acceleration [$m.s^{-2}$]					Travel speed[km/h]
		A0Z	A7Z	A4Z	A5X	A6Y	
Leo Express	59, frog part	20	43	108	25	32	163
	59 exchange part	2	38	40	10	17	160
RegioJet	59, frog part	10	26	95	17	26	156
	59 exchange part	3	24	49	11	20	154
150	59, frog part	2	10	33	6	10	83
	59 exchange part	2	40	65	15	25	67
151	59, frog part	7	24	46	8	13	120
	59 exchange part	2	26	42	10	18	101

Legend
in the vertical direction
in the longitudinal direction
in the transverse direction

It is clear from Table 1 that higher values of effective acceleration were achieved in the frog part of the turnout compared to the exchange part. This is true for most trainsets except the trains with the 150 locomotive type. Similar findings also show the analysis and comparison of time records and their amplitude frequency spectra.

To present a comparison of the dynamic stress in the exchange and the frog part of the turnout, the passage of the RegioJet train set at a travel speed of 156 $km \cdot h^{-1}$ was chosen (Fig. 3, Fig 4). Due to the limited space of the paper, the authors focused on a more detailed analysis of the measured data from the sensor, which was placed on the measuring rod in the gravel bed. This provides vertical values of the vibration acceleration at the attachment point. The analysis consists of images composed of three graphs.

The upper graph shows the time course of the oscillation acceleration. The left graph shows the amplitude spectrum of the vibration response calculated using the Fourier transform. The middle graph then shows a 3D representation of the time-frequency course of the amplitude spectrum of the vibration response. The smoothed form of the Wigner-Ville transform in discrete form was used to calculate the time-frequency spectrum. Note that a reference value of 10 $m \cdot s^{-2}$ was used in the calculation of the frequency and time-frequency spectrum.

From the comparison of time records, it is clear that higher values were measured during the transition of the wheels of the set from the wing rail to the tip of the frog.

Frequency spectra show that significant frequency components obtained from signals occur in the frog part in a lower frequency range, from about 120 Hz to 1 kHz.

In the case of the exchange part, the significant frequency components are distributed higher, in the interval from about 500 Hz to 1.5 kHz. Note that frequency components above 160 dB are considered significant. It is also evident that the significant frequencies are significantly higher in the frog area compared to the exchange part. The same conclusions are drawn with time-frequency analysis using the Wigner-Ville transformation method.

Even in the case of this analysis, it is clear that higher peaks in the time-frequency plane were achieved in the case of passing the trainsets over the frog part. It is also clear that the highest values of the spectrum were found at relatively low frequencies up to 500 Hz. It is clear from the exchange part of the turnout that lower values of the time-frequency spectrum have been achieved. However, this is spread over a wider frequency and time interval.

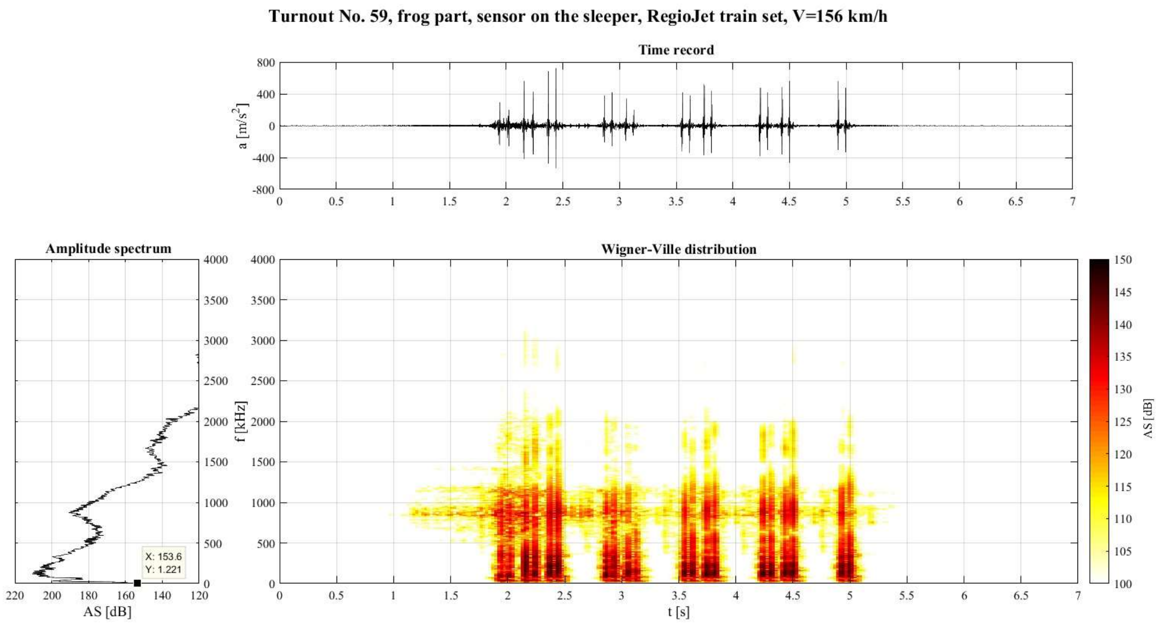

Fig. 3: Time, frequency and time-frequency characteristics of the vibrations, sensor on the sleeper, turnout no. 59 frog part, vertically direction, RegioJet, speed 156 km·h^{-1}

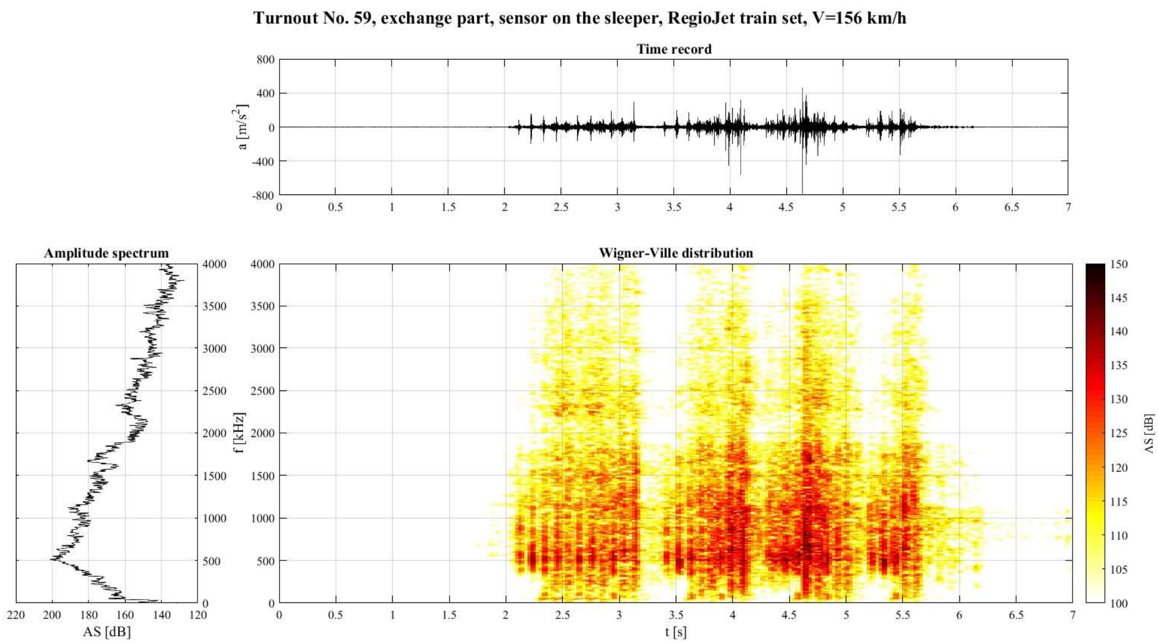

Fig. 4: Time, frequency and time-frequency characteristics of the vibrations, sensor on the sleeper, turnout no. 59 exchange part, vertically direction, RegioJet, speed 156 km·h^{-1}

Conclusions

The railway turnout No. 59, was selected for presentation of the modified Wigner-Villa's transformation in the analysis process of dynamic load from the train units. The selected railway turnout is located in the Choceň station. The results from the exchange section of the turnout were compared with those measured in the frog part of the same turnout.

The modified Wigner-Villa's transformation offers a comprehensive tool for analysing non-stationary signals in particular. Characteristic feature of presented transformation is the fact that its resulting distinguishment in time and frequency in not limited by Heisenberg principle of indefiniteness. This fact includes the high distinguishing ability in the time frequency plane that gives rise to a "precise" localisation of important frequency components in time. This method gives a fast and accurate localisation of frequency components included in the measured signal.

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