Для забезпечення міцності несучих конструкцій напіввагонів запропоновано впровадження концепту упряжного пристрою, який можна реалізувати на напіввагонах з несучими елементи з круглих труб. Особливістю концепту є те, що консольні частини хребтової балки заповнені в'язкої речовиною з демпфуючими та антикорозійними властивостями. Для перетворення кінетичної енергії удару в енергію дисипації в концепт входить поршень з двома дросельними клапанами (впускним та випускним).

З метою визначення динамічної навантаженості несучої конструкції напіввагону, обладнаного концептом упряжного пристрою, проведено математичне моделювання. Складено математичну модель динамічної навантаженості напіввагона при маневровому співударянні. Враховано, що на раму напіввагона діє повздовжнє навантаження у 3,5 МН. Розв'язок диференціальних рівнянь проведено за методом Рунге-Кутта в середовищі програмного забезпечення Mathcad. Встановлено, що максимальна величина прискорення, яка діє на напіввагон, з урахуванням заходів щодо удосконалення, складає близько 30 м/с^2. Запропоновані технічні рішення дозволяють знизити величину динамічної навантаженості несучої конструкції напіввагона при маневровому співударянні на 25 %.

Проведено комп'ютерне моделювання динамічної навантаженості напіввагона в програмному забезпеченні CosmosWorks. В якості розрахункового використаний метод скінчених елементів. Максимальні прискорення при цьому склали близько 37 м/с^2 та зосереджені в консольних частинах хребтової балки.

Перевірка адекватності розроблених моделей динамічної навантаженості несучої конструкції напіввагона здійснена за критерієм Фішера (F-критерієм). Оптимальна кількість вимірів визначена за критерієм Горсета (Стьюдента).

Результати проведених розрахунку показали, що гіпотеза про адекватність не відхиляється.

Проведені дослідження сприятимуть зменшенню динамічної навантаженості несучих конструкцій напіввагонів у експлуатації та витрат на позапланові види ремонту. Проведені дослідження дозволять створити рекомендації щодо проектування інноваційного рухомого складу з покращеними техніко-економічними показниками

Ключові слова: напіввагон, несуча конструкція, прискорення, динамічна навантаженість, упряжний пристрій, маневрове співударяння

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DETERMINING THE DYNAMIC LOADING ON AN OPEN-TOP WAGON WITH A TWO-PIPE GIRDER BEAM

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1. Introduction

The development of economic activity between Eurasian states necessitates providing transport industry with innovative rolling stock that has improved technical and economic indicators. It is known that one of the most common types of rolling stock in operation is universal open-top wagons. Along with this, the open-top wagons are one of the most damaged kinds of railroad cars during operation.

A significant amount of damage to open-top wagons is demonstrated by their bearing structures at shunting operations due to the elevated speeds of collisions that exceed standard (Fig. 1).

The humps of marshalling stations service a large number of cars on a daily basis. In this case, the operational speed of humping devices continuously increases. Shunting operations are accompanied by the increased speeds of wagons collisions and the elevated force loads on the components of

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their structures. In this regard, the amount of damage to cars at shunting is constantly growing [1].

a

b

Fig. 1. Damage to the body of an open-top wagon at the elevated speeds of collision: *a* — node of interaction between a girder beam and a pivot beam; *b* — node of interaction between a vertical rack and a pivot beam

When descending the humps, new open-top wagons are damaged as well. The largest amount of damage in this case is demonstrated by elements in the bearing structure of bodies. Significant damage is done to the pivot beam of a frame, which is predetermined by that the largest magnitudes of stresses during a shock collision between cars are concentrated in the area of its intersection with a girder beam.

Under conditions of the elevated speeds of collision, equivalent stresses in the elements of a body could exceed the permissible ones. Significant force loads could lead to the displacement of a cargo inside the body of the car, which causes additional force effect on the bearing structure. This is especially the case when long cargoes are weakly fixed in the middle of the body. The consequences of such an event are damage to the end walls of open-top wagons or doors.

Significant impact on the damage to the bodies of open-top wagons is exerted by shunting technical means. Tracks under humps sometimes have slopes, which greatly differ not only at separate stations operated under the same conditions, but even within the same park.

A large amount of all damage in the process of sorting wagons occur due to violation of the established technology of sorting operations. More than half of them are the fault of speed controllers and operators [1].

It is known that a traction device with an absorbent apparatus inside it is used to absorb the impact kinetic energy by a wagon's bearing structure during shunting operations. At significant collision speeds, in the case the total energy capacity of the apparatus is utilized, it «closes», that is, does not absorb energy. In this case, the vertical surface of rear supports receives the impact loading without taking into consideration possible absorption, which could lead to damage to the load-bearing structures of cars and their components.

To ensure the preservation of open-top wagons at shunting collision, which is the case of the largest loading on the structure during operation, it is essential to improve cars to reduce dynamic loading [2]. One of the most effective ways to resolve this issue is the practical implementation of the new concept design of a traction device that would absorb the longitudinal dynamic loads. Such a technical solution would make it possible to simplify the structure of the current traction device, and, accordingly, improve its reliability and energy capacity. This will ensure the strength of the bearing structures of open-top wagons' bodies under operational loading modes, as well as bring down costs for unplanned maintenance. In addition, the proposed measures could improve the efficiency of open-top wagons operation at the modern stage of development of the rail industry.

2. Literature review and problem statement

Patterns in experimental evaluation of the range of impact response of rolling stock are described in [3]. The work reports results of processing results from testing the container tank of model CTL-26/0,4, the type UN T14 under different modes of impact loads. The authors obtained the assessment of the investigated properties of the container tank. However, the work did not consider the issue of improving the traction device of an automated coupling in order to reduce the dynamic loading on a wagon during operation.

Paper [4] proposed measures for the improvement of a wagon's traction device with the aim of reducing the dynamic loading under operating modes. The work reported results from mathematical modeling and computer simulation of the dynamic loading on a wagon. The proposed models were verified. However, the dynamic loading on an open-top wagon whose girder beam consists of two round pipes was not examined in the work.

Study [5] substantiated the introduction of a joined implementation of the girder beam in pellet wagons. The results of theoretical calculation and experimental research on strength confirmed the feasibility of the proposed measure. No measures on reducing the dynamic loading on the bearing structure of a wagon under operational load were offered.

Features of mathematical modeling of spatial fluctuations of the system «subframe – track» were addressed in [6]. The calculation was performed using the method of finite elements, implemented in the programming environment Ansys. The work did not cover the issue on improving the design of rolling stock in order to reduce dynamic loading during operation.

Paper [7] determined the dynamic loading on the body of an open-top wagon when it is transported on a rail ferry [7]. A special feature of the car's body is the presence of nodes to fix it relative to the decks. The research was conducted for the main types of oscillations of a rail ferry. The work failed to determine the dynamic loading on an open-top wagon at shunting collision.

Features of hot baking of materials under pressure at alternating current are given in [8]. It was established that materials after this procedure demonstrate elevated hardness and certain elasticity. The paper did not address prospects for the use of a given nanomaterial for wagon structures in order to reduce their dynamic loading during operation.

Study [9] highlights strategic tasks for wagon engineering in the development of heavy-cargo transportation [9]. The authors examined possible options for increasing the carrying capacity of rolling stock, load per wagon, reducing the tare.

In this case, the work does not discuss possible measures for reducing dynamic loading on wagons.

The structural features of the innovative rolling stock designed at «Uralvagonzavod» (Russia) for the track gauge of 1.520 mm were considered in [10]. The authors described measures for the modernization of rolling stock and components to improve the efficiency of operation. The structures of the examined types of cars do not include the nodes that would contribute to reducing the dynamic loading on bearing structures under the most adverse conditions.

Paper [11] proposes measures for improving the design of a hopper wagon. Optimal design of a structure was used as the calculation method. The structural diagram of the designed bodywork made it possible to reduce the weight of the hopper wagon and improve its load bearing capacity while ensuring the required strength and reliability of the structure. The work did not examine the dynamic loading on a hopper wagon at shunting collision. Moreover, the proposed design of the hopper wagon does not imply any components that would contribute to reducing the dynamic loading on the body during operation.

Paper [12] reported a research into the dynamic loading and strength of the bearing structure of an open-top wagon's body at shunting collision. The chosen prototype is an open-top wagon of model 12-757, which exhausted its operational resource. The research results made it possible to draw a conclusion about the possibility to prolong service time of the open-top wagon. The paper did not consider the improvement of a car's traction device that would reduce the dynamic loading on a bearing structure.

Study [13] examined the factor of safety against derailment of rolling stock. The authors proposed a coefficient of safety against derailment of railroad rolling stock. They substantiated reliability of the proposed criterion. However, the work did not consider studying the dynamic loading on the rolling stock under operation modes, nor the improvement of its bearing structure in order to reduce dynamic loading.

3. The aim and objectives of the study

The aim of this work is to study the dynamic loading on an open-top wagon with a two-pipe girder beam at shunting collision.

To accomplish the aim, the following tasks have been set:

– to improve the bearing structure of an open-top wagon in order to reduce dynamic loading at shunting collision;

– to perform mathematical modelling of the dynamic loading on the improved bearing structure of a open-top wagon at shunting collision;

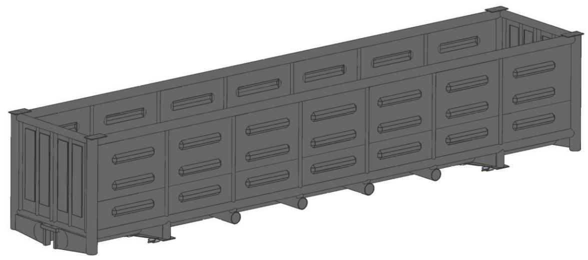
– to carry out computer simulation of the dynamic loading on the improved bearing structure of an open-top wagon at shunting collision;

– to test adequacy of the models of the dynamic loading on the improved bearing structure of an open-top wagon.

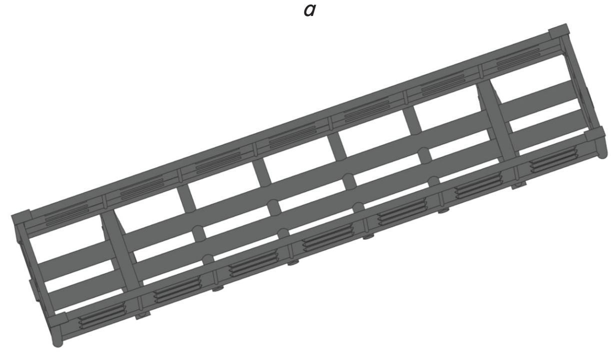
4. Improving the bearing structure of an open-top wagon in order to reduce dynamic loading at shunting collision

To reduce the tare of open-top wagons and bring down the cost of their fabrication while maintaining operational strength, we propose making the load-bearing structures from round pipes (Fig. 2). The parameters for round pipes were chosen based on strength reserve for a typical open-top wagon structure [5] accepted as a prototype – the open-top wagon of model 12-757, produced at JSC «KVBZ» (Kremenchug, Ukraine).

To decrease the dynamic loading on the bearing structure of the open-top wagon under operational load, we propose using, instead of the automated coupling traction device, a new concept design (Fig. 3, 4).



a



b

Fig. 2. Bearing structure of an open-top wagon made with round pipes: *a* – side view; *b* – bottom view

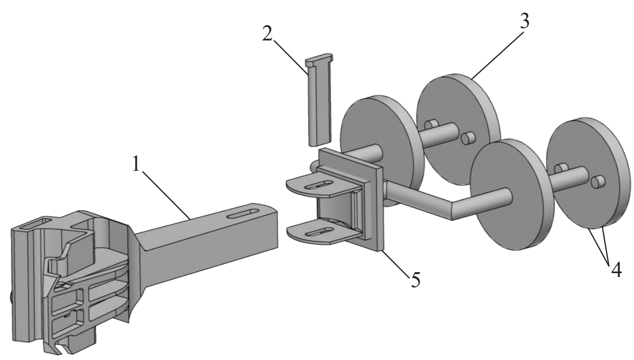


Fig. 3. Concept design of automated coupling traction device: 1 – automated coupling casing; 2 – wedge; 3 – piston; 4 – throttle valves; 5 – stop bracket

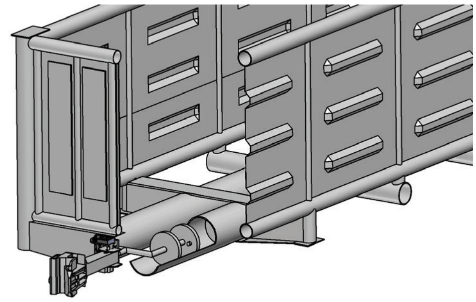


Fig. 4. Arrangement of the concept design of traction device in an open-top wagon

A special feature of the concept design is that the console parts of the girder beam are filled with a viscous substance with damping properties. To convert the impact kinetic energy into the dissipation energy, the concept design includes a piston with two throttle valves (inlet and outlet). The transfer of the longitudinal load from the automated coupling's casing to the concept design is performed through the stop bracket, which transmits it via a fork to the two-disk pistons. The pistons that move towards the wagon's rear side (void *A*) open the inlet valves, while the outlet valves are closed. The reverse movement of pistons (jerk, compression) opens the outlet valves of the pistons, while the inlet valves are closed. The viscous substance flows into cavity *B* from the side of the automated coupling's casing. Schematic of work of the concept design of a traction device is shown in Fig. 5.

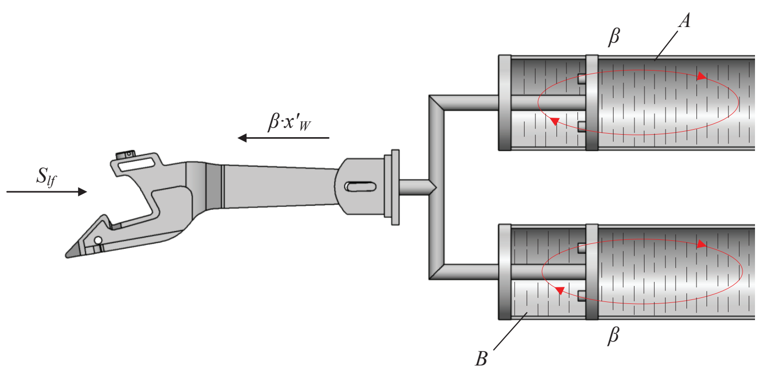


Fig. 5. Schematic of work of the concept design of a traction device in an open-top wagon

It is important to note that the presence of a viscous substance inside the console parts will also contribute to the anti-corrosion protection of a car's girder beam in these areas.

5. Simulation of the dynamic loading on the improved bearing structure of an open-top wagon at shunting collision

5. 1. Mathematical modeling of the dynamic loading on the improved bearing structure of an open-top wagon at shunting collision

In order to determine the dynamic loading on an open-top wagon equipped with the concept design of a traction device, we built a mathematical model (1) to (3). In this case, we used the mathematical model presented in [14], which was constructed to determine the loading on a wagon platform that carries containers. Therefore, a given model has been reworked and supplemented by introducing coefficients of viscous resistance. The estimated schematic of the dynamic loading on an open-top wagon is shown in Fig. 6.

$$\left(M_W + 2\cdot m_b + \frac{n\cdot I_{WL}}{r^2}\right)\cdot \ddot{x}_W + (M_W\cdot h)\cdot\ddot{\varphi}_W = S_{lf} - \beta\cdot\dot{x}_W, \quad (1)$$

$$\begin{aligned} I_W\cdot\ddot{\varphi}_W + (M_W\cdot h)\cdot\ddot{x}_W - g\cdot\varphi_W\cdot(M_W\cdot h) = \\ = l\cdot F_{fr}\left(sign(z_W - l\cdot\varphi_W)' - sign(z_W + l\cdot\varphi_W)'\right) + \\ + l\left(k_1\cdot(z_W - l\cdot\varphi_W) + k_2\cdot(z_W + l\cdot\varphi_W)\right), \end{aligned} \quad (2)$$

$$\begin{aligned} M_W\cdot\ddot{z}_W = k_1\cdot(z_W - l\cdot\varphi_W) + k_2\cdot(z_W + l\cdot\varphi_W) - \\ - F_{fr}\left(sign(z_W - l\cdot\varphi_W)' - sign(z_W + l\cdot\varphi_W)'\right), \end{aligned} \quad (3)$$

where M_W is the mass of the bearing structure of the wagon; I_W is the moment of inertia of the wagon relative to the longitudinal axis; S_{lf} is the magnitude of the longitudinal force of impact against an automated coupling; m_b is the mass of the bogie; I_{WL} is the moment of inertia of a wheelset; r is the radius of an medium-worn wheel; n is the number of axes in a bogie; l is half the base of a wagon; F_{fr} is the absolute value for a force of dry friction in the spring assembly; k_1, k_2 is the rigidity of springs in the wagon's bogie spring assembly; x_W, φ_W, z_W are the coordinates that correspond, accordingly, to the longitudinal, the angular around the transverse axis, and the vertical movement of the car.

We solved differential equations (1) to (3) in the programming environment MathCad. In this case, the equations were reduced to the normal Cauchy form, followed by solving them in line with the Runge-Kutta method at a fixed step. A given method was chosen as it is one of the most common ones when solving a Cauchy problem and demonstrates enough accuracy in comparison with other methods.

To solve equations (1) to (3), we used the standard MathCad-embedded function *rkfixed*(*Y*0, *tn*, *tk*, *n*, *Q*). The vector *Y*0 contains the initial conditions. The magnitudes *tn* and *tk* define the starting and resulting variable of integration, *n* is the fixed number of steps, *Q* is the symbol vector [15].

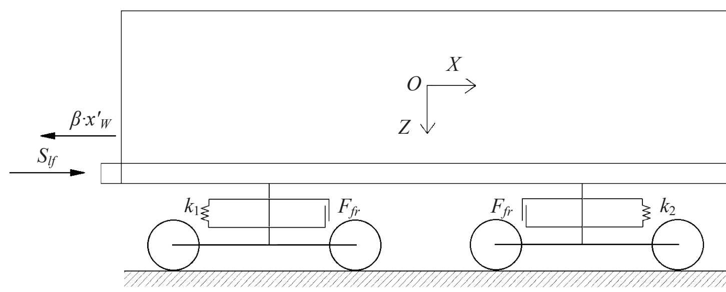


Fig. 6. Estimated schematic of an open-top wagon at shunting collision

The transition from differential equations of the second order (1) to (3) to the system of differential equations of the first order (6) was performed in order to apply the standard algorithms for solving a system using Mathcad.

Denote:

$$\begin{aligned} F_\varphi(t) = l\cdot F_{fr}\left(sign(y_3 - l\cdot y_2)' - sign(y_3 + l\cdot y_2)'\right) + \\ + l\left(k_1\cdot(y_3 - l\cdot y_2) + k_2\cdot(y_3 + l\cdot y_2)\right), \end{aligned} \quad (4)$$

$$\begin{aligned} F_z(t) = k_1\cdot(y_3 - l\cdot y_2) + k_2\cdot(y_3 + l\cdot y_2) - \\ - F_{fr}\left(sign(y_3 - l\cdot y_2)' - sign(y_3 + l\cdot y_2)'\right), \end{aligned} \quad (5)$$

then

$$Q(t,y)=\begin{bmatrix} y_4 \\ y_5 \\ y_6 \\ \dfrac{S_{lf}-\beta\cdot y_4-(M_W\cdot h)\cdot\dot{y}_5}{M_W+2\cdot m_b+\dfrac{n\cdot I_{WL}}{r^2}} \\ \dfrac{F_\varphi(t)-(M_W\cdot h)\cdot\dot{y}_4+g\cdot y_2\cdot(M_W\cdot h)}{I_W} \\ \dfrac{F_z(t)}{M_W} \end{bmatrix}, \qquad (6)$$

$$Z=rkfixed\,(Y0,tn,tk,n,Q).$$

Based on the performed calculations, it was determined that the maximal magnitude of acceleration that acts on an open-top wagon, taking into consideration the measures for improvement, is about 30 m/s^2. In this case, a viscosity coefficient was accepted equal to 120 kN·s/m. That is, the proposed measures make it possible to reduce the magnitude of dynamic loading on an open-top wagon's bearing structure at shunting collision by 25 %.

5. 2. Computer simulation of dynamic loading on the improved bearing structure of an open-top wagon at shunting collision

The programming complex CosmosWorks was used to perform computer simulation of the dynamic loading on an open-top wagon of improved design at shunting collision. The calculation was carried out using the method of finite elements.

The model of an open-top wagon's strength is shown in Fig. 7. The model accounts for the following loads: vertical static P_v^{st}, caused by gross weight, the spread of bulk cargo P_b, impact P_i.

The accepted bulk cargo was stone coal. The efforts of the spread of bulk cargo on the side walls and end side doors of an open-top wagon's body were determined in line with the procedure given in [16]. According to this procedure, it is accepted that the load of spread of bulk cargo on the side walls of the bodywork of a car is distributed by the law of triangle with a maximum at its base, and on the end side – by the law of trapeze.

Maximum loads near the bases of pillars of a lateral wall are determined from:

$$q_1=0.5\cdot p_a\cdot l_1, \qquad (7)$$

$$q_2=0.5\cdot p_a\cdot(l_1+l_2), \qquad (8)$$

$$q_3=0.5\cdot p_a\cdot(l_2+l_3), \qquad (9)$$

$$q_4=0.5\cdot p_a\cdot(l_3+l_4), \qquad (10)$$

where p_a is the active (static) pressure of the spread of bulk cargo, per unit area of the surface of a vertical wall at floor level, kPa; l_1 is the distance from the end beam of the frame to the geometrical axis of the wagon's rear, m; l_2 is the distance from the geometrical axis of the wagon's rear to the second pillar of the body, m; l_3 is the distance from the second pillar of body to the third, m; l_4 is the distance from the third pillar of the body to the vertical geometric axis of the wagon's body, m.

Active pressure of the spread of bulk cargo is defined from formula:

$$p_a=\gamma\cdot g\cdot H\cdot \mathrm{tg}^2\left(\frac{\pi}{4}-\frac{\varphi}{2}\right), \qquad (11)$$

where γ is the density of bulk cargo, t/m^3; H is the height of side wall, m; φ is the angle of repose of a cargo, rad.; g is the acceleration of free fall, m/s^2.

Pressure of the non-uniformly distributed load, applied to the end side door's sash is determined from formula:

$$p=p_a+p_n, \qquad (12)$$

where p_n is the passive pressure of bulk cargo, which is determined from formula (11), in which a squared tangent of the difference between two angles is replaced with a squared tangent of their sum taking into consideration the factor of vertical dynamics, as well as the angle of natural repose.

The intensity of the trapezoid load applied to the corner rack is determined from:

$$q_{T1}^{bottom}=0.5\cdot(p_a+p_n)\cdot b_1; \qquad (13)$$

$$q_{T1}^{up}=0.5\cdot p_n\cdot b_1; \qquad (14)$$

to the intermediate rack:

$$q_{T2}^{bottom}=0.5\cdot(p_a+p_n)\cdot(b_1+b_2); \qquad (15)$$

$$q_{T2}^{up}=0.5\cdot p_n\cdot(b_1+b_2); \qquad (16)$$

to the middle rack:

$$q_{T3}^{bottom}=0.5\cdot(p_a+p_n)\cdot b_2; \qquad (17)$$

$$q_{T3}^{up}=0.5\cdot p_n\cdot b_2. \qquad (18)$$

The finite elements that were considered in preparing the continual model are the spatial tetrahedra. To determine the optimal number of elements, we used a graph-analytic method. The method is based on the graphical (geometric) representation of possible solutions and the objective function of the problem. When solving a given problem, the method implies the construction of the dependence of maximum equivalent stresses on the number of finite elements. When this dependence starts to be described by a horizontal line, this is the optimum number of finite elements.

The number of nodes in the model was 219,157, elements – 686,568. The maximum size of the element was 85 mm, and the minimum was 17 mm. The percentage of elements whose ratio of the sides is less than three is 30.2, over ten – 11.2. The minimum number of elements in the circle was 15, the ratio of an increase in the size of the elements is 1.9.

To simulate viscous resistance, we established the connection spring-damper in the console parts of an open-top wagon's frame. In this case, the value for rigidity was zero, and the coefficient of viscous resistance was 120 kN·s/m. The model was fixed in the zones where the body leaned against the running parts of the wagon. The material that was used in the design is steel of grade 09G2S [17–19].

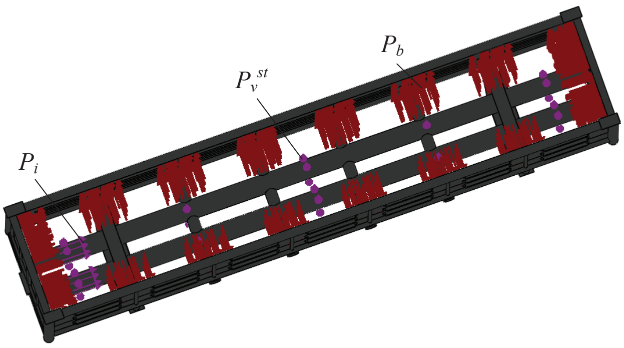


Fig. 7. Model for determining the dynamic loading on a platform that carries containers-tanks at shunting collision

The calculation results are shown in Fig. 8. The maximum accelerations acting on the bearing structure of an open-top wagon's body make up approximately 37 m/s^2 and occur in the console parts of a girder beam. In the middle of the frame, the acceleration amounted to about 34 m/s^2. In the middle parts of the side walls, the acceleration reached about 15 m/s^2.

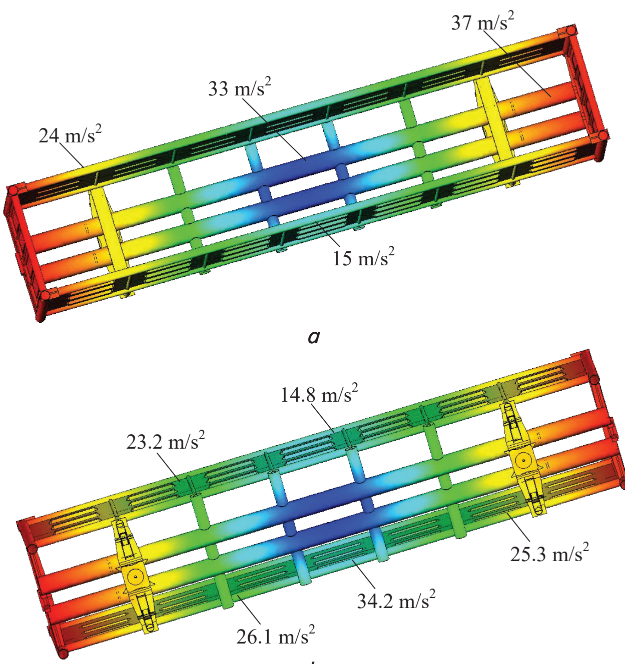


Fig. 8. Distribution of accelerations acting on the bearing structure of an open-top wagon at shunting collision: *a* – top view; *b* – bottom view

The maximum accelerations acting on the bearing structure of an open-top wagon taking into consideration the measures for improvement do not exceed the permissible ones [17–19].

6. Testing the adequacy of models of dynamic loading on the improved bearing structure of an open-top wagon

We tested the adequacy of the above models applying an F-criterion [20, 21]. The variation parameter used was the force when a wagon hits an automated coupling (Fig. 9). The optimal number of measurements was defined based on the criterion of Gorset (Student) [22]. At the value of variance 87.7, mathematical expectation 26.1 and the root-mean-square deviation 9.4, the optimal number of experiments was 6. That is, the estimated sample is sufficient.

Equation of the mathematical model's trend line takes the form:

$$y_M = 1.694x + 18.464. \quad (19)$$

Computer model:

$$y_C = 1.9107x + 21.814. \quad (20)$$

The percentage difference between the results obtained from mathematical modeling and computer simulation is given in Fig. 10. In this case, the maximum percentage difference is 15.2 % at the force of impact against an automated coupling 2.2 MN, the smallest – 12.9 % at the impact force 3.3 MN.

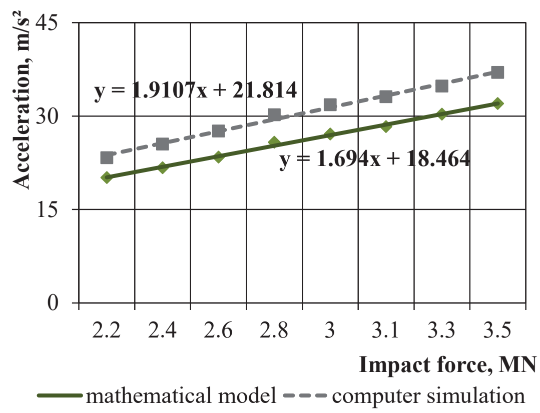


Fig. 9. Accelerations acting on the bearing structure of an open-top wagon at shunting collision

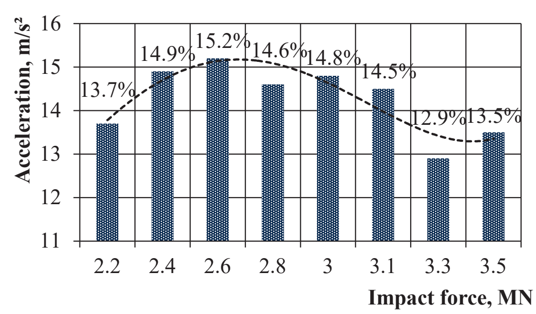


Fig. 10. Difference between the results of mathematical modeling and computer simulation

It was established that at the reproducibility variance $S_r^2 = 17.3$ and the variance adequacy $S_{ad}^2 = 22.07$, the actual value for F-criterion F_a=1.23, which is less than the tabular value for the criterion (F_t=3.07). In other words, the hypothesis on adequacy is not challenged.

7. Discussion of results of improving a bearing structure of an open-top wagon in order to reduce dynamic loading at shunting collision

To decrease the dynamic loading on an open-top wagon at shunting collision, it is proposed to use the new concept design of a traction device. A special feature of the concept design is that the console parts of a girder beam in an open-top wagon whose bearing elements are made from round pipes are filled with a viscous substance with damping properties. To convert the impact kinetic energy into the dissipation energy, the concept design includes a piston with two throttle valves (inlet and outlet). Receiving the longitudinal loads converts the kinetic energy of impact to the energy of dissipation due to the forces of viscous resistance in the concept design. The proposed technical solutions make it possible to reduce the magnitude of the dynamic loading on the bearing structure of an open-top wagon at shunting collision by 25 %.

It is important to note certain limitations in the current study. When constructing the models of dynamic loading on an open-top wagon, we did not take into consideration the possible deviation of an automated coupling upon impact from a wagon-striker or an adjacent car. Moreover, when building a computer model of dynamic loading on an open-top wagon, the covers for discharge hatches were not accounted for. That is, the model takes into consideration the structural elements that rigidly interact. As is known, covers for hatches are fastened by hinges.

In the further research in this area, it is necessary to take into consideration the aforementioned factors in order to obtain a more accurate assessment of the dynamic loading on an open-top wagon.

The prospects for the current study include the need to take into consideration different viscous substances in the concept design, as well as the influence of their properties on the dynamic load on a body. One should also consider the dynamic loading on other types of wagons provided they are equipped with the concept design of a traction device. The important stage of research is experimental modeling of dynamic loading. Since the fabrication of a natural sample of an open-top wagon is associated with significant difficulties, the planned initial stage of the experiment is based on a similarity method.

8. Conclusions

1. We have improved the bearing structure of an open-top wagon in order to reduce dynamic loading at shunting collision. To reduce the dynamic loading on a bearing structure of an open-top wagon at shunting collision, it has been proposed to apply the new concept design of a traction device. A special feature of the concept design is that the console parts of an open-top wagon's girder beam, whose bearing elements are made from round pipes, are filled with a viscous substance with damping and anticorrosive properties.

2. We have performed mathematical modeling of dynamic loading on the improved structure of an open-top wagon at shunting collision. A mathematical model has been constructed that takes into consideration the loading on a wagon's body at shunting collision with regard to the presence of a viscous resistance. Differential equations of the model were solved by the Runge-Kutta method. The calculation was performed in the programming environment MathCad. It was established that the maximal magnitude of acceleration that acts on an open-top wagon considering the measures for improvement is about 30 m/s^2 (≈3.0 g). Viscosity coefficient was accepted to be equal to 120 kN·s/m. The proposed measures make it possible to reduce the magnitude of dynamic loading on the bearing structure of an open-top wagon at shunting collision by 25 %.

3. We have performed computer simulation of dynamic loading on the improved structure of an open-top wagon at shunting collision. The calculation was carried out using the method of finite elements in the programming environment CosmosWorks. We have defined the fields of accelerations distribution as the components of the dynamic load, relative to the bearing structure of an open-top wagon. The maximum accelerations in this case amounted to about 37 m/s^2 (≈3.7 g) and were concentrated in the console parts of a girder beam.

4. The adequacy of models of dynamic loading on the improved bearing structure of an open-top wagon was verified. The calculation was performed based on a Fisher criterion. At the value of reproducibility variance $S_r^2 = 17.3$ and the variance adequacy $S_{ad}^2 = 22.07$, the actual value for the criterion was F_a=1.23. That is, it is less than the tabular value for the criterion (F_t=3.07). Thus, the hypothesis on adequacy is not challenged.

Our research will contribute to the reduction of the dynamic loading on bearing structures of open-top wagons' bodies at shunting collision. That would help bring down the cost of unplanned maintenance of cars, as well as improve the efficiency of their operation. In addition, the current study will contribute to compiling the guidelines on designing innovative rolling stock with improved technical and economic indicators.

References

1. GOST 22235-2010. Vagony gruzovye magistral'nyh zheleznyh dorog kolei 1520 mm. Obschie trebovaniya po obespecheniyu sohrannosti pri proizvodstve pogruzochno-razgruzochnyh i manevrovyh rabot. Moscow, 2011. 24 p.
2. Senderov G. K., Losev P. R., Drugal' S. A. Sohrannost' vagonov pri pogruzochno-razgruzochnyh i manevrovyh rabotah. Moscow, 1984. 158 p.
3. Experimental evaluation of shock spectrum response of rolling stock / Tretiakov A. V., Tretiakov O. A., Zimakova M. V., Petrov A. A. // Science and Transport Progress. Bulletin of Dnipropetrovsk National University of Railway Transport. 2017. Issue 3 (69). P. 147–159. doi: https://doi.org/10.15802/stp2017/103898
4. The influence of implementation of circular pipes in load-bearing structures of bodies of freight cars on their physico-mechanical properties / Fomin O. V., Lovska A. O., Plakhtii O. A., Nerubatskyi V. P. // Scientific Bulletin of National Mining University. 2017. Issue 6. P. 89–96.
5. Experimental confirmation of the theory of implementation of the coupled design of center girder of the hopper wagons for iron ore pellets / Fomin O., Kulbovsky I., Sorochinska E., Sapronova S., Bambura O. // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 5, Issue 1 (89). P. 11–18. doi: https://doi.org/10.15587/1729-4061.2017.109588

6. Mathematical Modeling of Dynamic Loading of Cassette Bearings for Freight Cars / Myamlin S., Lunys O., Neduzha L., Kyryl'chuk O. // Proc. of 21st Intern. Scientific Conf. «Transport Means. 2017». 2017. P. 973–976.
7. Lovska A. Peculiarities of computer modeling of strength of body bearing construction of gondola car during transportation by ferry-bridge // Metallurgical and mining industry. 2015. Issue 1. P. 49–54.
8. Ceramic cutting tools out of nanostructured refractory compounds / Gevorkyan E., Lavrynenko S., Rucki M., Siemiatkowski Z., Kislitsa M. // International Journal of Refractory Metals and Hard Materials. 2017. Vol. 68. P. 142–144. doi: https://doi.org/10.1016/j.ijrmhm.2017.07.006
9. Boronenko Yu. P. Car-builders' strategic tasks in development of heavy-weight rail traffic // Transport Rossiyskoy Federacii. 2013. Issue 5 (48). P. 68–73.
10. Innovacionniy podvizhnoy sostav proizvodstva «Uralvagonzavoda» dlya zheleznyh dorog «prostranstva 1520 mm» // Transport Rossiyskoy Federacii. 2010. Issue 3 (28). P. 20–21.
11. Improving the design of hopper wagons for transporting grain / Kebal Y., Shatov V., Tokotyev A., Murashova N. // Zbirnyk naukovykh prats DETUT. Seriya «Transportni systemy i tekhnolohiyi». 2017. Issue 30. P. 113–122.
12. Research into a possibility to prolong the time of operation of universal open top wagon bodies that have exhausted their standard resource / Okorokov A., Fomin O., Lovska A., Vernigora R., Zhuravel I., Fomin V. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 3, Issue 7 (93). P. 20–26. doi: https://doi.org/10.15587/1729-4061.2018.131309
13. Research on the safety factor against derailment of railway vehicles / Sapronova S., Tkachenko V., Fomin O., Hatchenko V., Maliuk S. // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 6, Issue 7 (90). P. 19–25. doi: https://doi.org/10.15587/1729-4061.2017.116194
14. Nagruzhennost' konteynerov-cistern, raspolozhennyh na zheleznodorozhnoy platforme, pri udarah v avtoscepku / Bogomaz G. I., Mekhov D. D., Pilipchenko O. P., Chernomashenceva Yu. G. // Zb. nauk. prats «Dynamika ta keruvannia rukhom mekhanichnykh system». Kyiv: ANU, Instytut tekhnichnoi mekhaniky, 1992. P. 87–95.
15. Domin Yu. V., Cherniak H. Yu. Osnovy dynamiky vahoniv: navch. posib. Kyiv: KUETT, 2003. 269 p.
16. Konstruirovanie i raschet vagonov / Lukin V. V., Shadur L. A., Koturanov V. I., Hohlov A. A., Anisimov P. S. Moscow, 2000. 731 p.
17. DSTU 7598:2014. Vahony vantazhni. Zahalni vymohy do rozrakhunkiv ta proektuvannia novykh i modernizovanykh vahoniv koliyi 1520 mm (nesamokhidnykh). Kyiv, 2015. 162 p.
18. GOST 33211-2014. Vagony gruzovye. Trebovaniya k prochnosti i dinamicheskim kachestvam. Moscow, 2016. 54 p.
19. EN 12663-2. Railway applications – structural requirements of railway vehicle bodies – Part 2: Freight wagons. BSI, 2010. 54 p. doi: https://doi.org/10.3403/30152552u
20. Kobzar' A. I. Prikladnaya matematicheskaya statistika. Moscow, 2006. 816 p.
21. Ivchenko G. I., Medvedev Yu. I. Matematicheskaya statistika. Moscow, 2014. 352 p.
22. Rudenko V. M. Matematychna statystyka. Kyiv, 2012. 304 p.