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Railway Traffic Monitoring System by Seismic Methods

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Abstract
This article describes a system for monitoring the movement of railway transport based on seismic methods. The current state and existing problems in the railway monitoring industry are briefly presented. It is proposed to use seismic signals in soils formed by passing trains in order to highlight information features and assess the characteristics of railway transport. These signals carry a large amount of useful information and can be used with proper processing and analysis. The characteristics of these signals are considered depending on the characteristics of rolling stock, such as speed and weight, and on a number of other external factors: the composition and condition of soils, the presence of rail joints and irregularities. An algorithm for processing seismic signals in order to distinguish the characteristics of railway transport is described. In the final section, a diagram and a block of data collection are presented, as well as a brief description and features of the application of the developed monitoring system. This system will allow to accelerate the implementation of large-scale monitoring of the movement of railway transport, as well as to increase its efficiency and functionality, due to simpler and more inexpensive solutions.

Keywords
Railway Monitoring, Railway Transport, Seismic Methods, Traffic Monitoring.

Introduction

Monitoring of railway transport remains an important and urgent task today. For its implementation, many methods of obtaining and processing various kinds of information are used. In view of the fact that the railway network of all developed and developing countries is constantly increasing, the total length of the tracks has reached enormous values. In addition, many of them are located far from large settlements and do not have access to high-tech networks and expensive and high-tech equipment. Consequently, the requirements for monitoring systems should include the ability to operate autonomously, low cost, allowing large-scale implementation, as well as broad functionality. These systems should provide not only actual information about the detection of a train but also determine its speed and weight characteristics, as well as monitor the state of railway tracks and embankments, warning and promptly signalling about the possible emergence of emergency sections, with a high degree of accuracy. Thus, the search for the best approach, by researching new technologies or improving existing solutions, which would better meet the requirements set, continues to this day. In this article, we have proposed a system for monitoring the movement of railway transport based on seismic signals recorded in the ground near the tracks. The resulting vibrations lead to the gradual destruction of the soil base and, as already noted, can cause accidents. Thus, their monitoring must be carried out in order to ensure safety and regardless of other tasks. However, in our opinion, vibrations generated by a moving object are one of the most important components of information signals. They carry a large amount of useful information and, with proper processing, can become a source of a number of other important characteristics of monitoring objects, in addition to assessing the condition of the soil base of the embankment, for example, such as the speed and weight characteristics of the rolling stock itself [1-9]. The system proposed in this article based on the registration and analysis of seismic signals, in our opinion, will accelerate the implementation of large-scale monitoring of the movement of railway transport. In some cases, it is fully capable of replacing complex induction systems, radio detectors, or expensive video equipment, as well as supplementing their work, increasing the accuracy of data acquisition and significantly expanding the functionality.

In the course of its movement, the train is constantly generating seismic signals or vibrations, which are transmitted from the wheel through the rail and sleepers into the unpaved embankment [2, 10-14]. Signals with the highest amplitude are generated when the wheel hits the rail joints. The presence of joints at the registration site leads to an increase in amplitude values by 2-5 times [2]. Therefore, the places near the joints or any characteristic irregularities of the rail are considered by us as more promising from the point of view of the location of the sensors for registering signals from the monitoring system.

The performed spectral analysis of seismic signals shows that most of the vibration energy is contained in the lower part of the spectrum at frequencies up to 180 Hz. The horizontal components of vibrations, in addition, have separate characteristic bursts at slightly higher frequencies of the order of 250-350 Hz. The main energy of all signal components (about 93% of the vertical and about 75% of the horizontal) is concentrated in the frequency range from 40 to 60 Hz and from 80-120 Hz, which makes these frequency bands the most attractive for analysis and processing. In addition, with increasing frequency, the rate of damping of vibrations in the ground also increases [2,15,16].

The amplitudes of the recorded seismic signals depend on a number of factors. Such as the range of the location of the sensor, the characteristics of the ground, the presence of a joint or unevenness, as well as the speed and mass of the rolling stock. Thus, an increase in speed up to 100 km / h is accompanied by an almost linear increase in the amplitude values of the signals. A further increase in speed leads to a slowdown in the increase in amplitude due to the inertial features of the soil and a reduction in the exposure time. In this case, the speed indicators do not affect the frequency composition of the oscillations.

An increase in the weight characteristics of the rolling stock also leads to a linear increase in the amplitude values.

As noted earlier, the amplitude level is strongly influenced by the presence of a rail joint and, to a lesser extent, by the material of the sleepers, composition, temperature and soil moisture. Thus, the amplitudes increase with increasing moisture content and decreasing soil density. Consequently, the listed parameters must be known or can be measured when registering signals and must be taken into account when monitoring [2,17-20].

Among other things, an excessive increase in the amplitude level of vibrations may indicate the presence of all kinds of ballast inhomogeneities in the soils and, as a consequence, a potentially dangerous emergency state of this section of the track. These inhomogeneities can arise due to the constant vibration effect of railway transport. Despite the fact that soils have the ability to restore their properties, long-term and periodic vibrations can lead to their destruction, due to a lack of recovery time [2].

Materials and Methods

Train seismograms display a characteristic pattern of periodic, spatially correlated signals whose time shift is proportionate to the train speed (for example, see Figure 1).

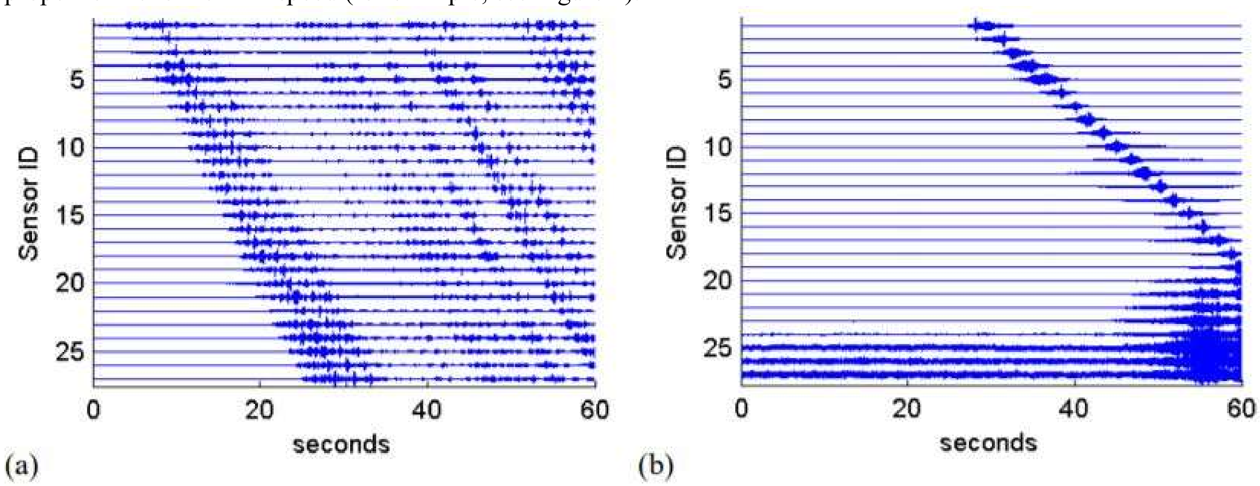

Figure 1: (a) Seismogram of a Train; (b) Example of a High-Rail Signal. Each Trace is Individually Normalized with its Peak Amplitude.

Ground vibrations induced by steadily moving trains and high-rails are consistent in terms of duration and sensor-to-sensor travel time. In this research, they will be referred to as “regular”, whereas accelerating, decelerating and stopping vehicles display irregular signal patterns. Some high-rail signals are a combination of multiple frequencies, probably generated by the vehicle’s engine, e.g. Figure 2. The example in Figure 2 also demonstrates that the characteristic ground and/or rail vibration induced by the high-rail was detected more than 10 s before the vehicle arrived at the sensor location (roughly equivalent to 100 m).

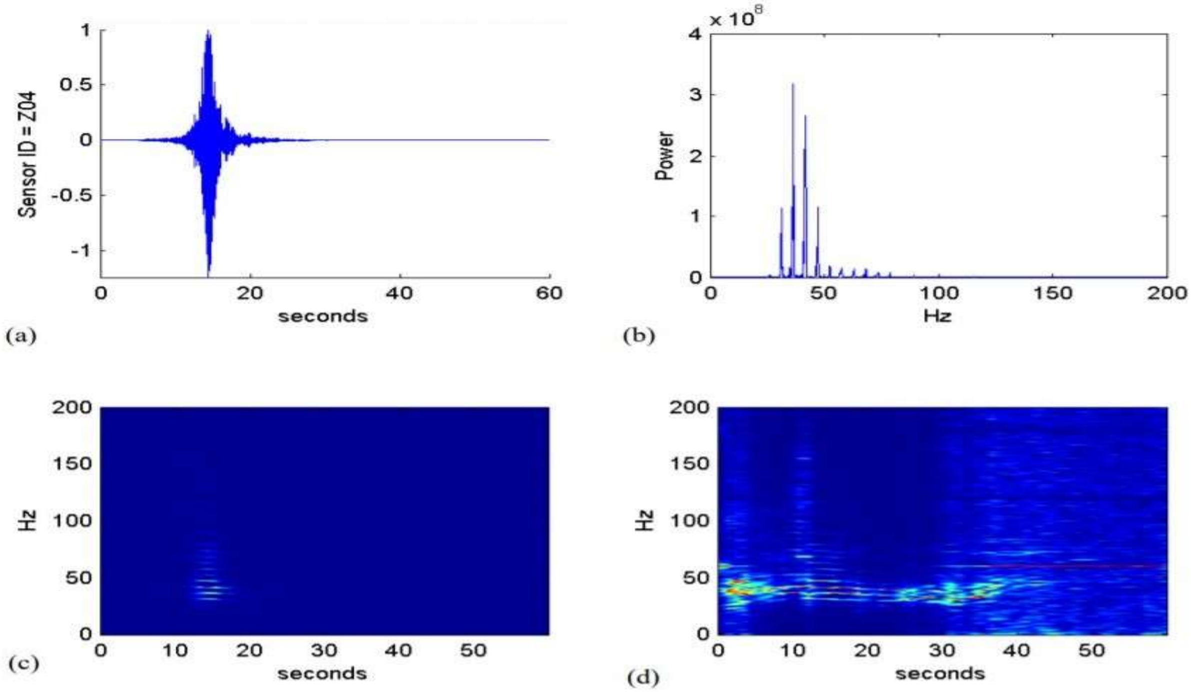

Figure 2: Example of High-Rail Signal with Comb Spectrum. (a) Source Data; (b) FFT is Dominated by 5 Hz Multiples; (c,d) STFT (Short-Time Fourier Transform). STFT was Computed Using 5 s Time Windows. The Windowed FFT in the Plot (c) is Globally Normalized, while in (d) is They are Individually Normalized.

The seismic signal in Figure 3 is an example of an "organ-pipe" signal induced by a westbound train and observed. This type of coherent precursor signal is usually detected at the 3-4 sensors closest to the tunnel portal, e.g. within 40-60 meters. The tunnel is 226 m long, and the timing at which this signal emerges ahead of the train is proportionate to the train's speed. For example, if a train is moving at five m/s, the signal is detected by the geophones located next to the portal 40-45 s before the train's arrival. These are typically narrow-band signals dominated by 1-3 99 frequencies; in the example in Figure 3, the dominant frequency is 50 Hz. An adaptive notch-filter can be applied to this kind of noise which will detect and remove the strongest frequencies. Peak amplitudes of these signals are inconsistent but can exceed the peak amplitude of ground vibration generated by high-rails.

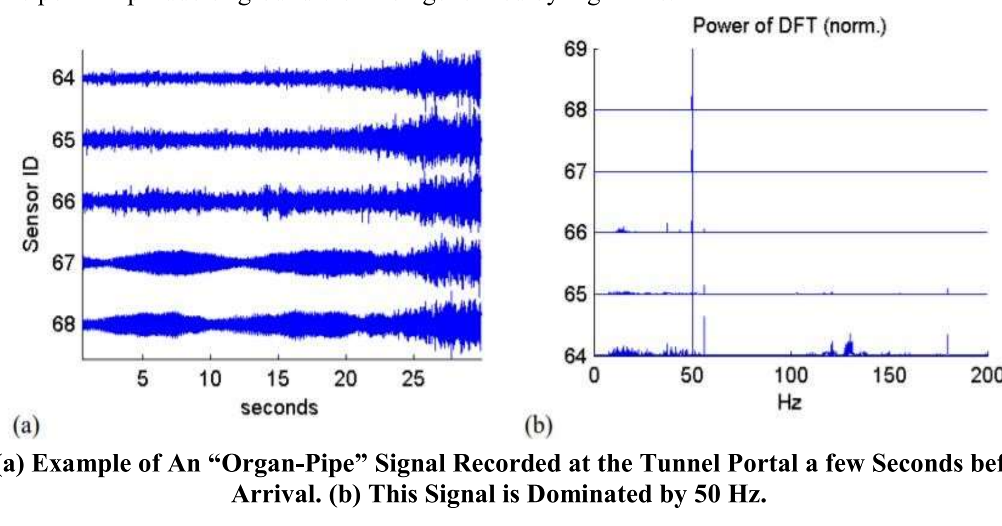

Figure 3: (a) Example of An "Organ-Pipe" Signal Recorded at the Tunnel Portal a few Seconds before Train Arrival. (b) This Signal is Dominated by 50 Hz.

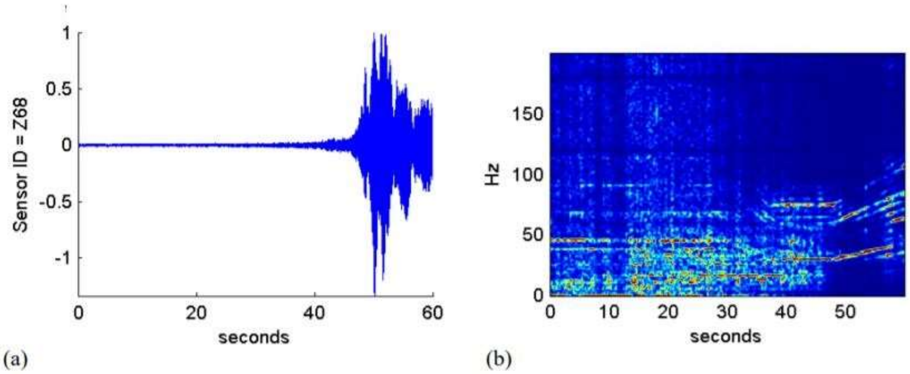

Figure 4: (a) Normalized Seismic Trace Recorded; (b) Short-Time FFT. Narrow-band Seismic Signal emerges about 20 s before the Locomotive Arrival at 50 s. In plot (b) The Dominant Frequencies Shift upon the Frequency Scale (~50 to 60 Seconds) as the Locomotive is approaching the End of the Tunnel which may be Indicative of the Train's Acceleration

Results and Discussion

In general, the algorithm for processing the recorded seismic signals of railway transport is a series of successive stages. The general scheme of the developed algorithm is shown in Figure 5.

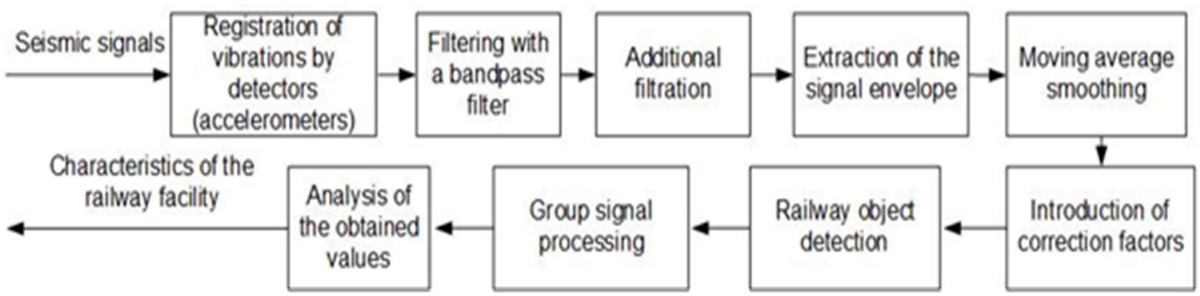

Figure 5: General Diagram of the Seismic Signal Processing Algorithm

The recorded signals are noisy harmonic oscillations described by the equations:

$$U_x = Ak\left(\exp(-qz) - \frac{2qz}{k^2+s^2}\exp(-sz)\right)\sin(kx - wt) \quad (1)$$

$$U_z = Ak\left(\exp(-qz) - \frac{2k^2}{k^2+s^2}\exp(-sz)\right)\cos(kx - wt) \quad (2)$$

$$q = sqrt(k^2 - k_l^2), s = sqrt(k^2 - k_t^2) \quad (3)$$

They are spread and registered by sensors along three axes, one vertical and two horizontals (longitudinal and transverse). The filtering is a band-pass filter with a bandwidth of 80 to 120 Hz. In addition, it is desirable to use additional filtering to eliminate the most significant interference, for example, 50 Hz. In order to simplify further processing, the signal envelope is extracted and smoothing with a moving average is performed (Figure 6).

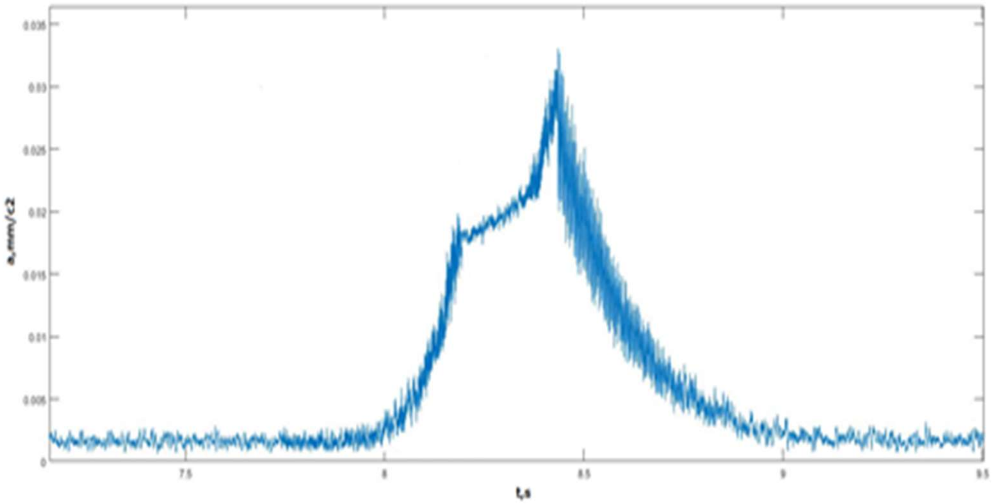

Figure 6: A Simulated Seismic Signal from Two Axes of a Railway Object

To improve the accuracy of the results, a correction factor is introduced, which consists of the characteristics and condition of the soil, rails and is characteristic for each measurement site. At the moment, it is selected experimentally. After that, the signal passes through the threshold detector, and in the event that an object is detected, group processing is carried out [10]. It consists of applying regression algorithms to the ratio:

$$Q = \int_{t=0}^{T} (S(t) - \tilde{S}(t))^2 \partial t \approx \left(\sum_{i-1}^{P} (S(\Delta t(i-1)) - \sum_{k=1}^{N} \sum_{m=1}^{M} S_0 sqrt(P_m(v^2)) \, exp(-\beta(\Delta t(i-1) - T_{km}))\right)^2 \quad (4)$$

According to preliminary results on simulated signals, taking into account the main characteristics of real measurement areas, such as noise levels and characteristic features of the soil, we obtained high results of the algorithm. With its application, it was possible to achieve an error in measuring the speed at the level of 5% and in determining the mass at the level of 10%. In this case, the error increases with an increase in the speed of movement, which is associated with an increase in the effect of overlapping signals and a decrease in the exposure time. In the future, it is planned to conduct a number of experimental studies using the developed and described below system based on the seismic method.

Thus, the analysis of seismic signals makes it possible to conduct large-scale monitoring of typical, weight and speed indicators, as well as to predict possible deformations and collapses of earth embankments, which cause long delays in movement, and are one of the main causes of disasters in railway transport caused by a train crash. The developed block diagram of the railway traffic monitoring system is shown in Figure 7.

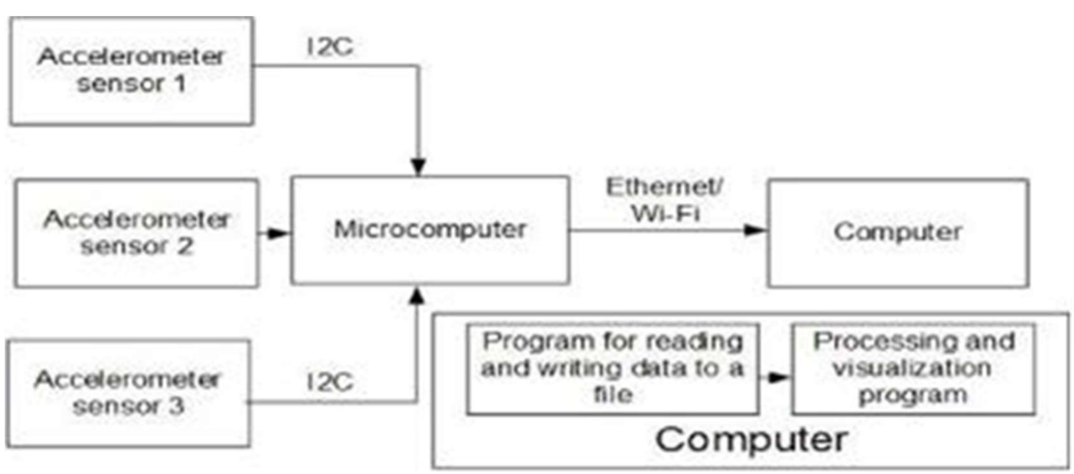

Figure 7: Block Diagram of the Railway Traffic Monitoring System

According to the diagram, seismic signals are recorded by several detectors (accelerometers) (Figure 8) under the control of the processor (Figure 9). It is a single-board computer, which, in addition to managing data collection, carries out primary processing and transmission of data to a remote computer to interpret the information received. To carry out work, each block of the system is placed in a sealed case (Figure 10).

Figure 8: Used Seismic Signal Detectors (Accelerometers)

Figure 9: Data Acquisition Control Unit

Figure 10: Seismic Signal Collection Unit

The used accelerometers have dimensions of about 5 cm and, together with the data acquisition control unit, are located in the ground near the railway tracks at a depth of about several tens of centimetres. The minimum required the number of sensors in the system is three and can be increased depending on the complexity of the railway tracks. Computer analysis of the data obtained includes filtering, detection of a moving object, as well as the determination of speed and weight indicators, by means of correlation analysis. Thus, using the group processing of seismic signals, described in detail in [10], monitoring will make it possible to obtain the main parameters of the movement of railway objects, while not requiring relatively large material costs for large-scale implementation and destruction of the existing railway infrastructure.

Conclusion

Monitoring of railway transport remains an important and urgent task today. For its implementation, many methods of obtaining and processing various kinds of information are used. It is obvious that the requirements for monitoring systems should include the ability to operate autonomously, low cost, allowing large-scale implementation, as well as broad functionality. In the current study, it was tried to propose a novel algorithm for processing the recorded seismic signals of railway transport. The results indicated that the proposed algorithm could accelerate the implementation of large-scale monitoring of the movement of railway transport. In some cases, it is fully capable of replacing complex induction systems, radio detectors, or expensive video equipment, as well as supplementing their work, increasing the accuracy of data acquisition and significantly expanding the functionality.

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