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Horizons of Railway Transport – Determinants of the development of the railway system in the context of the society-wide assessment of investments in railway infrastructure and public passenger transport

Innovative Trends in Railway Condition Monitoring

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Abstract

Provision of functional safety of a railway track requires complementing the existing system of assessment of the railway track condition with the stress-strain behaviour assessment of the rail substructure, i.e. the assessment of the effect of track structure elasticity on the change of its geometric parameters during rolling stock passage over time. There is a lack of available theoretical and practical information about any pivotal changes in this field of science. The subject of the study is the *in-situ* elasticity indicators of a railway track and geometric monitoring indicators of railway structure condition or similar indicators obtained by numerical processing of data provided by the measuring systems of a track recording car and enabling the determination of change of irregularity parameters over time taking into account of the tonnage passed. The outcome of the investigation is the proposed approach to the development of an unparalleled diagnostic loading system which has been the missing part of the "puzzle" in the existing system of integrated assessment of the technical condition of a railway track.

Keywords: condition monitoring; experiments; measurement; railway track ;

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1. Introduction

In contrast to other artificial structures, a railway track operates under the conditions of accumulation of local plastic deformations in all its elements, as the stresses developing in the ballast layer and subgrade are considerably lower than the threshold value that provides failure resistance (Castro et al. 2022; Indraratna et al. 2021; Kampczyk et al. 2022; He et al. 2023; Gu et al. 2022)

The proposed study is aimed at complementing the existing system of assessment of the railway track condition with the stress-strain behaviour assessment of the rail substructure, i.e. the assessment of the effect of track structure elasticity on the change of its geometric parameters during rolling stock passage. The stress-strain behaviour parameter characterizes the readiness of the railway track to perform the functions for normal operation within the limits of the acceptable risk level.

The relevance of the study stems from the necessity to conduct the investigations aimed at developing the criteria for quality assessment of the railway track condition (for fast and high-speed traffic as well as for the freight traffic sections, including the sections of interchange of the cars with higher axial loads) on the basis of the stress-strain behaviour of the railway track. The stress-strain behaviour criteria influence traffic safety and power consumption for train traction as well as the economic component of provision of functionally safe operations of the railway track throughout its life.

The present work aims at demonstrating the necessity to redefine and monitor the stress-strain behaviour parameters of the railway track structure.

The subject of the study is the in-situ elasticity indicators a railway track (Bondarenko et al. 2021; Mazilu et al. 2023; Fischer et al. 2023; Pircher 2021; Li et al. 2022) and geometric monitoring indicators of railway structure condition (Kisilowski and Kowalik 2022; Fernandey-Bobadilla and Martin 2023; Gonzalo et al. 2022; Guerrieri et al. 2023; Kraśkiewicz et al. 2021; Hodas et al. 2022)or similar indicators obtained by numerical processing of data provided by the measuring systems of a track recording car and enabling the determination of change of irregularity parameters over time taking into account of the tonnage passed, and their influence on the track deterioration caused by the stress-strain behaviour of the substructure. The "in-situ" irregularities are considered to be the irregularities that describe the actual plan and profile position of the track in an independent coordinate system and change at an increase in the tonnage passed.

2. Methods of Railway Condition Monitoring

Pursuant to the European norms (Standard B. Railway Applications/Track-Track Geometry Quality and UIC Code 518:2009. Testing and Approval of Railway Vehicles From the Point of View of Their Dynamic Behaviour), the railway track geometry is determined as the spatial position of the two rails. The following concepts should be differentiated:

- designed shape (track geometry or track alignment);
- deviation from the design position (irregularities).

The latter is related to the "quality of track geometry". The terms such as "track irregularity" and "track alignment" are often used. Track position or geometry may be described by the following characteristics:

- track gauge,
- parameters of horizontal circular curves with a certain radius and slope angle,
- parameters of transition curves and very large cants,
- longitudinal gradient of the track and vertical curves.

Standard EN13803-2:2011-03 describes the track alignment parameter requirements, while standard EN13803-2:2010-06 covers the curves and transition curves as well as comparable alignment design situations with abrupt changes of curvature. Based on these standards, a railway track is defined by four values of rail position along the track axis x: $y_L(x)$, $z_L(x)$ for the left rail and $y_R(x)$, $z_R(x)$ for the right rail with reference to the structure trajectory alignment (Fig. 1). Four values defining the rail position along the track axis should also be noted x: $y_L(x)$, $z_L(x)$ for the left rail and $y_R(x)$, $z_R(x)$ for the right rail with reference to the structure trajectory alignment (Fig. 2). The rail coordinate system represents the axis corresponding to the running direction, i.e. axis $\boldsymbol{x}$, while y – parallel to the running surface surface, and z – pointing downwards to the normal working surface. The both coordinate systems are equivalent and have the equation of connection. The commonly used terms do not always clearly refer to one of the coordinate systems:

- longitudinal level (vertical surface profile) z(x) of the track center line or $z_L(x)$, $z_R(x)$ of the two rails;
- alignment y(x) of the track center line or $y_L(x)$, $y_R(x)$ of the two rails;
- cross level $cl(x) = 2b_A \cdot \delta(x)$ of the running surface;
- track gauge g(x).

The information is mainly sourced by automated diagnostic tools, and the completeness and volume of the information obtained increases constantly. To facilitate the perception of the information obtained, it is necessary to be able to visualize the information about the object of diagnostics.

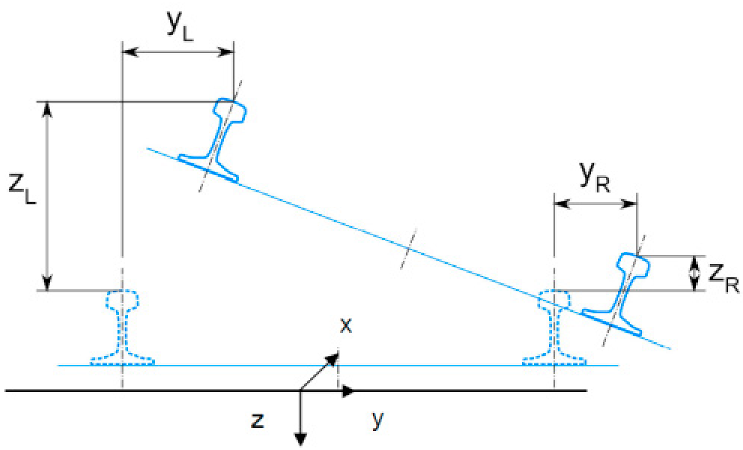

Fig. 1. Coordinate system of the rail.

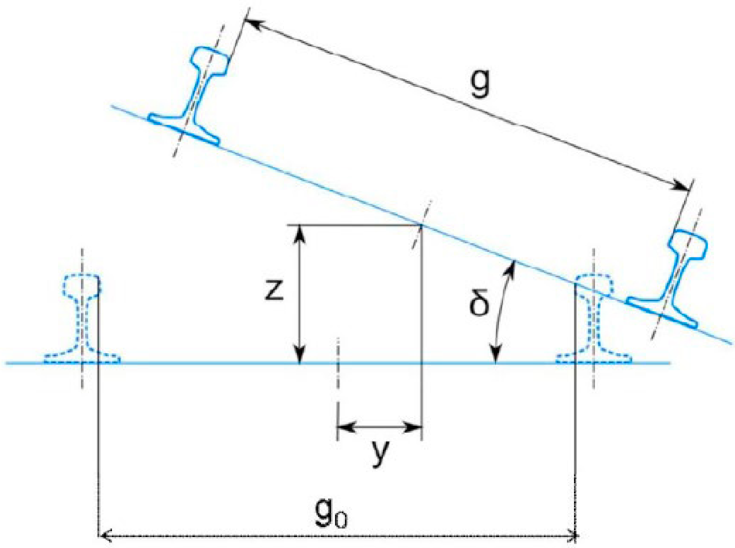

Fig. 2. Coordinate system of the track.

The existing regulations pertaining to the railway network of the Ukrainian Railways are very different from the European regulations in that the former are based on the chord measurements (subsidence, curve versine in the plan). On the other hand, the European regulations describe the irregularities, in addition to the assessment of chord measurements. The irregularities are obtained by the transfer functions or double integration of the accelerations at the axle box (vertical plane). The requirements are then developed for different measuring systems based on length chord measurements.

Figures 3-5 present the interpretations of deviations on the track measuring tape. The rail thread level position is characterized by the magnitude of deviation of the recorded line from the baseline. The actual positions of the rail threads may be depicted in the same way on the recording (Fig. 3).

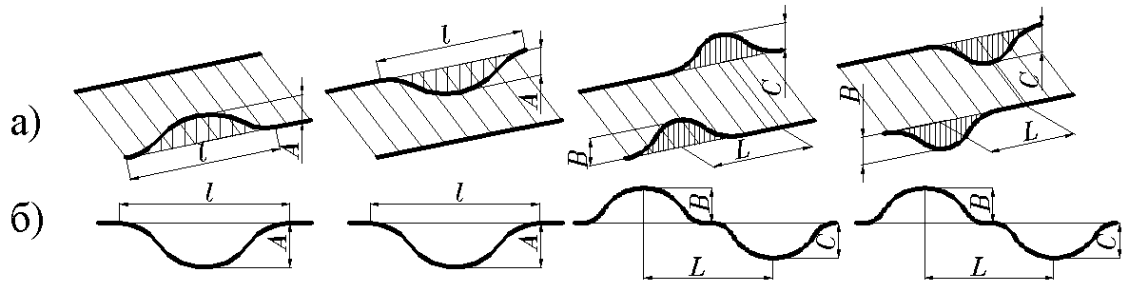

Fig. 3. Level deviations (a) and their depiction on the recording (b): A, B, C – level deviation; ℓ – deviation length; L – distance between the maximum level deviation points.

The direction of rail threads in the plan is reflected by the records of curve versines measured from the gauge face of the rail head to the 21.5 m chord at the point located at the distance of 4.1 m from the end of the chord. The shape of these records differs from the actual geometrical position of the rail threads in the plan and from the graph of curve versines measured from the center of the 20 m long cord. Hence, special templates are needed in order to decode them (Fig. 4).

The subsidence recordings are considered to reflect the actual subsidence of the track (Fig. 5). The shape of subsidence recordings differs from the actual position of the rail threads at the subsidence sites. The magnitude of subsidence is fully depicted on the recording only where the length of the half of subsidence (the zone of descent and ascent) is equal to or less than 2.7 m each (Fig. 5, a). If the subsidence is longer, the subsidence recording is shorter than the actual subsidence (Fig. 5, b).

It should be noted that, for the European railways, it is a commonly recognized practice to apply regulations to the in-situ irregularities as well as track measurement results obtained by other diagnostic methods, with the regulations varying depending on the respective measurement system. This is different from the Ukrainian railways.

Another modern method of continuous track inspection is load testing (Gage Restraint, TrackSTAR, modular rail cars). The method is subject to continuous development both in terms of technical capabilities (speed of diagnostics, measurement accuracy) and regulatory documentation (manuals, methods of instrumental diagnostics, regulatory framework). The main result of the load testing method is the elastic vertical subsidence of the rail-sleeper grid under a calibrated load. It should be noted that, at present, it is technologically possible to individually measure the elastic subsidence of sleepers, rails, and clamping. The magnitude of elastic subsidence depends on the stress-strain behaviour as an indicator of track quality.

Automated diagnostic and control data processing systems are widely used on foreign railways for comprehensive assessment of the condition of infrastructure facilities and identification of the need for maintenance and repair works. These are IRISSys (Germany, the Netherlands), ENSCO (USA), IFS (Sweden), and diagnostic train “Archimedes” (Italy). The assessment of the condition of a track and infrastructure is performed on the basis of integrated indicators and mathematical modelling of the track-rolling stock interaction taking into account the type of the rolling stock, operating conditions, and speeds, as well as loaded and unloaded state of the track with specific track coordinates. Systems of force action by the rolling stock on the track are widely used.

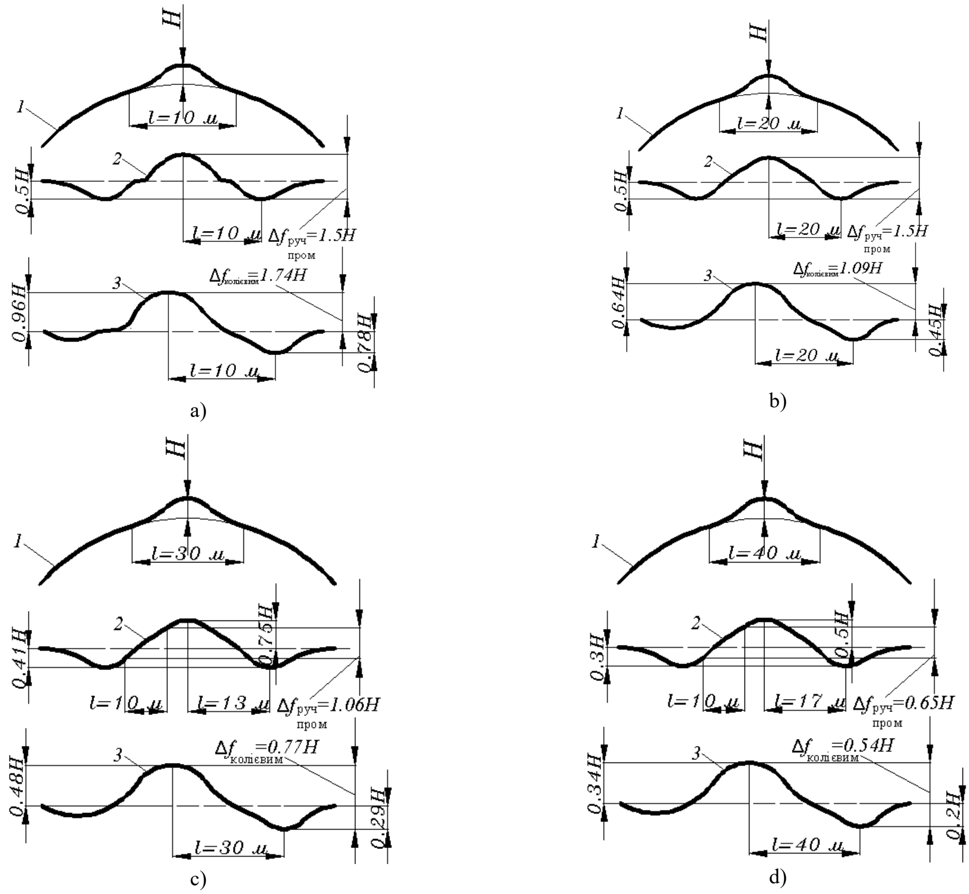

Fig. 4. Depiction of the track irregularities in the plan, length (m): a – 10; b – 20; c – 30, d – 40; 1 – actual track irregularity; 2 – graph of versines measured from the centre of the 20 m long chord; C – track measuring device recording; H – deviation of the track in the plan; ℓ – length of the deviation; Δ – maximum difference of the versines measured from the centre of the 20 m long chord at the points located at the distance of 10 m from each other; Δ – maximum amplitude of the recording.

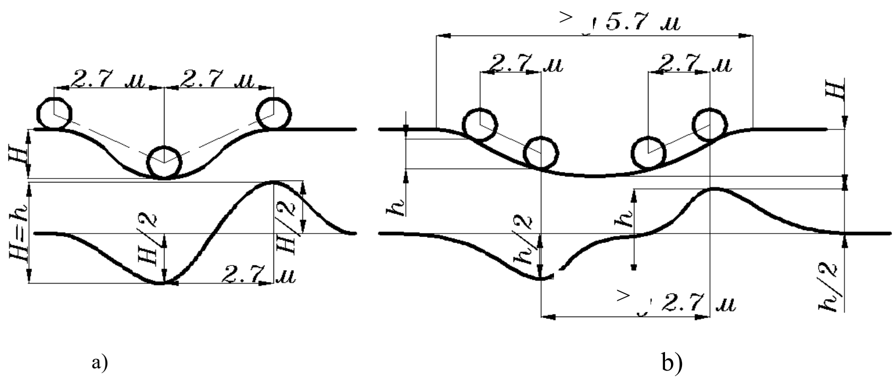

Fig. 5. Recording of the rail thread subsidence, with the lengths: a – up to 5.4 m; b – more than 5.4 m; H – actual subsidence; h – recorded subsidence.

3. Method proposed

Recently, the stress-strain behaviour has been gaining an important role of an integral indicator of reliability of a railway track. The development of technical capabilities and mathematical apparatus for the description of track structure behaviour have enabled not only qualitative, but also quantitative assessment of the stress-strain behaviour.

The key objectives behind the development of the new method are the following:

- implementation of "direct" measurements implying elimination of "indirect" methods of assessment;
- expedience of the method for high-speed traffic and freight traffic at different axial loads;
- necessity to assess the parameters of stiffness of the clamping components, ballast layer, and subgrade.

The major disadvantage of fixing the geometrical position of a rail-sleeper grid is the ambiguity of interpretation of the results of the assessment of its condition. This problem is aggravated by the complete absence of a system for condition assessment of a railway track structure in view of the condition of each of its elements. The introduction of stiffness criteria in the European norms for the track structural elements allows the regulation of their stress-strain state by means of establishing the necessary geometric dimensions of the elements, providing appropriate inter-element contact areas for stress distribution within the depth of the structure. This, however, helps obtain neither the dependence of value measurement on the running speed of the track measuring device nor the scatter of the measured values depending on the wheel pair position in relation to the track axis that determine the conditions of the rail-wheel contact and, in turn, the conditions of variation of load application at which the geometric parameters are established. Moreover, the same track structure would be subject to stress-strain changes specific to the action of a respective type of rolling stock; hence, the track condition assessment using a track measuring device does not enable risk assessment related to the action of other types of rolling stock.

The existing regulatory basis for the assessment of track condition using the loading test rolling stock is designed for the quasi-static condition of a track. Hence, the track loading tests are performed at speeds of up to 40 km/h. At these speeds, the contribution of the dynamic component of the stress-strain behaviour of a track is not accounted for. At high speeds, the track condition is characterized by the static and dynamic components of the stress-strain behaviour. Different speeds lead to different ratios of static to dynamic components of the stress-strain behaviour of a track. Measurement of the dynamic stress-strain behaviour of a track is currently not conducted during the loading tests.

The approaches towards the establishment of the geometric parameters are based on the Fourier transform. The approaches towards track elasticity modelling are based on the selection of a function (of expected occurrence of the changes). This offers an acceptable result that is revised by accounting for the probability of the expected result. These approaches have been prompted by the elasticity theory principles. This is the fundamental theory in the description of changes taking place during the dynamic processes of track-rolling stock interaction. The theory of elasticity describes the processes that change in a certain fixed interval of time. These processes are therefore viewed as quasi-dynamic. Although modern measuring equipment enables process recording, with the process changes being registered in real-time, the required characteristics of the measuring equipment are still prompted by the investigation objectives from the elasticity theory perspective. As a result, large amounts of information registered by the measuring equipment remain unused, since the registered processes are filtered using the filters developed from the practice of the experiments based on the principles of the elasticity theory.

Whereas the measuring equipment of the previous generation would react only to changes in the average energy value over a time interval much greater than the period of oscillation, knowledge of the spectrum was fairly sufficient for the determination of the energy of each harmonic, and thus the determination of the average energy of the total oscillation. For this reason, spectral decomposition played a crucial role in the study of oscillations. Nonetheless, knowing the spectrum of some non-sinusoidal oscillations does not enable the determination of the shape of the oscillation and the plotting of its graph. In addition, the harmonic energies depend only on the amplitude and frequency, and are independent of the phase of the oscillation.

As already mentioned, modern measuring equipment has the ability to record processes with their changes recorded in real-time. Therefore, it is necessary to combine the measurements of geometric parameters and track elasticity parameters, which are the force and geometric parameters, as the amplitudes of oscillations and the characteristics of the acting loads over time are the key information. Meanwhile, the elastic wave theory described by means of vectors should be used as a basis for theoretical modelling (Magalhães et al. 2022; Bondarenko et al. 2022; Bondarenko et al.

2023a,b). Thus, the proposed diagnostic loading system should consist of two wagons with different static loads F_1 and F_2 and measuring equipment located in different locations (I, II, III), registering force and geometric parameters, as shown in Figure 6. Consequently, the assessment of the condition of the track structure and its elements is reduced to the comparison of the registered data obtained for two wagons and recalculated using the theory of elastic waves to the same conditions of impact, taking into account the change in the values of force loads over time, the position of wheel pairs relative to the track axis and the running speed of the rolling stock.

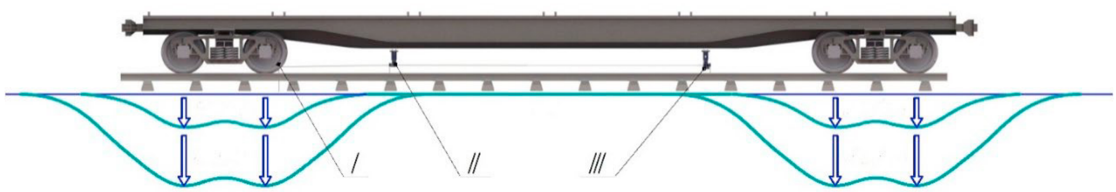

Fig. 6. Measurement scheme of the proposed diagnostic loading system.

4. Conclusions

In this work, an innovative method was proposed for creating a diagnostic loading system based on combining measurements recorded on track recording cars and load-testing trains. The main advantage of this combination is the ability to evaluate load measurements using both accelerometers and of strain gauge instrumented sections of wheelsets, under known static force loads. Fixed placement of measuring devices in certain locations both along the length and height of the diagnostic load complex ensures tracking of changes in force influences in the ongoing vibration processes. The combination of force and geometric measurement systems into a single time system ensures tracking of changes in vibration processes from the impact-response point of view. And the use of the ability of the theory of elastic waves to describe the superposition of various waves in time using the propagation of vectors in time combines force and geometric parameters in time, taking into account the time of achievement of impacts and the appearance of responses from various elements. This approach makes it possible to use the capabilities of modern measuring equipment and draw up correlation dependencies over time, expanding the understanding of the vibration processes that take place when rolling stock travels along a railway track.

The proposed approach towards track diagnostics will enable the determination of the following in view of risk assessment:

- permissible axial loads and permissible running speeds for the lines in operation;
- the optimal structure of the railway track;
- scope and types of track repairs;
- violation of the repair and construction process at the stage of work acceptance.

The proposed diagnostic loading system is unparalleled and is the missing part of the "puzzle" in the existing system of integrated assessment of the technical condition of a railway track. Determination of stress-strain behaviour parameters in the mode of continuous inspection will allow to considerably accelerate the track monitoring process and reduce the cost of its reconstruction. The system of measuring the stress-strain parameters under different axial loads will allow to use the diagnostic loading system both on high-speed and freight traffic lines.

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