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LOAD OF THE WAGON-PLATFORM FOR TRANSPORTATION OF BULK CARGOES

Purpose. To substantiate the improvement of the load-bearing element of the wagon-platform for the possibility of transporting bulk cargoes.

Methodology. In order to be able to transport bulk cargo on the wagon-platform, it is proposed to install a composite boiler module on it. In order to determine the dynamic load of the improved load-bearing structure of the wagon-platform, mathematical modeling was performed. The mathematical model formed by professor Bohomaz H.I. was used. However, within the framework of the research this model was refined to determine the load of the wagon-platform of the proposed design. The solution of the system of differential equations is carried out in the MathCad software package. To do this, the mathematical model was reduced to the normal Cauchy form, and then integrated by the Runge-Kutta method. The obtained acceleration is taken into account when calculating the strength of the advanced load-bearing structure of the wagon-platform. The calculation is performed in the SolidWorks Simulation software package, which implements the finite element method. Also, within the research the modal analysis of a load-bearing structure of the wagon-platform is carried out.

Findings. Based on the calculations, it is established that the acceleration acting on the load-bearing structure of the wagon-platform car is 0.38 g, i.e. it is within acceptable limits. The results of the calculation of the strength of the improved design of the wagon-platform showed that the maximum equivalent stresses occur in the area of interaction of the spine beam frame with the pivot and is about 340 MPa, the maximum displacement made 8.6 mm. That is, the obtained stresses do not exceed the yield strength of the structural material. The results of the modal analysis showed that the values of the natural frequencies of oscillations are within acceptable limits, because the first natural frequency has a value greater than 8 Hz.

Originality. The scientific substantiation of improvement of a load-bearing structure of a universal wagon-platform to transportations of bulk cargoes is carried out.

Practical value. The conducted research will promote increase in efficiency of operation of railway transport and creation of developments concerning planning of innovative designs of a rolling stock.

Keywords: *transport mechanics, wagon-platform, dynamic loading, strength, load modeling, modal analysis*

Introduction. One of the leading vectors of development of the National Transport Strategy of Ukraine until 2030 is the development of rolling stock. A promising direction in this regard is the introduction of removable bodies, which are characterized by mobility and the ability to transport almost all modes of transport. At the same time, it is possible to transport not only piled up, bulk, container and artificial cargoes, but also bulky ones, which is a significant segment of the transportation process of many European countries in international traffic.

However, the introduction of removable bodies in operation requires additional investment. Therefore, it is possible to create such modular systems based on existing wagon designs. Since the main component of this vehicle is the frame, the appropriate solution is to use the existing fleet of wagon platforms, taking into account their appropriate modernization.

In addition, when creating removable modules, it is advisable to use promising materials of their construction, which have a light weight while providing strength conditions.

In this regard, it is important to justify the feasibility and design of modular wagons based on existing structures. This will help to increase the efficiency of the railway industry, maintain its competitiveness, increase economic performance of states, etc.

Therefore, the issue of creating modular wagons on the basis of existing structures is a topical and promising issue.

Literature review. The issues of putting modular wagons into operation are quite relevant. It is important to use advanced materials in their manufacture to improve technical, economic, operational and environmental performance.

The paper [1] highlights the prospects for development and features of the introduction of multimodal removable bodies in China. The technical characteristics and transport advantages of different models of removable bodies are consid-

ered. However, the authors did not consider the requirements for the creation of promising designs of removable bodies.

The issues of dynamic loading of combined transport trains during transportation by rail ferries are considered in the study [2]. The conditions under which the safety of their transportation by sea is ensured are determined, taking into account the typical interaction of vehicles with each other. It is important to say that the authors of the work did not pay attention to the improvement of load-bearing structures of wagons to ensure the safety of their operation.

The issue of introducing advanced materials into the load-bearing structures of vehicles is covered in many scientific publications.

Thus, studies of the impact strength of railway wagons-tanks made of composite materials reinforced with fiber are given in the publication [3]. The influence of the initial tension on the strength of the boiler is considered. It was found that the effect of the initial tension is more significant in the case when the load acts in parallel in the direction of the main fiber. However, the study does not determine the influence of the use of composite materials on the dynamic load of wagons. The study [4] substantiates the use of polymer composite materials in wagon construction. These materials are proposed to be used in the manufacture of wagon flooring. The results of experimental research by the method of compression molding in the form are highlighted. It is important to say that the possibility of using this material in the manufacture of load-bearing elements of the bodies of the authors is not considered.

Features of production and use of modern polymer composite materials in the manufacture of railway wagons is carried out in the study [5]. The research focuses on the development of nanocomposites from recycled polypropylene reinforced with natural fiber. It should be noted that the work does not pay attention to the issue of determining the strength of the load-bearing structure of the wagon with the use of this material.

The study [6] highlights the peculiarities of the use of composite panels in freight wagon structures. This implementation is proposed to be carried out during the modernization of wagons to protect against corrosion damage and facilitate the unloading of trucks in winter conditions.

The authors herewith substantiate the use of composite elements (panels) on the example of side walls. To reduce the packaging of the wagon while providing conditions of strength, it is advisable to conduct research on the use of composite materials and other components of the load-bearing structures of wagons.

Peculiarities of Sgnss car body modernization are covered in the study [7]. This modernization is proposed taking into account the dynamic loads to which the wagon was subjected at the testing stage. The article also presents the results of numerical determination of the strength of its body under the action of operating loads. However, this wagon structure is made of steel and is characterized by significant packaging.

The study [8] gives the determination of the stress state of the wagon body with laminated composite walls. The authors determined the optimal wall thickness of the wagon, taking into account their operational strength. The use of composite material as components of the wagon body is justified. At the same time the design of this wagon does not allow to carry out transportation of bulk cargoes.

Unsolved aspects of the problem. The literature review shows that the issues of improving the technical and economic performance of vehicles, including removable bodies, through the introduction of new advanced materials are quite promising and relevant, but their development requires further study. This situation necessitates research and the creation of appropriate developments in this direction.

The purpose of the study. The purpose of the article is to substantiate the improvement of the load-bearing structure of the wagon-platform for the possibility of transporting bulk cargo.

Methods. To achieve this goal, the following tasks are defined:

- propose measures to adapt the wagon-platform to the transportation of bulk cargo;
- to determine the dynamic load of the improved design of the wagon-platform;
- to determine the main indicators of strength of the improved design of the wagon-platform;
- to conduct a modal analysis of the improved design of the wagon-platform.

Introduction of the basic material. In order to be able to use the load-bearing structure of the universal wagon-platform for the transportation of bulk cargo, it is proposed to install a boiler module on it (Fig. 1).

The boiler is supported on the frame of the wagon-platform by means of wooden bars mounted on metal supports. It means the braking scheme is used, identical to that which takes place in tank wagons.

The fastening of the metal supports to the frame of the wagon-platform can be done by welding or bolting, taking into account the previously performed strength calculations.

It is possible to use clamps or other fixing devices to keep the boiler. The use of composites is proposed as a material for making the boiler. This will reduce the total packaging of the wagon compared to the use of metal construction by 3.7 %.

This solution will facilitate the creation of multimodal wagons that can transport removable bodies and other vehicles.

It is important to note that this implementation is appropriate for the existing car fleet and can be implemented during upgrades or repairs. Also, the proposed solution can be used in the design of new structures of wagons, which will contribute to the creation of their multifunctional structures.

The wagon-platform model 13-401 was chosen as a prototype. The load-bearing structure of the wagon-platform of this model is represented by a frame, which includes a ridge beam welded from two I-beam profiles No60V variable in length, main longitudinal, intermediate longitudinal and transverse beams, as well as end beams.

Bevels are installed in the console part of the frame. The main longitudinal beams are made of I-beam profiles, and the pivot beams have a closed box-shaped cross-section. There are tenons at the intersection of the spinal beam with the pivot beams, on top of which there is a reinforcement of the tenon diaphragms. On the lower sheet of pivot beams slides are installed, over which reinforcing ribs are placed.

The main technical characteristics of the wagon-platform are given in Table 1.

The spatial model of the wagon-platform was created on the basis of an album of its drawings. The model was considered monolithic, i.e. it does not take into account the welds between its individual components.

To determine the load of the improved structure of the wagon-platform, the simulation of its dynamics during shunting collision was performed, as a case of the greatest load of the structure in operation.

The mathematical model formed by Professor Bohomaz H. I. is used for this purpose. This model describes the

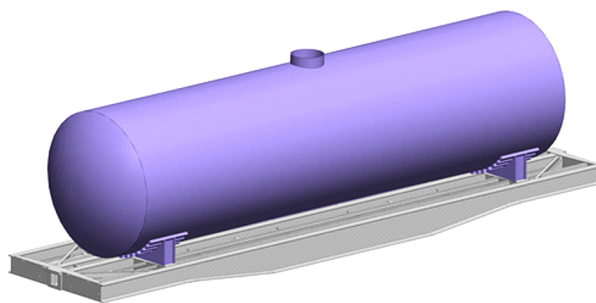


Fig. 1. A spatial model of the wagon-platform

Table 1

The main technical characteristics of the platform car model 13-401

Parameter name	Value
Load capacity, t	70
Packaging (min/max), t	18.0/20.0
Construction speed, km/h	120
Dimensions	0 – BM
Axial static load, kN/axis	223.01
Wagon base, mm	9,720
Length on axes of coupling of auto-couplings, mm	14,620
Length behind the end beams of the frame, mm	13,400
Height from the level of the top of the rail head to the floor level (maximum), mm	1,310
Number of axes, pcs.	4
Model of a two-axle cart	18–100
Presence of a parking brake	available
Body inside length	13,300
Body inside width	2,770
Ability to install buffers	impossible

dynamic load of the load-bearing structure of a long-base wagon-platform loaded with tank containers, taking into account the movement of bulk cargo in boilers. Therefore, this model was improved by taking into account the displacements of the load-bearing structure of the wagon-platform with a composite boiler.

When determining the load of the wagon-platform, it is taken into account that it has three degrees of fluency: in the longitudinal plane due to the impact and two in the vertical, due to the presence of spring suspension. It is accepted that the blow is absolutely hard. The model takes into account the friction forces that occur between the frame tenons and the cart bearings. At this stage of research, the movement of bulk cargo in the boiler is not taken into account.

The input parameters of the mathematical model (1) are the technical characteristics of the wagon-platform, as well as the perturbing action – the impact force. Initial displacements and velocities are set to zero.

$$\begin{cases} W_{gr} \cdot x'' + (W_w \cdot h) \cdot \varphi'' = P_l - 2P_{fr} \\ I_w \cdot \varphi'' + (W_w \cdot h) \cdot x'' - g \cdot \varphi \cdot (W_w \cdot h) = \\ = l \cdot F_{FR} (\text{sign}(z - l \cdot \varphi)' - \text{sign}(z + l \cdot \varphi)') + \\ + l(k_1 \cdot (z - l \cdot \varphi)' - k_2 \cdot (z + l \cdot \varphi)') \\ W_w \cdot z'' = k_1 \cdot (z - l \cdot \varphi) + k_2 \cdot (z + l \cdot \varphi) - \\ - F_{FR} (\text{sign}(z - l \cdot \varphi)' - \text{sign}(z + l \cdot \varphi)') \end{cases}, \quad (1)$$

where W_{gr} is gross weight of the wagon-platform; W_w is weight of the load-bearing structure of the wagon-platform; I_w is inertia moment of the wagon-platform; P_l is the longitudinal force on the rear stop of automatic hitch; P_{fr} is the friction force emerging between the frame tenons and cart bearings; l is a half of the wagon-platform base; F_{FR} is absolute value of the dry friction force in the spring set; k_1, k_2 are stiffness of springs of spring suspension of the wagon-platform carts; x, φ, z are coordinates corresponding, respectively, to the longitudinal, angular around the transverse axis and the vertical movement of the wagon-platform.

The solution of the system of differential equations (1) was carried out in the software package MathCad [9, 10] as follows

$$Q(t, y) = \begin{bmatrix} y_2 \\ y_4 \\ y_6 \\ \frac{P_l - 2P_{fr} - (W_w \cdot h) \cdot \dot{y}_4}{W_{gr}} \\ l \cdot F_{FR} (\text{sign}(y_5 - l \cdot y_3)' - \text{sign}(y_5 + l \cdot y_3)') + \\ + l(k_1 \cdot (y_5 - l \cdot y_3)' - k_2 \cdot (y_5 + l \cdot y_3)') - \\ - (W_w \cdot h) \cdot \dot{y}_2 + g \cdot y_3 \cdot (W_w \cdot h) \\ I_w \\ k_1 \cdot (y_5 - l \cdot y_3) + k_2 \cdot (y_5 + l \cdot y_3) - \\ - F_{FR} (\text{sign}(y_5 - l \cdot y_3)' - \text{sign}(y_5 + l \cdot y_3)') \\ W_w \end{bmatrix}, \quad (2)$$

$$Z = rkfixed(Y0, tn, tk, n, F),$$

where $Y0$ is the vector that includes initial conditions tn, tk are values that determine the initial and final change of integration, n' is the fixed number of steps, Q – issymbolic vector.

Herewith

$$y_1 = q_1, y_3 = q_3, y_5 = q_5, y_2 = \dot{y}_1, y_4 = \dot{y}_3, y_6 = \dot{y}_5.$$

The initial conditions are assumed to be zero [11, 12]. The results of the calculation showed that the acceleration acting on the load-bearing structure of the wagon-platform is 0.38 g, i. e. is within acceptable limits [13].

Fisher's criterion was used to check the adequacy of the mathematical model (1). The force of impact of the wagon-platform into the automatic hitch is taken into account as a variation parameter. The results of the calculations established that the hypothesis of adequacy is not rejected.

The acceleration value obtained according to the mathematical model (1) is taken into account when calculating the strength of the load-bearing structure of the wagon-platform, as a component of the dynamic load acting on it.

To determine the strength of the load-bearing structure of the wagon-platform, the calculation was performed by the finite element method, which was implemented in the SolidWorks Simulation software [14, 15] for the case of shunting collision.

This software package allows to calculate the strength not only of steel structures, but also of composite material with built-in options, so it was chosen to conduct research data.

The finite element model of the load-bearing structure of the wagon-platform is shown in the Fig. 2. Isoparametric tetrahedrons were used in compiling the model [16–18]. The optimal number of finite elements is calculated by the graphic-analytical method [19, 20].

The number of elements in the glass grid was 2,521,451, the number of nodes was 809,251. The largest value for the element of the model is 45.0 mm, the smallest is 9.0 mm.

When compiling the calculation scheme, it is taken into account that the improved load-bearing structure of the wag-

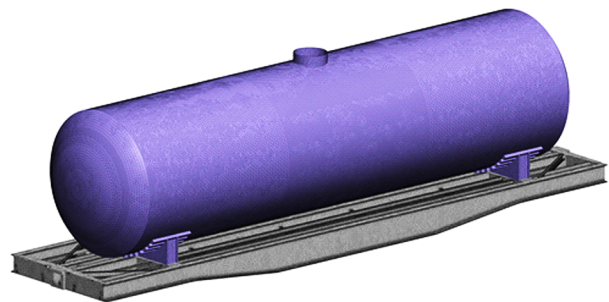


Fig. 2. Finite-element model of the load-bearing structure of the wagon-platform

on-platform is subject to vertical static load P_v^{st} , as well as longitudinal load P_l (Fig. 3).

The boiler is exposed to excess vapor pressure P_b , the pressure on the bottom due to the movement of the bulk cargo (hydraulic shock) P_{bt} , as well as the hydrostatic pressure P_h .

The value of the maximum pressure from the hydro impact is determined by the ratio of the force of inertia of the load to the area of the vertical projection of the bottom [13]

$$P_f = N \cdot \frac{w_c}{w_{gr}} \cdot \frac{1}{T}, \quad (3)$$

where N is impact force of the automatic coupling; w_c is weight of cargo in the boiler; w_{gr} is gross weight of the boiler module; T is the area of the internal cross section of the boiler.

Gasoline is considered as bulk cargo.

Hydrostatic pressure is calculated by the formula

$$P_{hydr} = \rho \cdot g \cdot h, \quad (4)$$

where ρ is the density of the bulk cargo; h is the height of the load distribution relative to the boiler.

Fastening of the model was carried out in the zones of support of the load-bearing structure of the wagon-platform on the carts. The load-bearing structure of the wagon-platform is made of the 09Г2С steel material, and the boiler is made of the composite. The main characteristics of the material of the construction of the wagon-platform, which were taken into account in the calculations are summarized in Table 2, and for the boiler – in Table 3. The model also takes into account

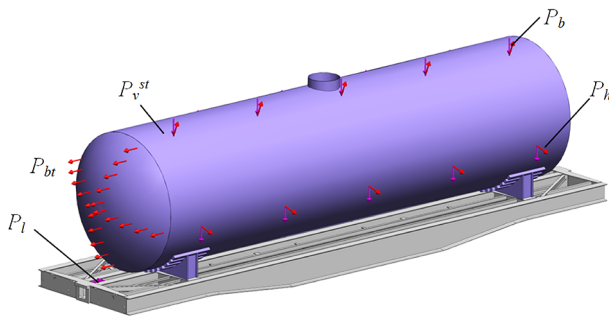


Fig. 3. Calculation of the load-bearing structure of the wagon-platform

Table 2

The main characteristics of the material of the load-bearing structure of the wagon-platform

Parameter name	Value
Modulus of elasticity, MPa	$2.1 \cdot 10^5$
Poisson's ratio	0.28
Shear modulus, MPa	$7.9 \cdot 10^4$
Strength limit, MPa	490
Liquidity limit, MPa	345

Table 3

The main characteristics of the boiler material

Parameter name	Value
Modulus of elasticity, MPa	$2.42 \cdot 10^5$
Poisson's ratio	0.394
Shear modulus, MPa	318.9
Strength limit in the direction of fibers, MPa	1,100–1,300
Strength limit in the transverse direction of the fibers, MPa	650

wooden bars, taking into account the relevant characteristics of the material.

Since the main part of the load-bearing structure of the wagon is made of steel, which is an isotropic material, and the composite is orthotropic, the calculation is based on two criteria – Mises and maximum stresses.

According to the Mises criterion, the strength of the load-bearing structure of the wagon-platform is provided if the maximum equivalent stresses do not exceed the allowable values for the steel grade of the metal structure. In this case, the allowable stresses are the yield strength of the material, that is, the margin of safety of the load-bearing structure of the wagon-platform is equal to 1.

According to the theory of maximum stresses, the failure of a composite material boiler will occur when the stress in one of the main directions of the material exceeds the strength in this direction.

The results of the calculation of strength are shown in the Figs. 4, 5.

The maximal equivalent stresses occur in the area of interaction of the spine beam of the frame with the pivot and make 340 MPa, the maximal displacement made 8.6 mm. It means the obtained stresses do not exceed the yield strength of the structure material [13].

When calculating the strength of the composite boiler, the maximal stresses were recorded along the fibers and amounted to 236 MPa. The maximal stresses across the fibers are 198 MPa. The calculations showed that the strength of the load-bearing structure of the wagon-platform, taking into account the proposed improvement measures is provided.

A modal analysis was performed to determine the frequencies and forms of natural oscillations of the load-bearing structure of the wagon-platform. The options of the SolidWorks Simulation software package were used. The calculation was carried out according to the calculation scheme shown in the Fig. 3. Some forms of oscillations of the load-

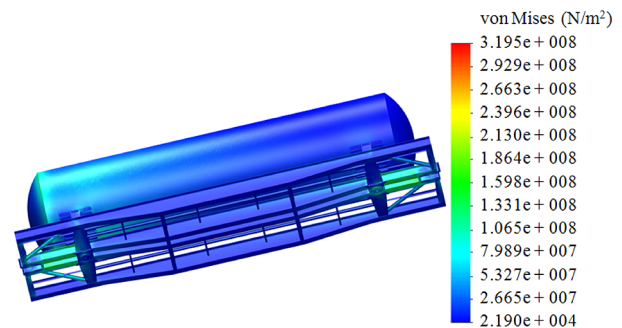


Fig. 4. Stress state of the load-bearing structure of the wagon-platform

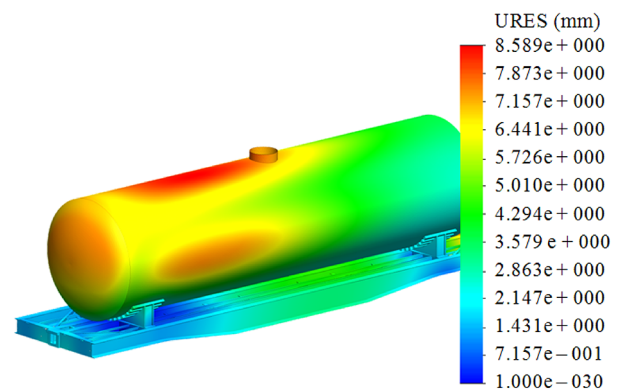


Fig. 5. Movement in the nodes of the load-bearing structure of the wagon-platform

bearing structure of the wagon-platform are shown in the Fig. 6.

Numerical values of natural frequencies of oscillations are summarized in Table 4.

It is known that to ensure the safety of the wagon, the first natural frequency of bending oscillations of the supporting structure in the vertical plane must be not less than 8 Hz [13]. The results of the calculation allowed to establish that the values of natural frequencies of oscillations are within acceptable limits.

It is important to say that in order to adapt the load-bearing structures of wagon-platform to the transportation of bulk cargo, other models can be used. Accounting for this, the scheme of interaction of metal supports with the frame of the wagon-platform can be changed, due to the peculiarities of their designs.

A further direction of these studies is to determine the impact of bulk cargo on the dynamic load of the wagon-platform. The questions of interaction and fastening of the boiler to a frame demands need to be solved. This issue requires special attention, as it depends on the safety of the wagon and, accordingly, the transportation of cargoes by rail.

The author's team also plans to conduct experimental studies of the load of the wagon-platform, taking into account the proposed measures to improve its design.

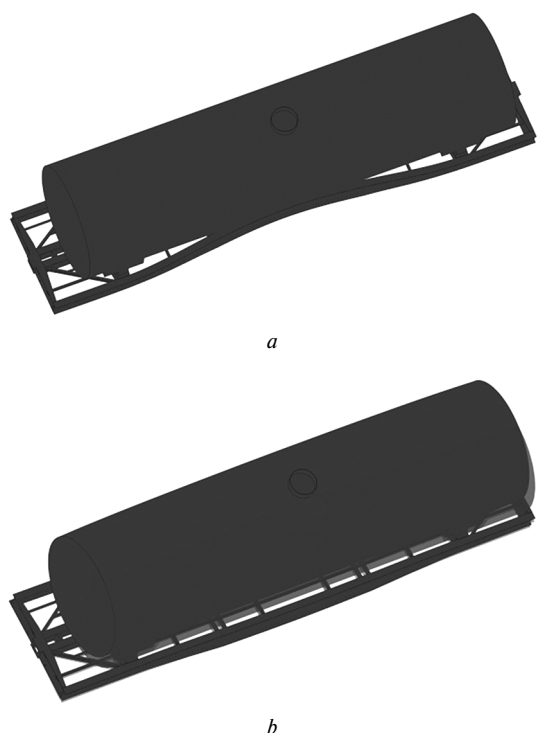


Fig. 6. Some forms of oscillations of the load-bearing structure of the wagon-platform (scale of deformations 20 : 1):

a – first mode; b – second mode

Table 4

Natural frequencies of oscillations of the load-bearing structure of the wagon- platform

Form of oscillations	Frequency, Hz	Form of oscillations	Frequency, Hz
1	11.38	6	17.46
2	12.19	7	17.48
3	17.3	8	17.54
4	17.31	9	17.62
5	17.45	10	17.86

Conclusions and recommendations on further implementation.

1. Measures are proposed to adapt the wagon-platform to the transportation of bulk cargo by installing a boiler module on it. The boiler is supported on the frame of the wagon-platform by means of wooden bars mounted on metal supports. It is proposed to use composites as a material for making the boiler. This will allow to reduce the general capacity of the wagon compared to a metal structure by 3.7 %.

2. The dynamic load capacity of the improved design of the wagon-platform at the shunting collision as in the case of the largest load capacity of the structure in operation. The results of the calculations showed that the acceleration acting on the load-bearing structure of the platform car is 0.38 g.

3. The definition of the main indicators of strength of the improved design of the wagon-platform is carried out. The maxima equivalent stresses occur in the area of interaction of the spine beam of the frame with the pin making about 340 MPa and do not exceed the allowable stresses. The maximal displacements were 8.6 mm and concentrated in the area of the manhole.

4. A modal analysis of the improved design of the wagon-platform was performed. The shapes and frequency of oscillations of the load-bearing structure of the advanced wagon-platform are determined. It is established that the first natural frequency oscillates more than 8 Hz. Therefore, the safety of the wagon movement is ensured.

The conducted researches will promote increase of efficiency of the railway transport operation and creation of developments concerning creation of innovative designs of a rolling stock.

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Навантаженість вагона-платформи для перевезень наливних вантажів

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Мета. Удосконалення несучої конструкції вагона-платформи для можливості перевезень наливних вантажів.

Методика. Для можливості перевезень наливних вантажів на вагоні-платформі пропонується встановлення на нього модуля котла з композитного матеріалу. З метою визначення динамічної навантаженості удосконаленої несучої конструкції вагона-платформи проведено математичне моделювання. При цьому використано математичну модель, сформовану професором Богомазом Г. І. Однак у рамках дослідження зазначену модель доопрацьовано до визначення навантаженості вагона-платформи запропонованої конструкції. Розв'язок системи диференціальних рівнянь здійснено у програмному комплексі MathCad. Для цього математична модель зводилася до нормальної форми Коші, а після цього інтегрувалася за методом Рунге-Кутта. Отримані прискорення враховані при розрахунках на міцність удосконаленої несучої конструкції вагона-платформи. Розрахунок здійснений у програмному комплексі SolidWorks Simulation, що реалізує метод скінчених елементів. Також у рамках дослідження проведено модальний аналіз несучої конструкції вагона-платформи.

Результати. На підставі проведених розрахунків встановлено, що прискорення, яке діє на несучу конструкцію вагона-платформи, складають 0,38 g, тобто знаходиться в допустимих межах. Результати розрахунку на міцність удосконаленої конструкції вагона-платформи показали, що максимальні еквівалентні напруження виникають у зоні взаємодії хребтової балки рами зі шворневою та складають близько 340 МПа, максимальні переміщення склали 8,6 мм. Тобто, отримані напруження не перевищують межі плинності матеріалу конструкції. Результати модального аналізу показали, що значення власних частот коливань знаходяться в межах допустимих, оскільки перша власна частота має значення більше 8 Гц.

Наукова новизна. Проведене наукове обґрунтування удосконалення несучої конструкції універсального вагона-платформи до перевезень наливних вантажів.

Практична значимість. Проведені дослідження сприятимуть підвищенню ефективності експлуатації залізничного транспорту та створенню напрацювань щодо проектування інноваційних конструкцій рухомого складу.

Ключові слова: транспортна механіка, вагон-платформа, динамічна навантаженість, міцність, моделювання навантаженості, модальний аналіз

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