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ABOUT DIAGNOSING OF IMPACT OF RAILWAY VEHICLES ON THE TRACK

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Summary: The report presents the results of the research aimed at justification of expediency of creating a system of experimental evaluation of indicators of impact of the rolling stock on the rails. The proposed system is based on the measurements of the vertical and horizontal accelerations of the rails under a movement of the rolling stock on the rail track section. This system for monitoring rail accelerations that are emerging from the impact of the rolling stock in the track structure is expected to be used to identify vehicles with high impact on the rails due to their design and technical condition of the running gears, including the defects of the wheels. Some results of the pilot testing of the proposed system for the monitoring of the accelerations, which were registered by passing the train consisting of five units, are presented. And the computational algorithm of the specialized pre-processing of the multidimensional signal that is recorded by this system is described. The offered algorithm in automatic mode allows dividing the signal on the separate segments that are associated with the particular wheelsets of a running train for subsequent analysis of each segment. This algorithm does not require input data about the train speed on the track section that is equipped with the monitoring system, about the number of wheelsets of the running train, and about the distances between them. These data are calculated as a result of the algorithm execution, since they are absent under the operating conditions of the proposed system.

Keywords: impact on the track, accelerations of the rails, signal segmentation, particular wheels

1. INTRODUCTION

The increased force impact of the rolling stock on the track results in intensive deterioration of the superstructure and premature failure of structural elements contrary to the established inter maintenance periods or repairs. Based on the conditions of preservation of the track structure, the main attention should be paid to the creation of methods and means of controlling the impact on the track by the rolling stock and, in particular, by the running gear of the freight cars. The requirements for the indicators of power impact of running gear on the track must be based on in-depth studies of the interaction of the rolling stock and the track. It is recommended to perform such studies with the use of modern methods and equipment, including computer modeling and field experiments. Thus, the results of studies constitute the scientific basis for the establishment
of the system of concurrent detection of cases of above-limit impact of the rolling stock on the track.

As a rule these systems consist of a stationary device in the form of a track section equipped with the sensors, and software complex that performs the collection, storage, visualization and processing of information signals from the sensors. The existing systems of control of the force impact of the rolling stock on the track, as a rule, are based on the use of means of strain gauge measurements. Such systems include, for example, the detector of the impact of wheel loading on the track structure WILD [1].

System for assessing the dynamic impact of the new and modernized rolling stock on the track, which is applied on the tracks of 1520 mm gauge, is regulated by the corresponding regulatory documents and involves evaluating the strain-stress state of the track elements under the influence of the rolling stock. The values of stresses in the rails and the forces of interaction are considered as random variables obeying the normal distribution law. The traditional method of processing of these data lies in their incorporation into one statistical sampling for each axis of the tested rolling stock according to the same interaction indicator in different sections of the track. Further, following actions are taken for the obtained population the: examination for compliance with the normal distribution law, determination of average values, mean root square deviation maximum probabilistic value.

In contrast to the common systems for control of interaction parameters of rolling stocks and the track on the basis of strain gauge measurements, the report discusses the possibility of using vibration acceleration sensors (accelerometers) for the assessment of dynamic load of the elements of the track super structure. It is assumed that the system, which is based on the measurement of acceleration of interfacing elements of the rolling stock and the track, should provide an opportunity for detection of units of the rolling stock with the above-limit impact on the track, their identification and prompt transmission of information for taking appropriate organizational and technical measures.

2. TECHNICAL MEANS OF DIAGNOSTIC SYSTEM

The purpose of the diagnostic system under development is the automatic detection of malfunctions of wheels and running gear as a whole. Such a system consists of hardware and software.

2.1. HARDWARE

The hardware of the complex includes a section of track equipped with accelerometers, analog signal transmission lines, station equipment and the system of transmission of data to the traffic controller [2]. The accelerometers mounted on both rails between the sleepers in increments of \( d_s \) are used for the measurement of dynamic load of the track as the
primary transducers. Accelerometers are used for the measurement of the rail accelerations in vertical and horizontal lateral direction with a sampling frequency of 1500 H. Analog signal transmission lines are the cables which provide connection of primary transducers with registration instruments; they are the component parts of the measurement system.

The measuring system includes a controller with real-time operating system PharLab, chassis and input-output modules. The chassis bears the core of a programmable logic integrated circuit (PLIC), which is directly connected with the universal and specialized input-output modules having a built-in means of coordination and processing of informational signals. Due to the built-in PLIC it is an opportunity to implement algorithms for processing of measurement data at the hardware level with determined execution time of 25 ns without transferring load to the CPU of the controller.

### 2.2. SOFTWARE

The general structure of the software, which provides registration of dynamic parameters, is shown in Fig. 1. The software is divided into three stages: virtual instrument HOST VI on the administrative PC with Windows OS, RTVI on the controller with the real-time OS, FPGA VI on PLIC, which does not have its own operating system because the program logic is implemented directly in hardware level. Each of these stages has its own functions and implements certain functions of the system as a whole [5].

![Fig. 1. Structure of the software](image-url)
Typical tasks performed by a HOST VI on a Windows computer are the following: data storage on the computer and access to data bases; integration with external information systems; interface arrangement. Tasks performed in the RT VI on the real time controller are the following: data processing; control; storage of data on the internal memory of the controller and on the external media. Tasks performed in the FPGA VI on PLIC involve input-output operations, hardware timing and managing the process of interaction with the equipment and the low-level processing of the measurement signals.

The FPGA Module package is an addition programming environment that allows setting the PLIC behavior as a conventional virtual device instead of its programming using the specialized VHDL language. This package allows creating programs with synchronous and asynchronous parallel loops executed on the hardware level, and provides data collection and analysis determined with the respect to time.

The FPGA Module software package fully undertakes multi-stage process of transformation of the virtual device into PLIC binary code. At the first stage the virtual device is converted into a text code in VHDL language, which then is compiled by the standard industrial Xilinx ISE compiler into binary form. In the process of compilation there is the optimization of code in accordance with the speed of execution and the number of logic gates involved.

The presented system does not have a virtual control unit, which is placed on a PC, but instead of it the system uses the Remote Panel mechanism. This function realizes the so called client-server model, where the controller performs the functions of the server, and any computer as a client. This function can significantly reduce the expenses of time that are necessary for the development of HOST VI, but it can produce a load on the data transmission network [3].

3. THE ALGORITHM FOR THE SEGMENTATION OF THE MULTIDIMENSIONAL SIGNAL

The operation of the proposed system in automatic mode requires addressing a number of specific problems of the digital signal processing. Accelerations of rails, that are caused by a passing train and recorded by the system, are the substantially transient high-frequency processes. Using traditional methods of spectral analysis and synthesis in the processing of these signals does not provide satisfactory results. Recorded signals require specialized processing wherein the impact on the rails from a certain wheel is analyzed. Thus, feature of processing of these signals is the need for their presentation by separate segments, which are associated with certain wheels, and subsequently analyzing of each segment. The complexity of such segmentation is due to deficiency or absence of a priori information about the actual speed of the train at the track section with the signal recording and the construction of the train that follows on this section under the operating conditions (but not during the tests). Therefore, it is offered to use computational algorithm, the main stages of which are presented below, for the pre-processing of the real signal.
When a train passes over track section that equipped with the proposed system, it produces a multi-dimensional signal \( S = [S_0 \ldots S_m \ldots S_{M-1}] \), where \( M = 4 \cdot M_s, M_s \) – is the number of placement points of sensors along of the track rail section. All signals \( S_m, m= 0 \ldots M - 1 \), are of equal length \( N+1 \). Each signal \( S_m \) can be presented conventionally as the union of three parts of the signals \( S_m = S'_m \cup S''_m \cup S'''_m \), where the parts \( S'_m, S''_m \) and \( S'''_m \) are corresponding to the measurements in periods of time before the train passage, during of the train movement and after the passage of the train over the sensor \( m \). During processing the part \( S''_m \) is the informative signal part, whereas \( S'_m \) and \( S'''_m \) are the auxiliary signal parts. Therefore, for each signal \( S_m \) it is necessary to allocate the parts \( S'_m, S''_m \) and \( S'''_m \), i.e. determine the beginning \( N_{m1} \) and the end \( N_{m2} \) of the signal part \( S''_m \). In general, the values \( N_{m1} \) and \( N_{m2} \) are dependent on the sensor number \( m \), on the distances between the sensors \( d_s \), on the length of the train \( L \) and its speed of movement \( v \) through the track section, which is equipped with the system, and on the duration of the signal registration \( T = \frac{N+1}{F} \). The length of a passing train and its speed are not known a priori (under the operating conditions of proposed system), so the signal preprocessing includes of the calculations of these values as well as the calculations of the distances between the wheelsets. It is noted that these calculations are made with the assumption that the speed of the train within the track section where the sensors are placed has a constant value, i.e. \( v = \text{const} \).

3.1. DECOMPOSITION

The first stage of the algorithm is needed for decomposition of the multidimensional signal \( S \) into three parts \( S'_m, S''_m \) and \( S'''_m \), i.e. calculating the values of \( N1 \) and \( N2 \). Therefore the iterative procedure is applied with the cost function \( E_N^m(x_{i,m}) \), estimated by the signal values \( S_N^m = \{x_{i,m}\}, i = 1, N \) [7]. The cost function is adapted for data and is expressed as

\[
E_N^m(x_{i,m}) = - \sum_{i=0}^{N} \left( \frac{x_{i,m}}{\sigma_m} \right)^2 \cdot \ln \left( \frac{x_{i,m}}{\sigma_m} \right)^2, \tag{1}
\]

where \( \sigma_m = \sqrt{\sum_{i=0}^{N}(x_{i,m})^2} \).

The process starts from calculating a total cost function \( E_{N1}^{0} \) for the signal \( S_{N1}^{0} \) from the first sensor. On the basis of the original signal is formed a truncated right side signal \( S_{N1}^{0} \) with a length equal to \( N1 = \text{floor}(0.1 \cdot N) \) is formed, and a cost function \( E_{N1}^{0} \) is calculated for it. The values \( E_{N2}^{0} \) and \( E_{N1}^{0} \) are compared: if \( E_{N1}^{0} < 0.005 \cdot E_{N2}^{0} \), then the length of the truncated signal is increased by a value of \( \Delta N1 = \text{ceil}(0.1 \cdot N) \), i.e.
\( N_1 = N_1 + \Delta N_1 \). Again, the cost function \( E_{2, N_1}^0 \) is calculated, and executed a comparison of values \( E_{2, N_1}^0 \) and \( E_{0, N_1}^0 \) is executed, if \( E_{2, N_1}^0 < 0.005 \cdot E_{0, N_1}^0 \), then again the length of truncated signal is incremented by \( \Delta N_1 = \text{floor}(0.1 \cdot N) \), etc. If on the \( k \)-th step \( E_{k, N_1}^0 \geq 0.005 \cdot E_{0, N_1}^0 \) then the length of truncated signal from the previous \( k-1 \)-th step is increased to \( \Delta N_1 = \text{floor}(0.05 \cdot N) \), the cost function is calculated and the comparison is performed again. The iterative process stops when increment of the length truncated signal on the iteration is equal to or less than \( \Delta N_1 \leq \text{floor}(0.001 \cdot N) \). As a result, the lower limit \( N_1 \) for the signal \( S' \) is calculated, where in the cost function of the signal \( S'_{m} \) does not exceed 0.5\% of the total cost function of the signal \( S_m \).

The upper boundary of signal \( S'' \) is calculated similarly, but the signal \( S''_N \) from last sensor is analyzed and the truncated signal \( S''_{N_2} \) is formed at the left side, i.e. iterative procedure is carried out in the reverse direction. As a result, the upper limit \( N_2 \) of signal \( S'' \) is calculated, wherein the cost function of the signal \( S''_{m} \) does not exceed 0.5\% of the total cost function of the signal \( S_m \).

Series of experimental runs during the development of the proposed system involved a train of five units: the electric locomotive of CHS8 type (two sections), grain car and the electric locomotive of CHS8 type (two sections). The train length \( L \), the total number of wheelsets \( (K = 20) \) and the distances between wheelsets were known during the test runs. The length \( N \) of the signal \( S \), which was registered by the proposed system, was changing in terms of the speed of train movement, which varied from 40 to 130 km/h in steps of 10 km/h and the 12 test runs were carried at each one. Thus, when speed \( v_1 = 60 \) km/h then signal length was equal to \( N = 22500 \) \((T=15,009 \) s\), when \( v_2 = 90 \) km/h \(- N = 19500 \) \((T=13,008 \) s\).

As a result of the iterative procedure described above, an informative signal part \( S'' \), which is located between the points \( N_1 = 6975 \) and \( N_2 = 16535 \), that is shown for the signal components \( S_0 \) and \( S_{56} \) in Fig. 2, is selected for the total signal length \( N = 22500 \).

![Fig. 2. Decomposition of signals into three parts](image-url)
3.2. DENOISING

At the second stage of the algorithm all components of the selected part $S''$ of the signal are filtered. For this purpose applied the known methodology of wavelet shrinkage with nonparametric removing noise by using Waveshrink function is applied [4]. Each signal component $S''_m$ on the right side is padded by zero values, so that the total length of the signal was a power of 2. After that, is applied a discrete wavelet transform using Daubechies4 wavelets is applied [4]. By using Waveshrink function the estimation of the noise level is made and “shrinking” smaller wavelet coefficients to zero is applied. Next an inverse wavelet transform is done and the length of the signal is set to the initial value. The results of removing the noise from the signal $\tilde{S}_0$ are shown on Fig. 3: a – the original signal $S_0$; b – the removed noise $r_0 = S - \tilde{S}_0$; c – the signal after filtering $\tilde{S}_0$.

![Fig. 3. Using Waveshrink function for filtering of the signal](image)

3.3. SIGNAL SHIFT

At the third stage of the offered algorithm the alignment of the signal components measured by the sensors, which are placed at different points of the track section, is performed. For this purpose, the ratio is set between the distance $d_x$ and the number of points of the signal discretization $n_x$, which corresponded to this distance. Each signal component $\tilde{S}_m$ is subjected to the Hilbert transform and the envelope $E\tilde{S}_m$ for each one is calculated [6]. Fragments of the components of the signal envelope $E\tilde{S}_0$ and the original signal $\tilde{S}_0$ are shown in Fig. 4.
Then the cross-correlation functions $CZL_{mp}$ ($CZR_{mp}$, $CYL_{mp}$, $CYR_{mp}$) between the envelopes of the similar signals, which registered at the first sensor ($mp = 0$) and at the sensor with number $mp$, $mp = 1, M_g$, are calculated. Here signals are accepted the signals of the rail accelerations that were measured on the same side of the track section ($L$ or $R$) and in the same direction ($Z$ or $Y$). The abscissa of the maximum value of each cross-correlation function $CZL_{mp}$ ($CZR_{mp}$, $CYL_{mp}$, $CYR_{mp}$) is approximately equal to $mp \cdot n_g$. (The first few values of these functions are excluded.) Fragments of the cross-correlation functions $CZL_{mp}$ of the signals from the sensors located on the left side of the track rail section and the accelerations measured in the vertical direction are shown in Fig. 5.
Based on the estimated values of $m_p \cdot n_s$ is performed the leftward shifts of values of the signal components that have been made by the sensor $m_p$. At the same time the lengths of all signal components on the right side are aligned accordingly. Similarly, the shifts of the envelope components are made.

3.4. SPEED CALCULATION

In the fourth stage of the algorithm the values of the actual speed for the different test runs of the train movement on the track section, on which the system was set, were calculated. Also the values of the number of the train wheelsets and the distances between them were calculated using the algorithm in automatic mode in the absence of input data. The actual train speed $\nu$ on this track section is:

$$\nu = \frac{d_s}{n_s} \cdot F.$$  \hspace{1cm} (2)

The wheelset number $K$ is calculated on based of a signal $SvES$, which is obtained by averaging the sum of the signal envelope components as

$$SvES_i = \frac{1}{2M_s} \sum_{mp=0}^{M_s} (EZL_{i,mp} + EZR_{i,mp}),$$  \hspace{1cm} (3)

where $EZL_{mp}$, $EZR_{mp}$ – the signal envelope components of the vertical rail accelerations that were measured on left and right sides of the rail track section. The local maximum values $A_{max_k}$, $k = 0, K - 1$, and the abscissas $n_{max_k}$, which are correspond to these values, are determined by using of the signal $SvES$ too. The distances between the abscissas of neighboring local maximums $\Delta n_k = n_{max_k} - n_{max_{k-1}}$ allowed us to determine the distances between the wheelsets as

$$l_k = \frac{\Delta n_k}{n_s} \cdot d_s.$$  \hspace{1cm} (4)

Furthermore, the values $n_{max_k}$ allowed us to separate all signal components into segments that correspond to the passage of the particular wheel over the sensor.

Fig. 6 shows the signal $SvES$, where we can see twenty calculated local maximum values, which corresponds to the actual number of wheelsets $K = 20$ of the train, that took part in the experimental runs. The verification of the proposed algorithm showed, that the calculated wheelset distances have coincided with the actual wheelset distances, which are determined by the train design.
On the basis of values $n_{\text{max}}$ segments $S_{m}^{k}$ of signal components, which correspond to the particular wheels, were allocated, consequently, it is allowed to carry out an advanced statistical processing for them.

**4. CONCLUSION**

The experimental system for the monitoring of the workloads, which appears due to the passage of the rolling stock by the rail track, is proposed. This system is based on measurement of the rail accelerations in the vertical and lateral directions. Measurements are carried out with using the biaxial accelerometers, which installed on the selected track section symmetrically on the underside of the rails between the sleepers on the right and left sides of the track structure. A total number of accelerometers installed in certain section of the track with the fixed step depend on the characteristics of the rail track section and on the monitoring purposes.

Developed and implemented hardware and software system provides the possibility of autonomous registration of the impact of railway vehicles on the track using the CompactRIO controller and experimental accelerometers as basic sensing device.

Multidimensional signal is registered during the train passage through the section, which is equipped by the proposed system. The number of the components of this multidimensional signal is equal to twice as much as the number of accelerometers. The computational algorithm of the pre-processing of the signal that is recorded by the monitoring system of the impact of the rolling stock on the rail track was offered.

This algorithm allows representing the signal components as separate segments that are associated with the particular wheels for subsequent analysis of each segment. The algorithm consists of four stages: decomposition – informative part of the signal is allocated; denoising – the noise is removed from the informative part of the signal; signal shift – alignment of the signal components obtained from different sensors; speed
calculation – actual speed and the distances between the wheelsets of the train are
determined. Several known techniques of the signals processing were used to design this
algorithm, they are: the use of the cost function of the signal parts, Hilbert transform for
the formations of the signal envelopes, the wavelet transform to remove the noise, the
calculations of the cross-correlation functions of the signals. At the same time this
techniques was adapted to data of the recorded multidimensional signal and with the aim of
provision of relevant pre-processing in automatic mode.

The advantage of this algorithm is that it does not require input data about the train
speed on the track section equipped with the monitoring system, about the number of
wheelsets of the train, and about the distances between them. These data calculated as a
result of the algorithm execution, since they are not available under the operating
conditions of the monitoring system.

The verification of the algorithm was performed on the basis of processing the real
records of the rail accelerations under effect of the experimental running train consisting of
five units. The results of the verification demonstrate satisfactory convergence of the
calculated values of the train speed and the distances between the wheelsets with
the corresponding values, which were known in the series of the experimental runs.

The next steps in this research are automation of the advanced statistical processing of
the selected signal segments of the rail accelerations for all wheelsets from various points
arrangement of the sensors and analysis to identify the wheels with a defects.

References

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