SATBAYEV UNIVERSITY

Architecture and Civil Engineering

Volume 2 (2025), Issue 2, 19-24

https://doi.org/10.51301/ace.2025.i2.04

Innovative approaches to the interaction of the metal bridge superstructure with rolling stock

A. Bondarenko[1], S. Shayakhmetov[2], A. Zhangabylova[2*]

[1]*Volga Region State Transport University, Samara, Russia*
[2]*Satbayev University, Almaty, Kazakhstan*

**Corresponding author:* zhangabylova@mail.com

Abstract. As part of the study, eight numerical experiments were conducted to simulate the movement of rolling stock across a span structure. To assess the influence of the elastic and inertial properties of the span structure on the safety of train operation, a series of calculations was performed for movement along an embankment, where both the track alignment and profile were assumed to be straight. However, rail irregularities and worn wheel profiles were considered, just as in the calculations for movement over the span structure. To reflect the fact that in actual operation wheel profiles undergo wear over time, all simulations were carried out using worn wheel profiles. This method essentially reduces the approximation of a continuous medium with an infinite number of degrees of freedom to a set of subdomains (or elements) with a finite number of degrees of freedom. For each element, shape functions are defined that allow for the determination of the displacement field within the element based on the displacements at the nodes, i.e., at the junctions of the finite elements (FE).

Keywords: *steel span structure, track superstructure, railway embankment, finite element method, mathematical modeling, bridge structures, rolling stock.*

1. Introduction

During the design process of any structure, the engineer must evaluate its stress-strain state. This requires understanding the distribution of stresses across all elements of the designed structure, as well as determining the displacements of key points under both static loading and time-varying loads. Today, the design and analysis of bridge structures are impossible without the use of modern computer technologies. Finite Element Method (FEM) software packages tailored for bridge design are widely employed. These tools enable the creation of computational finite element models of structures with minimal labor costs. They include specialized features necessary for bridge calculations, such as influence line construction for moving loads, node connection modeling, local stability checks, thermal stress analysis of supports, and more [11].

Traditionally, solving such problems requires determining a system of equations that satisfies both equilibrium conditions and compatibility of deformations. A key challenge arises when dealing with complex two- or three-dimensional structures: the system behavior is described by high-order equations with a large number of unknowns. One way to address this challenge is to use approximate solution methods. At present, the most effective approximation method for solving applied mechanics problems is the Finite Element Method (FEM) [17].

Essentially, FEM reduces the approximation of a continuous medium with an infinite number of degrees of freedom to a collection of subdomains (or elements) with a finite number of degrees of freedom. For each element, shape functions are defined to determine the displacement field within the element based on the displacements at its nodes—that is, at the junctions of finite elements (FEs).

Interaction between FEs occurs only through their nodes. External loads applied to an element—such as concentrated or distributed forces and moments—are translated to the nodes and are referred to as nodal loads. In FEM calculations, the nodal displacements are determined first. Internal forces within the element are proportional to these nodal displacements. The proportionality factor is a stiffness matrix, which is square in form and has a number of rows equal to the number of the element’s degrees of freedom. All other element parameters, such as stresses and displacement fields, are computed based on the nodal displacements.

The main types of finite elements used in practice are:

- Beam (or bar) elements;
- Shell/plate elements;
- Solid (volume) elements.

A wide range of structural models and components can be described using different types of FEs or their combinations. However, this approach is not applicable to geometrically unstable structures that may transform into mechanisms during deformation.

1.1. Analysis of Existing CAD Systems Used in the Design of Metal Structures

Currently, the design and analysis of bridge structures are impossible without the use of modern computer technologies. These technologies are implemented through FEM-based software packages tailored for the analysis of bridge structures, such as LUSAS (UK), GTSTRUDL (USA), MIDAS/CIVIL (Korea), RM BRIDGE (Austria), SOFISTIK, MICROFE (Germany), SCAD Soft (Russia), LIRA

(Ukraine), ANSYS, NASTRAN, Cosmos-M, SolidWorks (USA), among others. These tools enable the creation of finite element models of structures with minimal labor input. They include essential features specific to bridge design, such as influence line generation for moving load analysis, node connection modeling, local stability checks, and stress-strain state analysis of supports, among others [24].

Experience using MIDAS/CIVIL in bridge structure analysis has repeatedly demonstrated that serious calculation and design errors can occur, particularly when working with complex bridge structures. Therefore, the results obtained using this software must be carefully analyzed and verified.

The RM BRIDGE software package specializes in dynamic analysis of bridge structures. Particularly valuable are its developments in the field of aerodynamic analysis of cable-stayed bridges, implemented as separate advanced modules. RM BRIDGE enables end-to-end parameterization of finite element models, allowing models to be rebuilt in a short time. It also accounts for rebar and pre-stressed reinforcement in concrete structures. The software integrates design codes, allowing for checks of strength, stability, crack resistance, and durability.

The most labor-intensive part of the structural analysis process is the creation of finite element models. When calculations need to be performed on the same structure using different software packages, the model must be recreated multiple times, significantly increasing workload. In such cases, special tools for automatic conversion of source data between software systems are essential. However, bridge-oriented programs usually lack built-in data conversion modules. As a result, bridge engineers often need to develop such tools independently, for example, to convert models from GTSTRUDL to MIDAS/CIVIL or from MIDAS/CIVIL to SCAD. These converters help prevent errors when creating analysis models. Thus, model conversion tools are a necessary part of the software suite used for analyzing bridge structure elements.

In this work, the use of the aforementioned software packages is primarily aimed at investigating lateral vibrations, their causes, and the factors influencing the interaction between rolling stock and the span structure.

Using mathematical modeling methods, the loss of stability in the motion («hunting oscillation») of empty freight wagons on model 18–100 bogies was studied [3, 4, 5]. The influence of wheel profile wear on the critical speed at which the hunting motion begins was determined. This zigzag motion leads to periodic lateral impacts of wheels against the rails [6], which is a key factor in exciting lateral vibrations of the span structure during interaction with rolling stock. Numerical modeling revealed a resonant mode of lateral horizontal vibrations in the span structure at the maximum permissible freight train speed of 90 km/h, caused by the coincidence of the span's natural lateral frequency with the frequency of the wagon's hunting motion.

To assess the effect of the elastic and inertial (dynamic) properties of the span structure on the safety of wagon movement, additional simulations were performed where the span structure was not modeled, and the train moved solely along the railway embankment. By comparing the dynamic behavior of wagons in both scenarios, conclusions were drawn about the influence of the span structure under specific operating conditions—namely, deviations of rail geometry from the ideal, wheel profile wear, and train speed.

Analysis of the forces arising in the wheel–rail contact made it possible to determine safe speed limits for the movement of empty freight wagons under the given track conditions, wheel wear, and in the absence of wind.

Additionally, with access to early 20th-century experimental data [7] on the interaction between rolling stock and simply supported girder spans of railway bridges, it became possible to compare the magnitudes of lateral vibrations in historical and modern span structures, considering all changes in railway infrastructure. This comparison highlighted key factors influencing lateral vibrations of span structures during train interaction, both in the early 20th century and today.

2. Materials and methods

Currently, to achieve the highest accuracy and the most comprehensive understanding of the phenomena occurring during the interaction between train loads and the bridge span structure, it is advisable to use specialized software packages—for example, the RM BRIDGE software suite, which enables dynamic modeling of the «span structure – track – rolling stock» system. Safety analysis of train movement becomes explicitly possible based on the results of solving the wheel–rail contact problem for each wheel of the rolling stock at every integration step. Let us consider the process of mathematical modeling of the interaction between a steel bridge span structure and rolling stock.

Span Structure

A three-dimensional finite element model was created for the span structure. In this model, the transverse and longitudinal girders of the top chord were represented using plate elements, while the remaining structural components were modeled using beam elements (Figure 1).

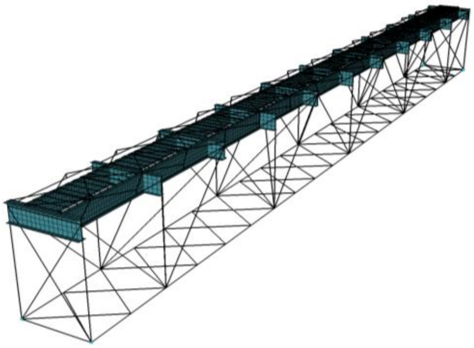

Figure 1. Finite element model of the span structure

The elastic displacements of the span structure were determined using the Craig–Bampton method. This method allows the nodal displacements of the finite element model of the span structure to be expressed through the elastic mode shapes of the structure:

$$\bar{u} = Hq \qquad (1)$$

where: u - is the nodal displacement vector of size N × 1; N - is the number of degrees of freedom in the finite element model; H - is the modal matrix of size N × k, whose columns contain the transformed eigenmodes and static modes; k - is the total number of modes used; q - is the modal coordinate vector of size k × 1.

The main advantage of representing structural displacements in a basis of elastic modes, as opposed to direct integration of the full finite element model, is the significant reduction in the number of unknowns from N to k. For example, the current model includes 8,585 nodes, which corresponds to a total of 8,585 × 6 = 51,510 degrees of freedom (unknowns). After applying kinematic boundary conditions, this number is reduced to 51,503 unknowns. To build the dynamic model of the span structure, 168 transformed vibration modes and 24 static modes were used. The resulting system contains 192 modal coordinates as unknowns, which are determined by integrating the equations of motion of the «span structure – track – rolling stock» system. Thus, the number of unknowns was reduced by two orders of magnitude.

To account for structural damping in the system, a damping ratio of $\zeta = 0.5\%$ was assigned to each modal coordinate. This corresponds to a logarithmic decrement of $\delta = 0.03$, as specified in the standards [8] for bridges with high-strength bolted connections.

Track Superstructure

The track superstructure on the bridge was modeled as a ballastless bridge deck (BBT). For modeling the reinforced concrete BBT slabs, beam elements were used. For the rails and rail fasteners, Timoshenko beam elements were applied. Unlike the Bernoulli beam model, the Timoshenko beam model accounts not only for bending deformations but also for shear deformations, which may be significant in this case. A system of springs and dampers was used to simulate the rail fastenings.

The finite element model of the rail in Universal Mechanism software approximates a system of six partial differential equations [9]. To illustrate the modeling concept of the track structure, Figure 2 presents the track model on the railway embankment.

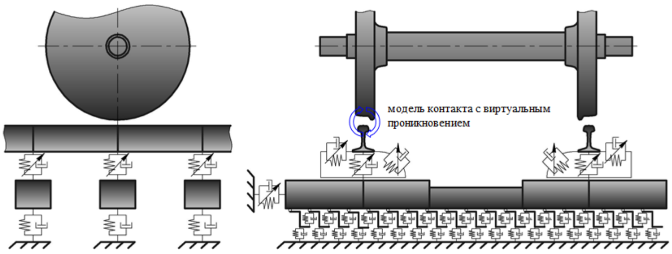

Figure 2. Diagram of the mechanical interaction between the wheelset and the track

Rolling Stock

In this study, the rolling stock is modeled as a train consisting of 23 empty open freight wagons (Figure 3).

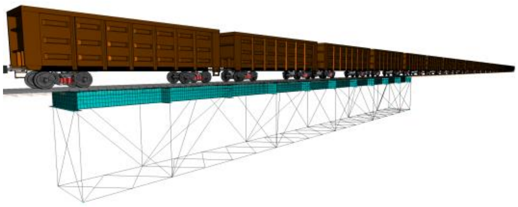

Figure 3. Model of the rolling stock

In this study, a double locomotive is not included in the simulation, as its influence on the lateral vibrations of the span structure can be neglected. This is supported by previous research [10], which showed that the motion of locomotives and loaded freight wagons is significantly more stable. Each bogie (running gear) is modeled as a system of rigid bodies connected by elastic and dissipative elements. Figure 4 presents the first two natural modes and corresponding frequencies of an empty open freight wagon.

Figure 4. Forms of wagon oscillations: upper lateral roll – on the left, bouncing – on the right

Table 1. Natural frequencies of oscillations of an empty gondola car

№ п.п.	Mode	Frequency, Hz
1	Upper lateral sway	2.42
2	Bouncing	4.89

Solution of equations of motion

In general, the system of equations of motion of the system «span structure - track - rolling stock» is presented in the form (2):

$$M(q,t)\ddot{q} + k(q,\dot{q}) = Q(q,\dot{q}) + G(q)\lambda \qquad (2)$$

To integrate this system of equations, the implicit Park method is used, which is capable of solving stiff differential equations [11]. The implicit integration scheme leads to solving a system of nonlinear algebraic equations at each time step, which is handled using the Newton–Raphson iterative method [12].

Influencing Factors on System Behavior

The following factors were considered in the study:

- Train speed;
- Wheel profile wear;
- Track irregularities;
- Elastic and inertial characteristics of the span structure.

The simulations were conducted across a speed range of 40 to 120 km/h, in increments of 10 km/h.

To account for the real-world effect of wheel profile wear over time during wagon operation, all simulations were performed using worn wheel profiles. The worn profile was obtained through numerical experiments using the problem-oriented UM Wheel/Rail Wear module. The term «moderately worn» indicates a wear state corresponding to a running distance of 100,000 kilometers, which is approximately half the distance to scheduled wheel re-profiling.

The calculation methodology considers statistical operational factors that influence wheel wear, including track macrogeometry (distribution of straight and curved sections), train speed, loading, and other parameters. The worn profiles used in this study were generated using the Archard wear model [13], based on the hypothesis of a linear relationship between the volume of wear and the work done by frictional forces.

Figure 5 shows the new and worn wheel profiles used in the simulations.

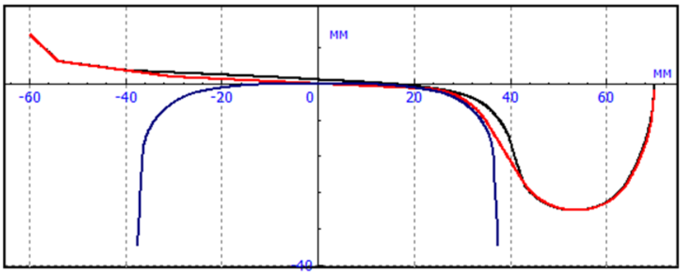

Figure 5. New profile – red, worn profile – black

At the same time, the track superstructure exhibits both vertical and horizontal deviations from standard geometric parameters. To account for this factor, track irregularities were included in the numerical experiments (Figure 6).

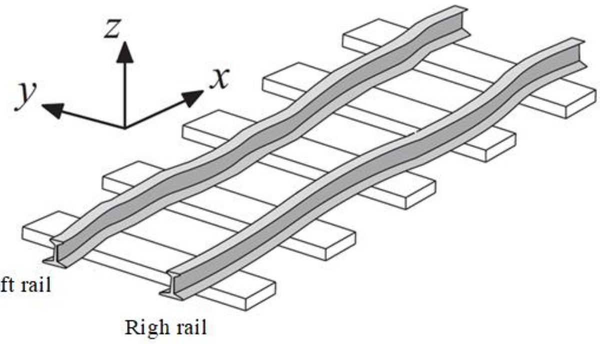

Figure 6. Track irregularities

The track irregularities were generated based on power spectral densities and correspond to a good track condition in accordance with UIC standards [14] (International Union of Railways). The applied empirical formulas are provided in [15, 16].

3. Results and discussion

As part of the study, eight numerical experiments were conducted to simulate the movement of rolling stock over the bridge span structure. To assess the impact of the elastic and inertial properties of the span structure on train running safety, a series of calculations was also performed for train movement along the railway embankment, where the track alignment and profile were assumed to be straight. However, rail irregularities and wheel profile wear were considered, just as in the simulations involving the span structure.

Figure 14 shows the dependence of the amplitude of lateral vibrations of the span structure on the train speed.

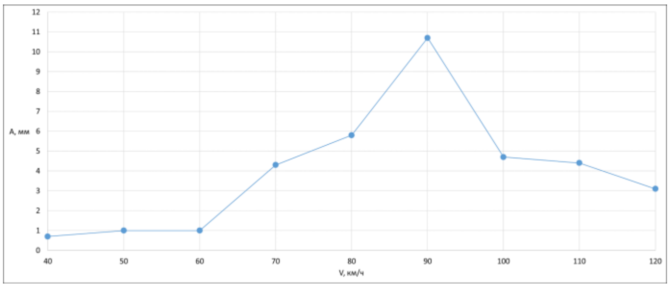

Figure 14. Dependence of the amplitude of transverse vibrations in the middle of the span on the speed of the train

Comparison of Experimental Data from Table 3 on Span Structure Vibrations in the Early 20th Century with the Results of Modern Structure Simulations Leads to the Following Conclusions:

- Under modern operating conditions and at speed regimes similar to those in Table 3, the impact of rolling stock on the span structure is significantly lower. For example, in a simulation at 60 km/h, the amplitude of lateral vibrations was 1 mm, whereas the experimental data from the early 20th century shows amplitudes of 9 mm for span vibrations caused by steam locomotives. The much larger vibration amplitudes observed during early 20th-century tests can be attributed to the design features of steam locomotives, such as oscillations induced by the eccentric drive mechanisms of the wheels [20]. Analysis of the critical speeds of modern locomotives and results from previous studies of a special-span structure with two 176 m spans [10] also confirm their significantly lower dynamic impact on the span structure compared to steam locomotives.
- However, with increased train speeds, a new issue has emerged—instability in the motion of empty wagon bogies, known as hunting oscillation. According to the simulations, this factor now primarily determines the critical operating speeds and the maximum dynamic interaction between the rolling stock and the span structure. In the resonance mode, the lateral vibration amplitudes can reach 11 mm, which exceeds the dynamic impact observed with steam locomotives.

4. Conclusions

The results obtained in this and previous studies [1], [2] demonstrate that, with the current level of advancement in computational technologies and numerical methods, it is now possible to solve highly complex problems that were previously addressed only through full-scale physical experiments. Numerical methods make it feasible to simulate phenomena for which the development of analytical models and their general solutions is extremely difficult or impossible.

It is essential to conduct a comprehensive numerical study of a typical railway bridge span with a length of L = 55 meters, featuring top-running track, considering the wide range of factors that affect the safety of rolling stock movement, including wind loads, which were previously excluded for the sake of simplification and factor differentiation.

Key directions for further research include:

- Solving the combined-effect problem, incorporating multiple factors such as rail irregularities, wheel wear, wind loads, etc., and establishing acceptable limits for these factors within a numerical methodology for railway bridge traffic safety assessment;
- Applying the developed methodology to analyze a broad range of bridge span types;
- Reevaluating existing approaches to defining and regulating vertical and horizontal stiffness of bridge structures, as well as camber (construction rise).

Acknowledgements

The author expresses his sincere gratitude to Doctor of Technical Sciences Aleksey Alekseevich Bondarenko for valuable recommendations and assistance in preparing the article. Also thank you for providing the data necessary for the study and for assistance in the technical processing of materials.

References

[1] Savenko, A.I., Semeiko, N.V. (2020). Study of the Influence of Span Structure Stiffness on the Dynamics of Rolling Stock. *Institute Giprostroymost. (14), 194–202*

[2] Savenko, A.I., Semeiko, N.V. (2021). Study of Resonant Oscillations in a Typical 55 m Span Structure During Dynamic Interaction with Freight Rolling Stock. *Institute Giprostroymost, (15), 196–215.*

[3] Bondarenko, A.A., Savenko, A.I. & Semeiko, N.V. (2023). On the Application of Modern Methods for Analyzing Safety on Railway Bridges. *Railway and Track Economy, (1), 28–30*

[4] Shayakhmetov, S.B., Seitkazinov, O.D. & Sikimbekova, K.T. Automated Design of Railway Bridge Structures. *Bulletin of the Kazakh Leading Architectural and Civil Engineering Academy, 4(78)*

[5] Roman, Yu.S. (2019). Stability of Wagon Movement on Bogies 18–100. *Bulletin of VNIIZHT, 78(3), 149–154*

[6] Kossov, V.S., Berezin, V.V. & Bykov, V.A. (2012). Factors Affecting the Stability of Empty Wagons. *World of Transport, (2), 168–177*

[7] Bondar, N.G., Kozmin, Yu.G., Roitburd, Z.G., Tarasenko, V.P. & Yakovlev, G.N. (1984). Interaction of Railway Bridges with Rolling Stock. *Moscow*

[8] Yatsyna, M.N., Paton, E.O. (1926). On the Issue of Free Lateral Oscillations of Span Structures. *Study of Deformations in Metal Span Structures Under Temporary Load, (3–5), 213–235*

[9] EN 1991-1-4:2005+A1. (2010). Actions on Structures – Part 1-4: General Actions – Wind Actions. *European Committee for Standardization (CEN), Brussels*

[10] User Manual. Modeling the Interaction of Railway Crews and Track in the «Universal Mechanism» Software Package. *Retrieved from*: http://www.universalmechanism.com/download/90/rus/27_um_flexible_railway_track.pdf

[11] Pogorelov, D. (1998). Differential-Algebraic Equations in Multibody System Modeling. *Numerical Algorithms, (19), 183–194*

[12] Archard, J.F. (1953). Contact and Rubbing of Flat Surfaces. *Journal of Applied Physics, 24(2), 981–988*

[13] UIC. (2005). Code 518 – Testing and Approval of Railway Vehicles from the Perspective of Their Dynamic Behavior – Safety – Track Fatigue – Ride Quality. *UIC, Paris, France*

[14] Quarz, V. (2004). Generation of Track Disturbances for Given Spectral Densities Using Orthogonal Functions. *Dissertation, Dresden: University of Dresden*

[15] Berawi, A.R. (2013). Improving Track Maintenance Using Power Spectral Density (PSD). *Dissertation for Doctor of Philosophy in Transport Systems, Porto*

[16] EN 14067-6. (2010). Railway Applications – Aerodynamics – Part 6: Requirements and Test Procedures for Cross Wind Assessment, European Committee for Standardization (CEN). *Brussels*

[17] Nadal, M.J. (1896). Theory of Locomotive Stability, Part 2, Yawing Motion. *Annales des Mines, (10), 232*

[18] SP RK 3.03-113-2014. Bridges and Culverts. Rules for Inspections and Testing. *Almaty, Committee for Construction, Housing and Communal Services, and Land Resources Management of the Ministry of National Economy of the Republic of Kazakhstan*

[19] Rules for the Arrangement and Maintenance of Artificial Structures on Railway Transport. *Astana: JSC «NC «Kazakhstan Temir Zholy»*

[20] Order of the Minister of Transport and Communications of the Republic of Kazakhstan No. 944 dated November 26, 2013. On Approval of the Professional Standard «Current Repair and Maintenance of Artificial Structures on the Railway Main Network

[21] Instruction for the Maintenance of Artificial Structures CP-628-78-03. *Astana, Ministry of Transport and Communications of the Republic of Kazakhstan*

[22] SNiP 3.03-113-2014. Bridges and Culverts. Rules for Inspections and Testing. *Almaty, Committee for Construction, Housing and Communal Services, and Land Resources Management of the Ministry of National Economy of the Republic of Kazakhstan*

[23] NTP RK 03-02.1-2012. Design of Steel Structures. Part. Steel Bridges

[24] Instruction on the Application of High-Strength Bolts in Operational Bridges. (1997). *Approved by the Order of the Minister of Transport and Communications*

[25] Donets, A.N., Solovyov, L.Yu. & Tikhomirov, S.A. (2010). Design of Metal Bridges. Calculation of the Roadway. *Novosibirsk: Publishing House of SGUPS*

Жылжымалы құраммен металл көпір қондырмасының өзара әрекеттесуінің инновациялық тәсілдері

А. Бондаренко[1], С. Шаяхметов[2], А. Жанғабылова[2*]

[1]*Еділ мемлекеттік қатынас жолдары университеті, Самара, Ресей*
[2]*Satbayev University, Алматы, Қазақстан*

**Корреспонденция үшін автор:* zhangabylova@mail.com

Аңдатпа. Зерттеу барысында көпірдің үстіңгі құрылымымен жылжымалы құрамның өзара әрекеттесуін модельдеу үшін сегіз сандық тәжірибе жүргізілді. Көпірдің серпімділік және инерциялық қасиеттерінің пойыздардың қауіпсіз қозғалысына әсерін бағалау мақсатында, жолдың түзулігі мен профилі тікелей деп қабылданған жағдайда, жер төсемі бойынша қозғалу үшін бірқатар есептеулер жүргізілді. Алайда, рельс ақаулары мен тозған доңғалақ профилдері есептеулерде ескерілді. Шынайы пайдалану барысында доңғалақ профилдерінің уақыт өте келе тозатынын көрсету үшін барлық модельдеу тозған доңғалақ профилдерімен жүргізілді. Бұл әдіс үздіксіз ортаны шексіз еркіндік дәрежелерімен аппроксимациялауды шектеулі еркіндік дәрежелері бар элементтер жиынтығына айналдырады. Әр элемент үшін пішін функциялары анықталады, олар түйіндердегі орын ауыстыруларды негізге ала отырып, элемент ішіндегі орын ауыстыру өрісін анықтауға мүмкіндік береді.

Негізгі сөздер: *металл көпірдің үстіңгі құрылымы, теміржол төсемі, жер төсемі, шекті элементтер әдісі, математикалық модельдеу, көпір құрылымдары, жылжымалы құрам.*

Инновационные подходы к взаимодействию металлической мостовой надстройки с подвижным составом

А. Бондаренко[1], С. Шаяхметов[2], А. Жанғабылова[2*]

[1]*Приволжский государственный университет путей сообщения, Самара, Россия*
[2]*Satbayev University, Алматы, Казахстан*

**Автор для корреспонденции: zhangabylova@mail.com*

Аннотация. В рамках исследования проведено восемь численных экспериментов для моделирования движения подвижного состава по пролетной конструкции. Для оценки влияния упругих и инерционных свойств пролетной конструкции на безопасность движения поездов выполнен ряд расчетов для движения по земляному полотну, где как выравнивание, так и профиль пути предполагаются прямыми. Однако учтены неровности рельсов и изношенные профили колес, как и в расчетах для движения по пролетной конструкции. Для отражения того, что в реальной эксплуатации профили колес со временем изнашиваются, все симуляции проводились с использованием изношенных профилей колес. Этот метод, по существу, сводит аппроксимацию непрерывной среды с бесконечным числом степеней свободы к набору поддоменов (или элементов) с конечным числом степеней свободы. Для каждого элемента определяются функции формы, позволяющие определить поле перемещений внутри элемента на основе перемещений в узлах, то есть на стыках конечных элементов (КЭ).

Ключевые слова: *стальная пролетная конструкция, верхнее строение пути, железнодорожное полотно, метод конечных элементов, математическое моделирование, мостовые сооружения, подвижной состав.*

Received: 19 January 2025
Accepted: 15 June 2025
Available online: 30 June 2025