Development of Devices for Long-Term Railway Track Condition Monitoring: Review of Sensor Varieties

Dmytro Kurhan[1*], Vitalii Kovalchuk[2], Ruslan Markul[1] and Denis Kovalskyi[3]

[1]Department of Transport Infrastructure, Ukrainian State University of Science and Technologies, Lazaryan St. 2, 49010 Dnipro, Ukraine
{d.m.kurhan, r.v.markul}@ust.edu.ua

[2]Department of Railway Transport, Lviv Polytechnic National University, Stepan Bandera St. 12, 79013 Lviv, Ukraine
vitalii.v.kovalchuk@lpnu.ua

[3]Dnipro Institute of Infrastructure and Transport, Ukrainian State University of Science and Technologies, Lazaryan St. 2, 49010 Dnipro, Ukraine
proectbud@obz.diit.edu.ua

Abstract: There are numerous methods for monitoring the condition of railway tracks. In most cases, either the geometry of the railway track or its interaction parameters with moving trains are checked. This work is a component of a project aimed at developing a methodology for installing sensors (sensor networks) for continuous (long-term) monitoring of railway track condition. Therefore, its main objective is to analyse and discuss interim results regarding the feasibility of applying various types of sensors installed on railway track elements. The authors considered three options for sensor application for the overall assessment of railway track condition: measuring stresses in rails with strain gauges, measuring accelerations of rail and sleeper vibrations with accelerometers, and measuring the speed of wave propagation in ballast. Each method has its own advantages and disadvantages. Considering the analysis conducted, each method, both independently and in combination with others, can be applicable for building systems for long-term monitoring of railway track condition. Such systems can be useful, both for solving practical track maintenance tasks during operation and for scientific research.

Keywords: railway; railway track monitoring; sensors; strain gauges; accelerometer

1 Introduction

Today, there are numerous methods for monitoring the condition of railway tracks. In most cases, either the geometry of the railway track or its interaction parameters with rolling stock are checked. Corresponding sensors are used to monitor the characteristics of the interaction between the track and rolling stock, which can be installed on both railway track elements and rolling stock.

This work is a component of a project aimed at developing a methodology for installing sensors (sensor networks) for continuous (long-term) monitoring of railway track condition. One of the main requirements for such a monitoring system is its cost and limitation in power consumption, which must be self-renewable. The number of sensors that can be used on a single section is significantly limited. Additionally, the system should minimize the volume of information it transmits [1]. On the other hand, the monitoring system should cover as many factors affecting the track condition as possible. In addition to typical methods of assessing the geometric condition of the railway track, modernized measurement systems [2] and signal processing techniques [3] can also be applied. Therefore, the deformation modulus of the railway track is considered as the main parameter to be monitored. Factors affecting track stiffness include disruptions in fastening conditions, sleepers, contamination, and degradation of ballast, as well as changes in the geometric profile of the track, such as settlements and irregularities.

This work considers three options for sensor application to assess track stiffness characteristics: measuring rail bending stresses, measuring rail and sleeper vibrations, and measuring the speed of propagation of elastic waves through the ballast layer. For each option, an analysis of current scientific publications and the results of the authors' own experience regarding the use of relevant sensors are provided.

Therefore, the purpose of this publication is to analyse and discuss interim results regarding the feasibility of applying various types of sensors installed on railway track elements.

2 Measurement of Rail Stresses with Strain Gauges

Measuring rail bending stresses can be carried out using strain gauges. The relative simplicity and cost-effectiveness of such sensors allow them to be installed at any location on the rail that does not have direct contact with the wheel, and to obtain bending stresses at the railhead, web, and foot in real-time from the action of rolling stock. An example of a railway section equipped with such sensors is shown in Fig. 1. A more detailed description of the design of such a measurement system is provided in paper [4].

With these sensors, it is possible to assess not only the condition of the rails but also the sub-rail base as a whole, as one of the factors affecting rail deflection. For this purpose, as with most calculations of the stress-strain state of the track, it is sufficient to use the well-known, quasi-static differential equation of rail deflection, Eq. (1). In paper [5], the method for calculating stresses in embedded rails is based on such a differential equation of rail deflection; in work [4], this equation is used to compare static and dynamic methods of calculating the force impact from the wheel on the rail; in work [6], it is used to calculate stresses in track superstructure elements when organizing high-speed passenger train traffic.

$$\frac{d^4z}{dx^4} + 4k^4z = 0 \tag{1}$$

where z is the vertical deflection of the rail; x is the distance from the point of force application (position of the wheel on the rail) to the calculated cross-section;

$$k = \sqrt[4]{\frac{U}{4EI}} \tag{2}$$

U is the general deformation modulus of the sub-rail base; E is the modulus of elasticity of the rail steel; I is the moment of inertia of the rail.

Figure 1

Railway section with strain gauge sensors installed on the rails

Based on the classical solution of Eq. (1) for the rail as a beam supported on a continuous elastic foundation, the bending stresses in the rail will be determined by the equation:

$$\sigma = \frac{fP}{4kW}\mu \tag{3}$$

where f is the coefficient that considers the sensor position across the rail section; P is the wheel load force on the rail; W is the rail resistance moment;

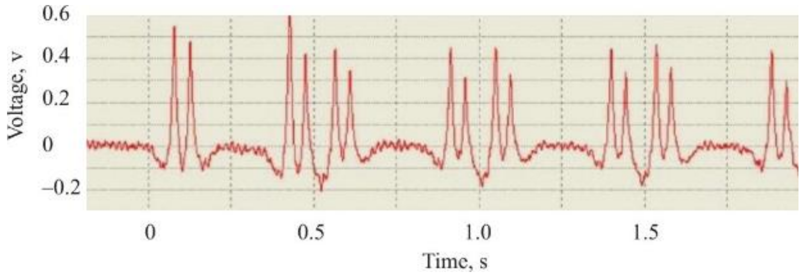
$$\mu = e^{-kx}(coskx - sinkx) \quad (4)$$

From Eq. (3), it is evident that the coefficient μ can be experimentally determined through the ratio of stresses in the section under the wheel and at a certain distance x:

$$\mu = \frac{\sigma_x}{\sigma_0} \quad (5)$$

where σ_0 is the stress in the rail at the section under the wheel; σ_x is the stress in the rail at a distance x from the wheel.

Figure 2 depicts an example of recording by a strain gauge sensor installed on the rail during the passage of a passenger train at a speed of 175 km/h. The recording frequency was 4 kHz. The vertical axis is shown in volts. This methodology only utilizes the stress ratios in the rails, thus conversion to MPa is not mandatory.



Example of stress recording in the rail during the passage of a passenger train at a speed of 175 km/h

Through equations (2) and (5), the coefficient μ uniquely determines the general deformation modulus of the sub-rail base, U. This parameter can be considered as a generalized characteristic of the sub-rail base condition [7]. Figure 3 illustrates the dependence of the modulus of elasticity of the sub-rail base on the stress ratio (coefficient μ) for UIC60 rails (I=3038 cm^4) at different distances between sensors ranging from 0.5 to 1.5 m.

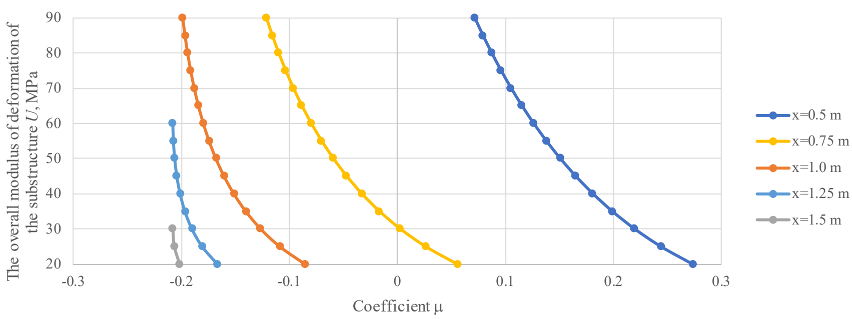


Figure 3

Stresses along the rail length dissipate quite rapidly. Therefore, it is preferable to install sensors on rails close together, for example, every one or two sleepers. It is advisable to avoid distances greater than $\pi/2k$. In Fig. 3, lines for x=1.25 and x=1.5 m are restricted by this criterion. To mitigate the influence of adjacent wheels of the rolling stock, only the extreme positioning of the train should be considered, when the first locomotive wheel enters the section with the first sensor. It is possible to install a sequence of not two, but three sensors, allowing for result averaging and sensor performance monitoring.

3 Measurement of Rail and Sleeper Vibration Accelerations Using Accelerometers

Accelerometers are widely used for measuring accelerations of the object on which they are installed. They can be piezoelectric, capacitive, inductive, etc., based on their operating principle. Accelerometers allow for the measurement of vibration accelerations of railway track elements in three directions (vertical plane, horizontal, and longitudinal). For instance, authors have employed accelerometers in various studies to assess the condition of railway track elements, such as ballast [8], switches [9] and metal corrugated structures [10], among others.

In addition to vibration amplitude, accelerometer measurements enable the determination of force acting on the object through the classical definition of force as the product of the object's mass and its acceleration. Therefore, accelerometers are often used on rolling stock components (locomotives, wagons) to determine interaction forces between wheels and bogie, bogie and car body, etc., considering that the masses of crew units are known and constant during motion.

A similar issue arises for determining forces between railway track elements regarding their mass. For example, what to consider as the mass of the rail or ballast for calculating forces acting on them through acceleration measurements. The masses of elements operating not on displacement but on elastic deflection are time-varying quantities and require reasoned interpretation depending on the problem being solved [11]. Perhaps, the necessity of applying additional mathematical tools for further analysis of acceleration measurement results on track elements explains their limited practical application. However, such issues already have examples of solutions today.

In paper [12], results obtained from acceleration measurements on rails confirm the hypothesis that at high speeds (the authors conducted measurements for a speed of 300 km/h) on ballastless railway track, the dynamic wheel profile interacting with the rail corresponds to a 20th-order polygon. In work [13], the results of acceleration measurements on rails and sub-rail base elements were used to assess noise pollution from sections of railway track with slab track. In work [14], rail vibration accelerations were used to assess the condition of railway track on ballast.

Frequency analysis of vibrations in track superstructure elements was conducted in work [15] to evaluate the performance of intermediate rail fastenings. An autonomous device for monitoring the condition of a switch, which includes measurement of vibration accelerations of its elements, was proposed in work [16]. A methodology for assessing the condition of rolling stock wheels was proposed in work [17].

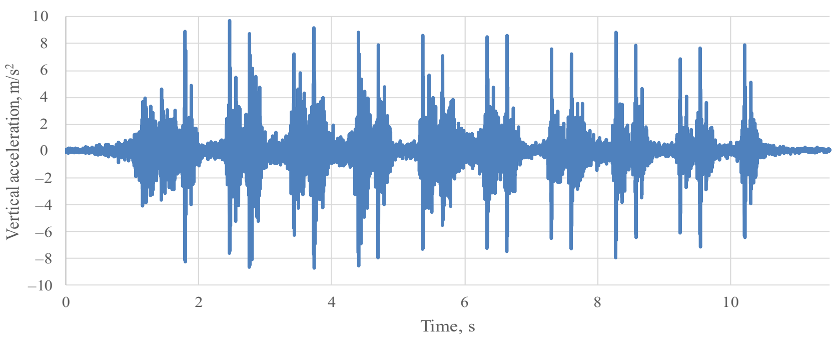
Figure 4 shows excerpts from experiments with the installation of accelerometers on the rail foot and on the sleeper surface near the rail fastening node. As a result of the measurements, the authors of this study obtained acceleration amplitudes in three directions from various rolling stock. A more detailed description of the design of such a measurement system is provided in paper [10].

a) b)

Figure 4

Installation of accelerometers: a) on the rail foot; b) on the sleeper surface

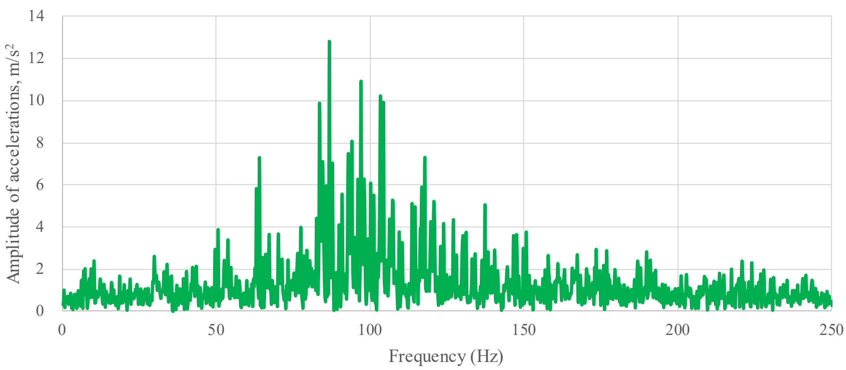
Figure 5 illustrates an example of recording vertical accelerations on a concrete sleeper from a passenger train traveling at a speed of 130 km/h. The recording frequency was 1 kHz.



Recording vertical accelerations on the sleeper from a passenger train traveling at a speed of 130 km/h

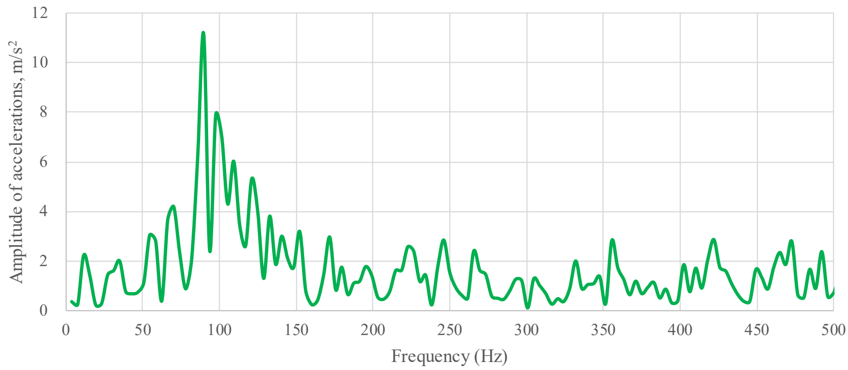
Analysis of measurements from various sensor positions revealed that the vibration disturbance on the sleeper is less compared to the readings on the rail. This is attributed to the attenuation of energy transmitted from the rail to the sleeper through fastenings. Vibrations on the sleeper reflect many dynamic processes and are influenced by a wide range of factors: the direct deflection of the track from each wheel, the natural oscillations of the rail, the natural oscillations of the sleeper, cyclic rotations of the wheels, wheel irregularities, rail surface irregularities, deviations of the track from the constant profile, etc. Most oscillatory processes can have several modes. Additionally, in some cases, sensors may register additional noise due to electrical power supply and communication signals [18], which can occur across a wide frequency range [19] and be caused by various factors such as forced losses in power supply [20], particularly due to regenerative braking [21], imbalance effects caused by alternating current at high voltage [22], directly the power supply systems of electric transport [23].

Therefore, further analysis of the acceleration recording requires an examination of the signal's frequency characteristics. The spectrogram of vibration acceleration obtained by Fourier transformation is shown in Fig. 6. The presence of multiple frequencies, separated by amplitude, confirms that the signal is a result of a combination of various factors. Based on the analysed spectrograms, vibrations can be distinguished at frequencies of 50…55, 65, 80…85, 95…105, 115…120, and 135 Hz. Such vibrations are perceived not only as mechanical influence but also as low-frequency noise pollution.



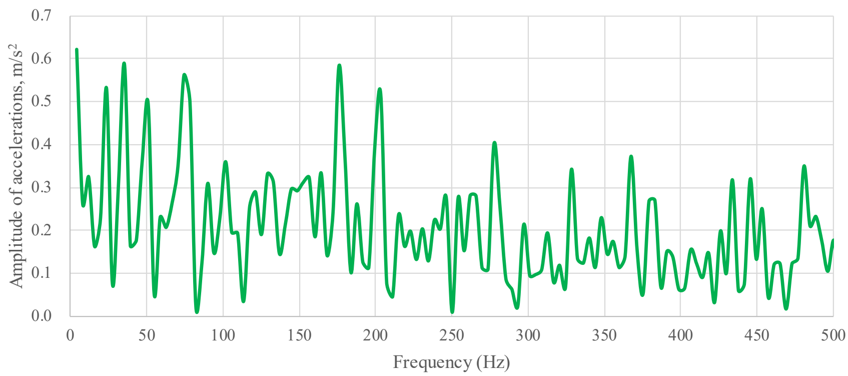
The spectrogram of the vertical vibration acceleration of the sleeper

Perhaps the most significant importance lies in the recording of the signal when the wagon passes directly over the section of the track with the installed sensor. The spectrogram of such local segments of the recording shows the presence of a distinct frequency significantly separated from other vibrations. For the data from these experiments, this frequency was observed at around 100 Hz, as shown in Fig. 7, corresponding to one of the modes of the natural vibrations of the concrete sleeper on the continuous support [13] [24].



Local spectrogram of vertical vibration acceleration of the sleeper during the passage of a wagon over the sensor

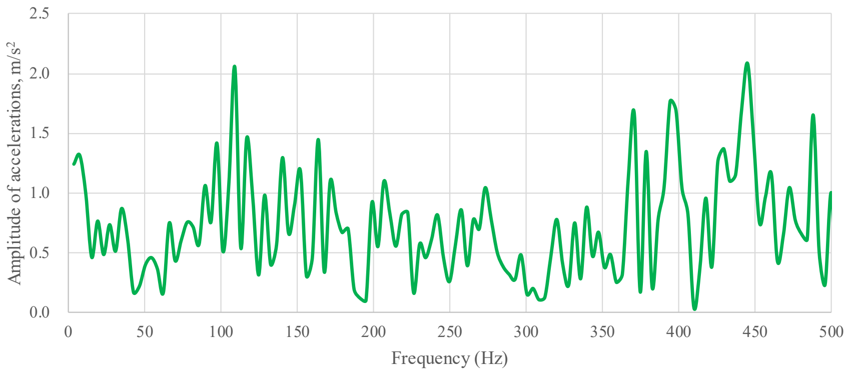
A similar analysis of the spectrum of a local segment between the wagon bogies, on the other hand, showed the presence of vibrations with different frequencies and small amplitudes, demonstrating the damping of dynamic processes after the wheel action disturbance, Fig. 8.



Local spectrograms of vertical vibration acceleration of the sleeper in the absence of direct loading (between wagon bogies)

Frequency characteristics can serve as a tool for analysing the condition of railway track sections. A beam (rail or sleeper) supported on a soft foundation will have a broader spectrum of vibrations than a beam supported on a rigid foundation. This is because a soft foundation will absorb less vibration energy, leading to an increase in vibration amplitudes at higher frequencies. A beam supported on a heterogeneous foundation will have a broader spectrum of vibrations than a beam supported on a homogeneous foundation. This is because the heterogeneity of the foundation will result in local changes in vibration frequencies, which in turn will broaden the spectrum.

Figure 9 shows the local spectrogram of vertical vibration acceleration of the sleeper during the passage of a wagon over the sensor. The sensor was installed on the sleeper where track settlement was present. The presence of clearance under the sleeper and irregularities in ballast compaction is vividly reflected in the broadening of the frequency spectrum of vibrations compared to the section of the track in good condition.



Local spectrogram of vertical vibration acceleration of the sleeper on a track section with track settlement

4 Measurement of Wave Propagation Velocity in Ballast

One of the key elements of railway track whose condition affects the entire structure is undoubtedly the ballast layer. It plays a crucial role in ensuring the longevity and reliable operation of the track. However, due to dynamic loads on the ballast, residual deformations accumulate quite rapidly. This can be monitored through the degree of ballast compaction.

Various methods are employed to monitor ballast compaction during operation. One of the modern and innovative methods involves assessing ballast compaction by measuring the velocity of sound wave propagation impact. This can be carried out using accelerometers, geophones, and so forth.

In well-known methods such as SASW (Spectral Analysis Surface Waves) and MASW (Multichannel Analysis of Surface Waves) [25] [26], the principle of kinematic and dynamic interpretation of the impulse response of surface waves is utilized. However, these methods have a drawback due to their low resolution in estimating the properties of soils with heterogeneities.

It should be noted that monitoring ballast compaction during operation will enable the assessment of repair work quality, such as ballast tamping, which directly affects the longevity of the railway track.

The paper [27] discusses theoretical and experimental methods for optimizing the transition zones between ballastless tracks and ballasted tracks in tunnel areas. The optimization parameters are based on the values of vertical displacements, vertical speed, and vertical acceleration. In [28], modelling of track settlement under long-term impacts in transition zones is performed.

To improve the selection of materials for railway infrastructure design, [29] presents the results of studies on the interdependence between track performance improvement and the geometric parameters of ballast stones. Additionally, the elasticity of the subgrade under the sleepers affects track performance [30]. Long-term studies [30], based on data recordings from vehicles, show that after six years, the degradation of the track is reduced due to the influence of under-sleeper pads. In [31], using advanced computer technologies, functions are derived that provide interpreted information on the geometric changes of the track throughout its life cycle.

In [32] [33], it was demonstrated that ensuring the design degree of ballast prism compaction and sub ballast compacting filler contributes to the reliable operation of railway engineering structures. In [34], experimental measurements of vibration in the gravel ballast of the track are presented. Vibration measurements were conducted on the surface of the ballast layer of the railway track. The paper [36], ballast diagnostics are performed based on impact testing. However, long-term experimental studies are needed to assess the condition of the track ballast through vibration measurement. In [35], based on the method of tensometry, dynamic characteristics of prestressed reinforced concrete sleepers are studied under the passage of railway rolling stock. An overview of non-destructive methods for assessing railway track ballast compaction is provided in [37]. Powerful methods for analysing the propagation of sound waves in the ballast prism include machine and deep learning methods [38], as well as cluster and discriminant analysis methods for identifying characteristic features of ballast layer compaction. In [29], changes in ballast characteristics during degradation were obtained as a result of comprehensive laboratory studies. Deformation indicators of ballast depending on its condition were investigated in [7], both through experimental stress measurements in the ballast layer and through analytical calculations using a dynamic model of elastic wave propagation [39].

This paper discusses the method of assessing the degree of ballast prism compaction, using inertial technologies, specifically accelerometers.

To assess the degree of compaction of the railway track ballast prism, the method of determining the velocity of sound wave propagation impact is utilized. Analytically, the propagation velocity (V) depends on the physical properties of the substance (Eq. (6)), and experimentally, it can be measured as the time taken for the wave to travel from the impulse generator (striker) to the impulse receiver (accelerometer), considering the time of impulse generation.

$$V = \sqrt{\frac{E(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \quad (6)$$

where E is the Young's modulus of the substance (ballast layer); ρ – is the density; μ is the Poisson's ratio.

The diagram of the device for measuring the degree of ballast prism compaction is shown in Fig. 10.

At this stage of the research, the authors conducted measurements in laboratory conditions using a glass box filled with granular material. An accelerometer was embedded in the bottom of the box, Fig. 11.

An analogy accelerometer ADXL335 with a working frequency of 30 kHz was used as a sensor to register the time of sound wave propagation impact. A metal striker, onto which a load of 1 kg falls from a fixed height and strikes a metal plate, was used to generate the impact. This generates a sound wave. At the moment of impact, the initial time of impact is recorded by closing the contacts: one contact to a microcontroller channel, and the other contact to the +3.3 V power supply from the microcontroller. Then, using MEMS microphones of the ADMP401 type, the moment of impulse arrival through the thickness of the ballast is recorded.

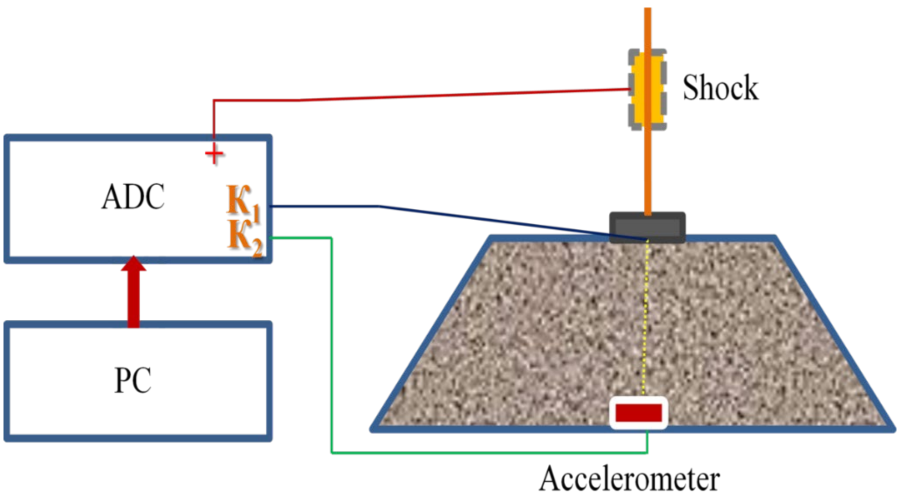


Figure 10
Scheme for measuring ballast compaction on the railway track: K1 and K2 are channels for signals from the striker and accelerometer

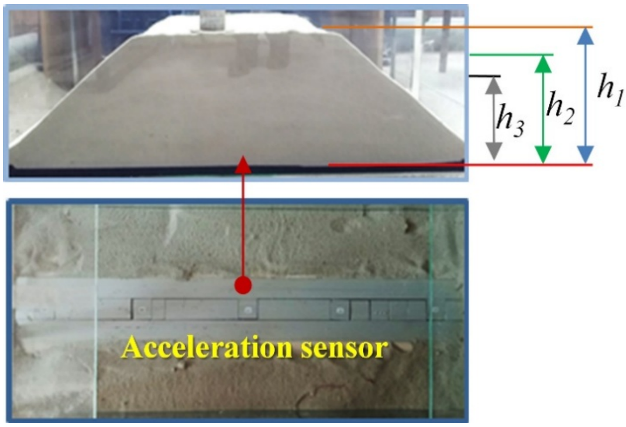


Figure 11
Appearance of the ballast prism and the accelerometer's position: h_1 – height in the uncompressed state of the ballast prism; h_2 – intermediate compaction; h_3 – maximum compaction

To accurately record the time of sound wave propagation from the striker to the accelerometer, it is necessary to know the beginning of the impact. To fix it, two channels on the analogy-to-digital converter are used. One channel is supplied with +3.3 V, and channel K1 is supplied to the analogy input corresponding to the striker. Channel K2 is connected to the accelerometer. As a result of the striker falling onto the metal plate, the contacts close, and as a result, a signal of 3.3 V appears on channel K1. This indicates the beginning of the impact, and consequently, the beginning of the sound wave propagation. Then the wave propagates through the thickness of the ballast prism and reaches the accelerometer. The time difference between the arrival of the wave at the accelerometer and the time of impact corresponds to the time of sound wave propagation from the striker to the accelerometer.

An example of such measurements is presented in Fig. 12. The measurement of the sound wave propagation time was performed in three cycles of the experiment: the initial bulk density of the ballast prism, intermediate compaction, and maximum layer-by-layer compaction of the ballast prism. The height from the base to the top of the ballast prism in the uncompressed state was h_1=305 mm, during intermediate compaction h_2=295 mm, and at maximum compaction, the height of the ballast prism was h_3=270 mm.

According to Fig. 12, there is a linear distance observed from the moment of impact until the arrival time of the wave at the accelerometer. It corresponds to the time of sound wave propagation from the impact. The distance varies depending on the degree of compaction of the ballast prism. In the case of an increase in the degree of compaction of the ballast prism, the distance (number of points) from the beginning of the impulse to the arrival at the accelerometer decreases. The results of experimental determinations of the speed of sound wave propagation are shown in Fig. 13.

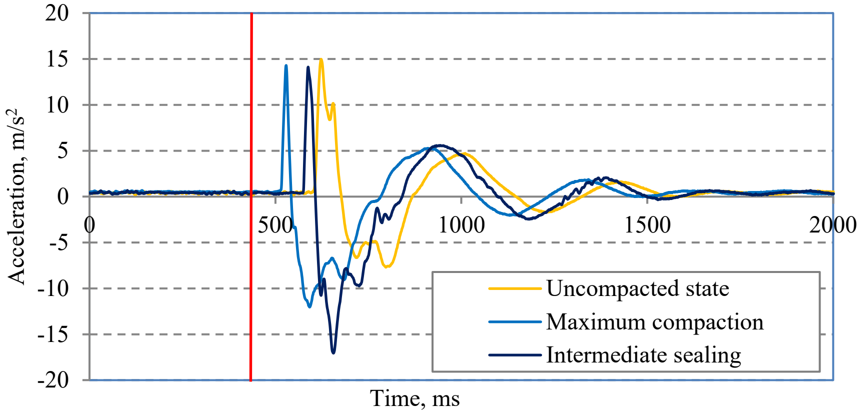


Figure 12

Records wave propagation in three cycles of the experiment

In this experiment, for the case of uncompressed state of the ballast prism, the average speed of propagation of the elastic wave of impact is 137 m/s, for intermediate ballast compaction – 161 m/s, and for maximum layer-by-layer compaction – 188 m/s.

When transferring such a methodology for measuring the speed of wave propagation in the ballast layer from laboratory conditions to operational conditions on a railway track, the sources of radiation will be the wheels of the rolling stock, and the sensor for marking the beginning of the impact can be a strain gauge installed on the rail, which will record the position of the wheel over the calculated section.

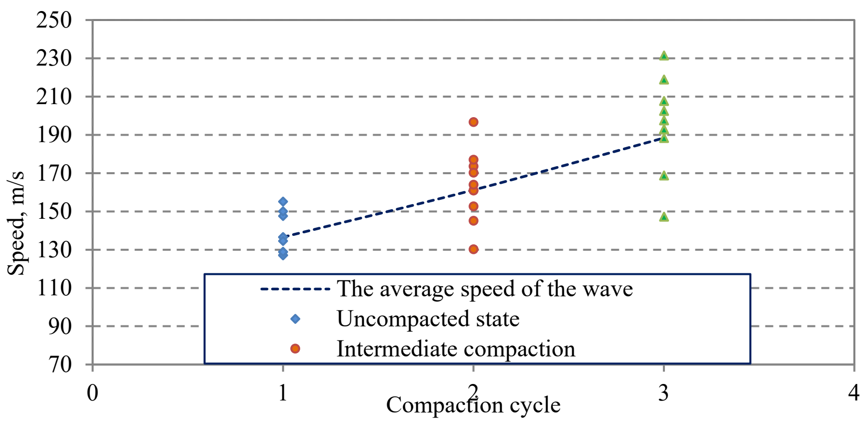


Figure 13

Sound wave propagation velocity

The measurement of the propagation speed of the impact sound wave was conducted by applying ten impacts in each cycle of the experimental studies. In Figure 13, these are represented by different symbols. The measurements for the loose density ballast are indicated by diamonds, the intermediate ballast compaction by circles, and the maximum layered ballast compaction by triangles. Subsequently, the average values of the propagation speed of the impact sound wave were determined.

Conclusions

In order to justify recommendations for the development of a decentralized railway track monitoring system, this study considered several methods of equipping track sections with sensors for long-term use. The general condition was to obtain data on the state of the railway track by assessing its deformation characteristics based on measuring the interaction parameters of the track with rolling stock with a minimal number of installed sensors. The following options were analysed: 1) measuring rail bending stresses with strain gauges; 2) measuring the acceleration of rail and sleeper vibrations with accelerometers; 3) measuring the propagation speed of waves in the ballast. Each method has both advantages and disadvantages.

The method of measuring rail bending stresses with strain gauges uses inexpensive sensors that are easily installed in accessible locations. Stress values not only indirectly indicate the overall track condition but also allow for a direct assessment of a performance indicator such as the axle load of trains. Among the drawbacks, it should be noted the low sensitivity of the results to changes in the general deformation modulus of the sub-rail base.

The method of measuring the acceleration of rail and sleeper vibrations is based on the use of accelerometers, which are installed in easily accessible locations of track elements and are now a common type of sensor. The recorded results depend not only on the condition of the railway track but also on the condition of the rolling stock, especially the wheels. This will expand the application scope of the monitoring system. However, such dependence on many factors is a significant drawback. Separating and evaluating vibration from a specific factor requires amplitude-frequency analysis of the signal and other mathematical tools, so the results do not always have the same interpretation.

The method of measuring the propagation speed of waves in the ballast allows for a direct assessment of the condition of the ballast layer, an important component of the railway track as a whole. However, applying such a method directly to an active section requires installing a sensor beneath the ballast layer, which presents certain technological challenges. Additionally, the combination of the high speed of elastic wave propagation in the ballast with its relatively small thickness necessitates equipment capable of detecting and processing signals at significantly higher frequencies than previous methods.

According to the authors, each of the methods considered, both independently and in combination with others, may have applications in the construction of long-term monitoring systems for railway track condition. Such systems can be useful, both for solving practical track maintenance tasks during operation and for scientific observations.

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