The object of research is the processes of occurrence, perception, and redistribution of loads in the supporting structure of a gondola car with unloading hoppers. In order to increase the carrying capacity of the gondola car, and accordingly the profitability of railroad transportation, it has been proposed to improve its structure. This improvement implies the installation of unloading hoppers in its middle part. According to preliminary calculations, the use of unloading hoppers could increase the usable volume of the body by 2.82 m^3. At the same time, the carrying capacity of the car would increase by 3.8 tons. Accordingly, the axial load on the wheelsets would increase. It is possible to solve this issue by using wheelsets with increased axial load in bogies.

As part of the research, a mathematical modeling of the vertical dynamics of the gondola car during its movement in the empty and loaded states of the rail track was carried out. It was established that the movement of the car is evaluated as "excellent". The calculation of the strength of the gondola car body under the main operational load modes was carried out. The stability of the car's equilibrium was determined, and its modal analysis was also carried out.

The peculiarity of the results within the framework of the study is that the proposed improvement could be implemented not only when designing a new car structure but also during modernization.

The area of practical application of the results is the machine-building industry, in particular, railroad transport. The conditions for the practical application of the research results are compliance with the axial load within the permissible values.

The research reported here will contribute to improving the technical and economic indicators of cars, as well as increasing the profitability of railroad transportation

Keywords: gondola car with hoppers, vertical dynamics of the car, body strength, modal analysis of the car

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DETERMINING THE LOAD ON A BODY OF THE GONDOLA CAR WITH UNLOADING HOPPERS UNDER THE BASIC OPERATING MODES

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1. Introduction

Prospects for the development of the economy of Eurasian countries predetermine the increase in the efficiency of operation of the transport industry [1, 2]. To ensure the profitability of the transport industry, it is important to update it with vehicles with improved technical and operational performance [3–5].

Railroad transportation has been the most promising and competitive component of the transport industry for a long time. The freight fleet of railroad transport is formed by a large number of structural features and the technology of processing cars. The most common among them are gondola cars. The peculiarity of this type of car is that its supporting structure is made without a roof. Therefore, most often, such cars are used for transporting goods that do not need protection from atmospheric precipitation. If necessary, this type of car can be supplemented with a removable roof or a tent that performs the functions of a roof.

To improve the efficiency of the operation of gondola cars under the modern conditions of competition in the transportation services market, it is important to improve their technical and economic indicators. It is possible to achieve this by reducing the car's tare, increasing the carrying capacity, speed of movement, etc. Ensuring traffic safety is an equally important aspect of their operation. Achieving the specified goal is possible by improving dynamic indicators, the coefficient of stability of balance against overturning, as well as when moving, etc. Therefore, research aimed at improving the technical and economic indicators of gondola cars is relevant.

2. Literature review and problem statement

The issue of improving the load-bearing structures of cars to increase the efficiency of their operation is discussed in a considerable number of scientific publications. So, for example, in work [6], in order to reduce the weight of the car and improve its strength indicators, it is proposed to use fiber-reinforced composite as the material for its manufacture. Prospects for further research in the specified direction by changing the angle of placement of reinforced fibers in the material are given. However, the authors did not investigate the possibility of increasing the carrying capacity of the car through the reduction of its tare. This may be due to the fact that, first of all, attention was paid to the issue of the rational arrangement of fibers in the material. Perhaps in the further works of the authors, the possibility of increasing the carrying capacity of this type of car will be investigated.

Work [7] considers the issue of reducing the tare of a freight car. This is achieved due to the use of composite panels in the structure, which have a lighter weight compared to steel. The results of tests on the durability of composite panels are presented. The method of testing panels is reported, and the expediency of their use on freight cars is substantiated. At the same time, as in work [6], the authors did not investigate the possibility of increasing the carrying capacity of the car through the reduction of its tare.

Paper [8] proposed a solution for the construction of multi-layer structures of freight car bodies. At the same time, the authors suggested the use of panels in the form of "egg boxes". This configuration increases the moment of resistance of the structure and helps improve its durability in operation. An example of the implementation of such a decision is given and further prospects of this direction are indicated. However, the research was conducted only on the example of tank cars for the transportation of dangerous goods. Apparently, this is explained by the fact that the transportation of dangerous goods by rail requires special attention. It would be appropriate to consider this decision also in relation to gondola cars as the most common type of car in operation.

The gondola car body structure improvement is proposed in [9]. At the same time, the authors focused attention on improving the safety of cargo transportation in a gondola car. For this purpose, a version of a retracTable rod in a wall rack has been developed. This improvement makes it possible to fasten loads whose height exceeds the limits of the upper strapping of the car. This ensures the reliability of its fastening in the car and transportation by railroad. Along with this, loading a car with a «cap» affects the increase of its payload. However, the authors did not investigate the issue of increasing the load on the car body. Perhaps this is due to the fact that it requires a complex of additional studies and will be covered in further works of the authors team.

In [5], the peculiarities of constructing the body of a railroad vehicle from extruded aluminum panels are considered. Each panel is made of sandwich panels that interact with each other by welding. At the same time, the proposed structure of the vehicle body helps reduce its tare while maintaining sufficient strength. At the same time, the authors did not pay attention to the issue of determining the dynamic load of the car taking into account the reduction of its tare.

The justification of the use of a profile sheet in the car body to simplify its design is provided in article [10]. The authors note that such a decision also contributes to reducing the car's weight and improving the mechanical properties of its structural components. The results of the modal analysis of the car body are presented. The results of the research confirmed the feasibility of the proposed improvement. In addition to improving the strength of the car body, this solution also contributes to the possibility of increasing its carrying capacity. However, the authors did not conduct research into the loading of the car body, taking into account the increase in its payload.

The results of the design of sandwich structures with a lattice core for lightweight structures of railroad cars are highlighted in [11]. North American standards were used to determine the strength indicators of the designed car. The results of computer simulation of the strength of the car body are presented, which confirmed the feasibility of the decisions made during the design. However, once again, the issues of the dynamics of the lightweight design of the car, in particular when moving in an empty state, were not investigated. This is a rather important aspect of research from the point of view of ensuring the safety of carriage movement. In addition, the question of the possibility of increasing the carrying capacity of the car in connection with the reduction of its container is of interest.

In order to increase the efficiency of the operation of the gondola car, work [12] proposed to manufacture the main bearing elements of its structure from round pipes filled with aluminum foam. This solution makes it possible to reduce dynamic loads on the body, and, accordingly, to improve its strength. The results of strength calculations proved that this decision is appropriate. At the same time, this improvement does not contribute to improving the profitability of railroad transportation.

The above review of literature [5–12] allows us to conclude that the issue of increasing the carrying capacity of the gondola car body by improving its design requires further research. The probable reasons for the existence of such a problem are that earlier research into this area was mostly aimed at using new materials in the construction of bodies, reducing the load under operating conditions, etc. That is, such solutions are expedient at the stage of manufacturing new car structures. Under the conditions of a shortage of rolling stock, a more rational option is the modernization of the existing fleet of cars for the transportation of the assigned cargo range. Therefore, the research aimed at the justification of the improvement, determination of the dynamic load and strength of the gondola car body with increased carrying capacity is promising.

3. The aim and objectives of the study

The purpose of this study is to determine the dynamic load and strength of the body of a gondola car with unloading hoppers under the main operational modes. This will help increase the carrying capacity of the car, and, accordingly, the profitability of railroad transportation.

To achieve this goal, the following tasks are set:

– to investigate the vertical dynamics of the gondola car body with unloading hoppers;

– to determine the main indicators of strength of the body of a gondola car with unloading hoppers;

– to investigate the coefficient of stability of the balance of the body of a gondola car with unloading hoppers and conduct its modal analysis.

4. The study materials and methods

The object of our research is the processes of occurrence, perception, and redistribution of loads in the supporting structure of a gondola car with unloading hoppers.

The main hypothesis of the study assumes that the improvement of technical and economic indicators of the gondola car is possible through the increase of its carrying capacity. This is achieved through introduction of unloading hoppers into its structure (Fig. 1). Such a decision will help increase the carrying capacity of the car, and, accordingly, the profitability of transportation. According to preliminary calculations, the use of unloading hoppers could increase the usable volume of the body by 2.82 m^3. At the same time, the carrying capacity of the car would increase by 3.8 tons. Accordingly, the axial load on the wheelsets will increase. It is possible to solve this issue by using wheelsets with increased axial load in bogies.

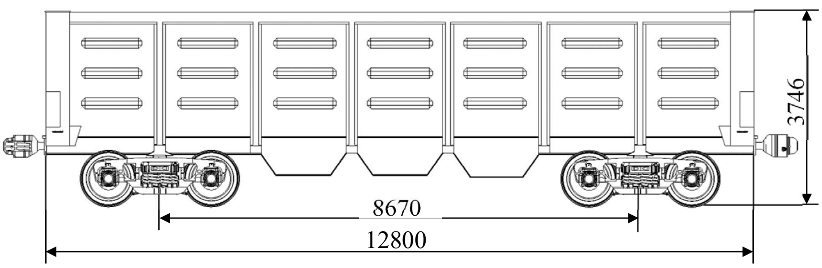
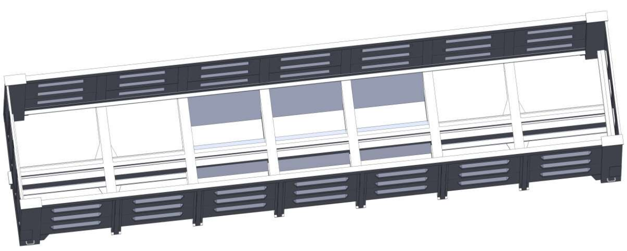


Fig. 1. Gondola car with unloading hoppers

The spatial model of the supporting structure of a gondola car with unloading hoppers is shown in Fig. 2.



a

b

Fig. 2. The supporting structure of a gondola car with unloading hoppers: *a* – top view; *b* – bottom view

Placement of hoppers is proposed to be carried out in the middle part of the body. At the same time, the typical design of the unloading hopper, which is used on grain cars, for example, model 19-7016 (Fig. 3), can be used. Such a hopper consists of four inclined sheets, 4 mm thick. Corners are used in the areas of their interaction with each other. The lower part of the unloading hopper has a guide for dumping the cargo.

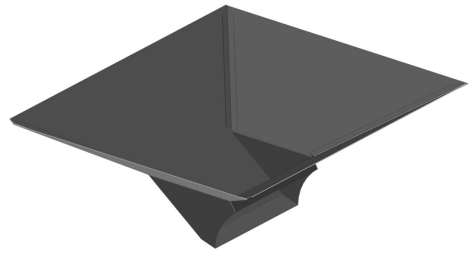
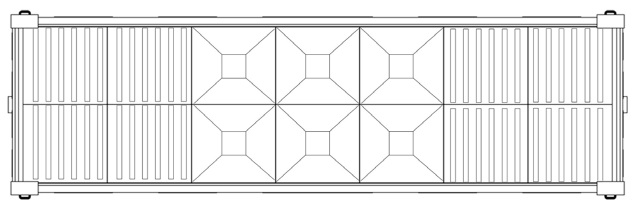


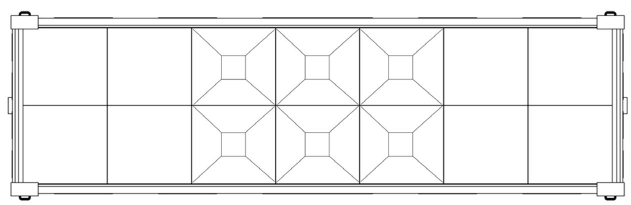
Fig. 3. Car unloading hopper

The structure of the unloading hopper shown in Fig. 3 is adopted as a prototype. However, during its installation on the body of a gondola car, the appropriate dimensions of the hopper were adjusted. The research was carried out on the example of a gondola car model of 12-757. The floor of such a gondola car is formed by the covers of the unloading hatches. When installing unloading hoppers instead of hatch covers, it is possible to make the hopper shut or with the possibility of unloading. There is also a possibility of a gondola car body version with the covers of the unloading hatches in the console parts (Fig. 4, *a*) or with a floor (Fig. 4, *b*).

It is important to note that the introduction of such an improvement is possible not only during the manufacture of cars but also their modernization during planned types of repairs.



a



b

Fig. 4. Versions of the body of the gondola car: *a* – with covers of the unloading hatches in the cantilever parts; *b* – with a floor in cantilever parts

Due to the fact that this implementation helps increase the load on the frame, to ensure its strength, it is proposed to strengthen the girder beam with additional intermediate diaphragms.

To substantiate the proposed improvement, a calculation was made on the strength of the body of the gondola car. In this case, the method of finite elements was applied as it is the most common when calculating the strength of machine-building structures [13, 14]. This method is implemented in the SolidWorks Simulation software package (France). The CAD model of the gondola car body was built in SolidWorks (France) [15–17] according to the album of drawings of a typical design. When building the model, it was taken into account that the hopper along the upper contour has a width of 1590 mm and a length of 1405 mm. That is, its contour dimensions are identical to the dimensions of the hatch cover.

Mathematical modeling was carried out to determine the dynamic loads that would act on the gondola car body of the improved design. The calculation diagram of the car is shown in Fig. 5.

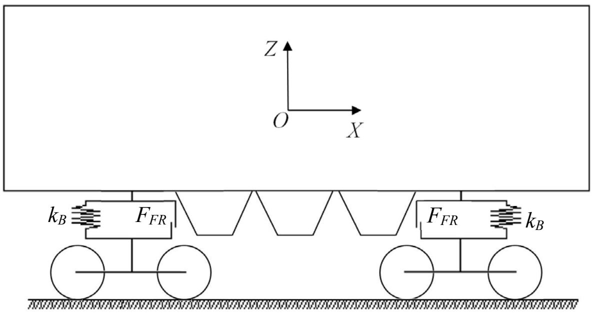


Fig. 5. Design scheme of the gondola car

The mathematical model, which characterizes the movement of a gondola car in a vertical plane, takes the following form:

$$M_1 \cdot \frac{d^2 q_1}{dt^2} + 2 \cdot k_B \cdot q_1 = = -F_{FR} \cdot \left(\operatorname{sign}\left(\frac{d}{dt} \delta_1 \right) + \operatorname{sign}\left(\frac{d}{dt} \delta_2 \right) \right), \quad (1)$$

$$M_2 \cdot \frac{d^2 q_2}{dt^2} + 2 \cdot l^2 \cdot k_B \cdot q_2 = = F_{FR} \cdot l \cdot \left(\operatorname{sign}\left(\frac{d}{dt} \delta_1 \right) + \operatorname{sign}\left(\frac{d}{dt} \delta_2 \right) \right), \quad (2)$$

where M_1, M_2 are, respectively, the mass and moment of inertia of the supporting structure of the gondola car during bouncing and galloping oscillations; k_B – stiffness of springs of spring suspension of bogies; q_i – generalized coordinates corresponding to translational movement relative to the vertical axis and angular movement around the vertical axis; l – semi-base of the car; δ_i – deformations of elastic elements of spring suspension; F_{FR} is the force of absolute friction in the spring assembly.

When building the model, it was taken into account that the gondola car body rests on typical two-axle bogies of model 18–100 [18–20]. It is assumed that the car has the rated geometric parameters. That is, possible wear and tear of the supporting structure during operation was not taken into account. The model was resolved in Mathcad (USA) [21–23]. When setting the initial conditions, it is taken into account that the initial displacement is 0.004 m, and the initial speed is zero [18].

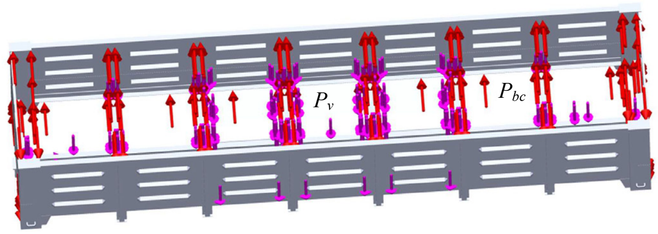
The determined accelerations are taken into account when calculating the strength of the car body. To this end, the calculation scheme shown in Fig. 6 is built. It takes into account the following loads: vertical P_v, spacer of bulk cargo P_{bc}, as well as longitudinal P_l acting on the stops of the auto coupling. The calculation was implemented for the I and III calculation modes of operation in accordance with DSTU 7598:2014. Freight cars. General requirements for calculations and design of new and modernized cars of 1520 mm gauge (non-self-propelled). The international analog of the specified standard is EN 12663-2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight cars.

When determining the pressure of the spacer of the bulk cargo, it is taken into account that the body is loaded with hard coal.

Isoparametric tetrahedra were used in the construction of the finite-element model of the car [24–26]. This type of element was chosen due to the fact that the mesh was created on a solid body. The number of model elements was 363353, and nodes – 120116. The maximum size of the model element is 100 mm, and the minimum is 20 mm.

When calculating the strength, it is taken into account that the body rests on bogies. Therefore, rigid ties were attached to the horizontal surfaces of stops [27, 28]. That is, possible shifts of stops relative to sub-stops were not taken into account. Low-alloy steel grade 09G2S is used as the construction material. This brand is typical for the manufacture of load-bearing structures of cars [29–32].

At the next stage of research, the coefficient of stability of the balance of the car body was determined. This calculation was carried out due to the fact that the introduction of unloading hoppers contributes to lowering the center of gravity of the body, and, accordingly, to improving its stability. The calculation was made according to the calculation scheme, which was formed to determine the strength of the car body. According to the same scheme, a modal analysis of the car body was carried out. In this case, the safety assessment of its movement was carried out based on the first natural frequency of oscillations.



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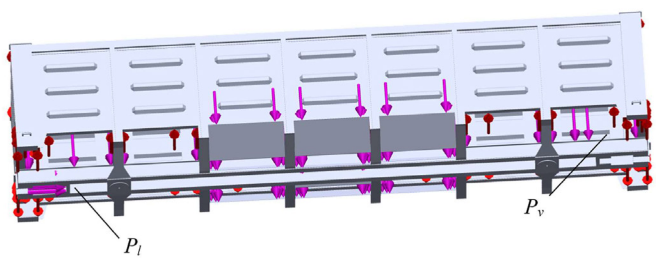

b

Fig. 6. Calculation diagram of a gondola car: *a* – top view; *b* – bottom view

5. Results of determining the loading capacity of the gondola car body with unloading hoppers

5. 1. Investigating the vertical dynamics of the gondola car body with unloading hoppers

Solving the mathematical model (1), (2) has made it possible to obtain the accelerations that act on the car body when moving in empty and loaded states. The acceleration acting on the car body when moving in an empty state is about 0.5 g (Fig. 7). This acceleration takes place in the center of mass of the body. The acceleration of the body in the zones of support on the bogies was about 0.6 g (Fig. 8). These indicators correspond to the "excellent" movement of the car. In this case, the speed of the car is assumed to be equal to 80 km/h.

When the car was moving in a loaded state, the acceleration acting in the center of mass amounted to 0.17 g (Fig. 9). The accelerations that act at the points of support of the body on the bogies are equal to 0.22 g (Fig. 10). The obtained indicators correspond to the "excellent" movement of the car.

The calculated accelerations were taken into account to determine the strength of the gondola car body.

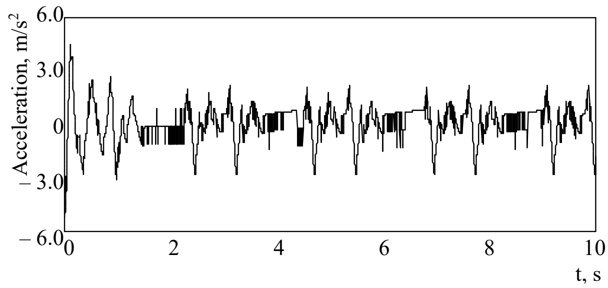

Fig. 7. Acceleration of the car in the center of mass (movement in an empty state)

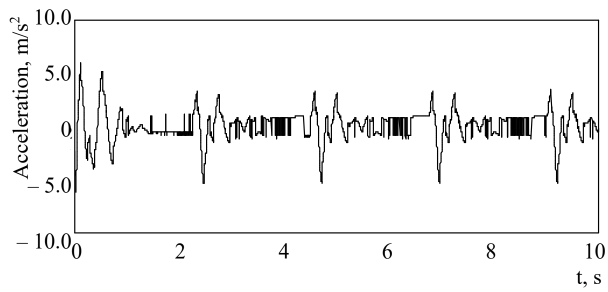

Fig. 8. Acceleration of the car in the areas of support on bogies (movement in an empty state)

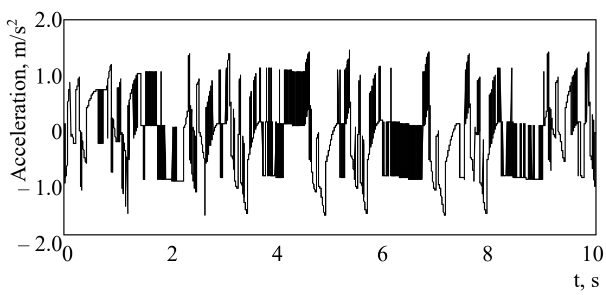

Fig. 9. Acceleration of the car in the center of mass (movement in a loaded state)

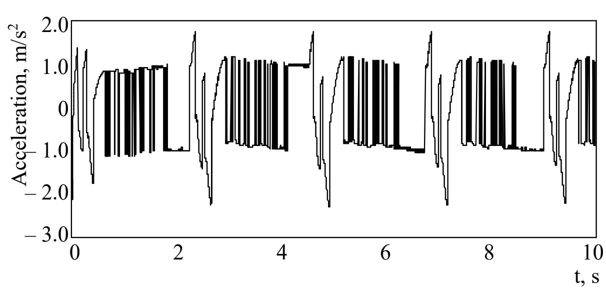

Fig. 10. Acceleration of the car in the areas of support on bogies (movement in a loaded state)

5. 2. Determining the main strength indicators of the body of a gondola car with unloading hoppers

According to the results of vertical dynamics modeling (Fig. 9), the strength of the load-bearing structure of the gondola car body was calculated. The calculation results are shown in Fig. 11, 12. In this case, the maximum stresses were recorded in the zone of interaction of the girder beam with the pivot beams. These stresses amounted to 305.2 MPa (Fig. 11) and are lower than permissible. Permissible stresses for the 1st design mode are taken to be equal to 310.5 MPa.

The maximum displacements in the car body occur in the middle part of the girder beam and amount to 4.4 mm (Fig. 12).

The results of the calculation of the gondola car body with other load calculation schemes are given in Table 1.

Table 1 demonstrates that the greatest stresses in the gondola car body occur during the "impact" (I load mode). This is explained by the fact that the body is subjected to the largest longitudinal load during operation.

Table 1

The results of calculating the body of a gondola car

Strength indicator	Load mode				
	I			III	
	Impact	Compression	Jerk - stretching	Impact-compression	Jerk - stretching
Stress, MPa	305.2	287.4	278.5	271.5	267.2
Movement in nodes, mm	4.4	4.3	4.3	4.3	4.4

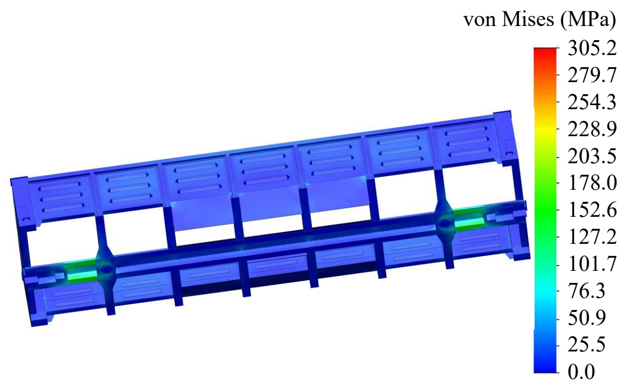

Fig. 11. The stressed state of the gondola car body

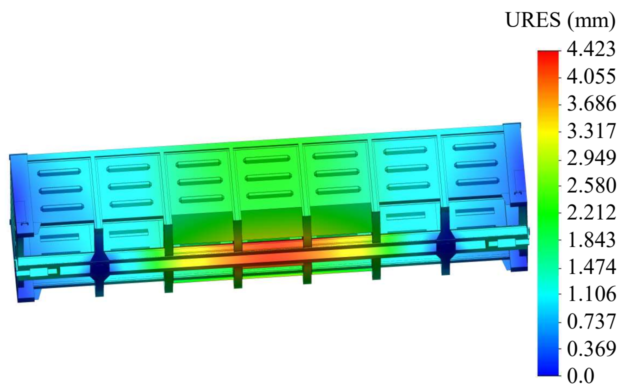

Fig. 12. Movement in the body of a gondola car

5. 3. Examining the coefficient of stability of the gondola car body and its modal analysis

The introduction of unloading hoppers will also contribute to the improvement of the coefficient of stability of the car's balance against overturning. This is explained by the fact that the center of gravity of the body will be placed lower than in a typical design.

It is known that in order to ensure stability of the balance of the car body against overturning, the following condition must be fulfilled [33]:

$$k_s = \frac{M_{rest}}{M_{mag}} \geq 1, \quad (3)$$

where M_{rest} is the value of the restoring moment; M_{mag} is the magnitude of the overturning moment.

To determine the dependences of overturning and restoring moments, the calculation scheme shown in Fig. 13 was built.

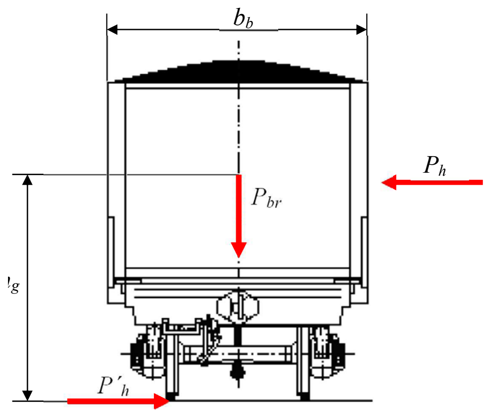

Fig. 13. Calculation scheme for determining the stability of the balance of the car

Then, one can record:

$$M_{mag} = P_h \cdot h_g, \quad (4)$$

$$M_{rest} = P_{br} \cdot \frac{b_b}{2} + P'_h \cdot 4 \cdot \frac{h_w}{2}, \quad (5)$$

where P_h is the horizontal force acting on the body in the transverse plane; h_g – the height of the center of gravity of the car body from the level of the rail head; P_{br} – gross body weight; b_b – body width; h_w is the height of the wheel crest.

Taking into account our calculations, it was established that the balance stability of the car body with unloading hoppers is 7 % better than that of a typical car design.

According to the calculation scheme shown in Fig. 6, a modal analysis of the body of the gondola car was carried out. To this end, the options of the SolidWorks Simulation software package were used. Some forms of oscillations of the body of a hopper car are shown in Fig. 14.

Numerical values of the oscillation frequencies corresponding to each mode are given in Table 2.

Table 2

Oscillation frequencies of the hopper car body

Mode	1	2	3	4	5	6	7	8	9	10
Frequency, Hz	14.07	21.09	30.7	7.6	41.07	42.9	43.9	45.7	53.3	59.9

The lowest value of the frequency occurs at the 1st mode. With further modes, the values of the oscillation frequencies increase, as their periods increase. However, in order to determine the safety of the carriage movement from the point of view of frequency analysis, it is necessary to pay attention to the first natural frequency of oscillations, which should not be less than 8 Hz.

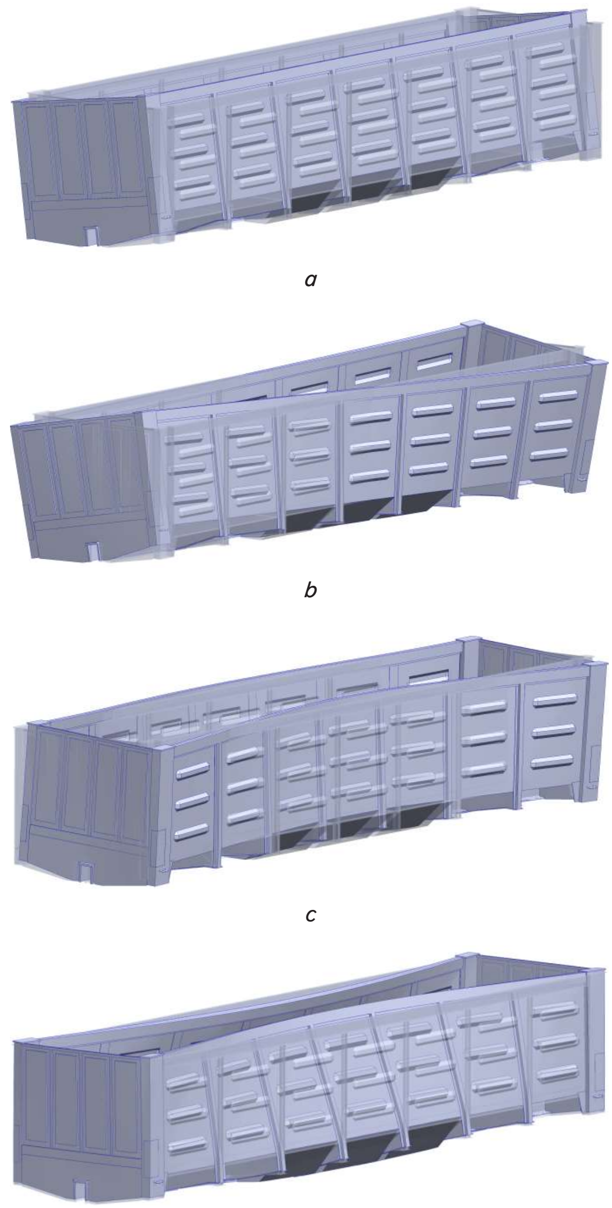

Fig. 14. Forms of oscillations of the car body at a scale of 20:1: *a* – the first mode; *b* – the second mode; *c* – the third mode; *d* – the fourth mode

6. Discussion of results of determining the load capacity of the gondola car body with unloading hoppers

In order to improve the technical and economic indicators of the gondola car, it is proposed to introduce unloading hoppers into its structure. Such a solution will help increase the usable volume of the body by 2.82 m^3. In this case, the carrying capacity of the car will increase by 3.8 tons. This solution is proposed at the concept level.

In order to substantiate the proposed improvement, the loading of the gondola car body under the main operating modes was determined. At the first initial stage of the research, mathematical modeling of the vertical loading of the gondola car body was carried out. The movement indicators were evaluated based on vertical accelerations that act in the center of mass of the supporting structure. It was established that when the car is moving in an empty state, the acceleration of the body is about 0.5 g (Fig. 7). These accelerations correspond to the "excellent" movement of the car.

The acceleration of the body in the areas of support on the bogies is about 0.6 g (Fig. 8). When moving in a loaded state, respectively, 0.17 g (Fig. 9) and 0.22 g (Fig. 10). The evaluation of the movement of the car is "excellent". This allows us to conclude that from the point of view of dynamics, the safety of the carriage is ensured. This research result can be explained by the fact that an increase in the carrying capacity of the body leads to a decrease in its center of gravity and, accordingly, to an improvement in dynamics.

The obtained accelerations are included in the determination of the main indicators of the body strength of the gondola car. The results of the calculations showed that the strength of the gondola car body under the main load modes is maintained. In this case, the maximum stresses occur at the I calculation mode and are equal to 305.2 MPa (Fig. 11). The result can be explained by the fact that with this calculation mode, the car body experiences the largest longitudinal load. In this case, due to the fact that the proposed improvement of the body provides an increase in its carrying capacity, we proposed strengthening the girder beam with additional diaphragms. Therefore, the overall stiffness of the girder beam increases, and the strength indicators of the body are ensured within the permissible values.

The maximum movements occur in the middle part of the girder beam and amount to 4.4 mm (Fig. 12). This circumstance is explained by the fact that the frame rests on the bogies through pivot beams. Therefore, the middle part of the frame has the greatest flexibility in the vertical plane.

Taking into account the results obtained during the determination of the dynamics and strength of the body is appropriate at the stage of designing cars or their modernization.

At the next stage of research, the coefficient of stability of the body's balance was determined, as well as its modal analysis. These results are important from the point of view of the safety of operation of cars on main lines.

It was established that the equilibrium stability of the proposed gondola car design is 7 % better than that of the typical structure. This is explained by lowering the center of gravity of the body through the introduction of unloading hoppers.

The evaluation of the safety of the gondola car movement was carried out according to the first natural frequency of oscillations. The results of the calculations showed that the first natural frequency of oscillations has a value of 14.07 Hz (Table 2). This oscillation frequency exceeds the limit, which is 8 Hz. Therefore, traffic safety from the point of view of frequency analysis is ensured.

The limitation of this study is that when determining the strength of the body of the hopper car, we did not take into account the welding seams between the components of its structure. In addition, possible movements in the planes of the stops of auto couplings were not taken into account.

As a drawback of this study, we can note the need to analyze the dynamic indicators of the car body with other types of oscillations.

The advantage of the current research in comparison with works [6, 7, 11] is that the improvement of technical and economic indicators of the car is achieved through the increase of its carrying capacity. This will contribute to increasing the profitability of railroad transportation. In comparison with work [8], our research is focused on improving one of the most common types of cars in operation. In contrast to works [5, 9, 10], the improvement of the body of a gondola car is justified not only by strength calculations but also by dynamic ones. The results of the substantiation of the introduction of unloading hoppers into the structure of a gondola car will contribute to increasing the profitability of railroad transportation by increasing the carrying capacity of the body, in contrast to the results reported in [12].

The advantages of our results in comparison with known analogs are that the proposed improvement not only contributes to the improvement of the profitability of rail freight transportation but also the safety of the movement of the car as part of the train.

The conditions for the practical application of the research results are compliance with the axial load within the permissible values. It is known that the load on one axle should not exceed 235 kN/axle, provided that standard 18–100 bogies are used. To this end, it is necessary to comply with the relevant requirements when loading the body. However, taking into account the introduction of unloading hoppers on gondola cars, it is advisable to use bogies with an increased axial load, i.e., more than 235 kN/axle. This will make it possible to use the full usable carrying capacity of the body during operation.

The further development of this research is to determine the main indicators of the dynamics of the car with other types of vibrations of the car. Also, one of the options for the development of this area is the introduction of sandwich panels into the structure of the car body. Such a solution could contribute to the reduction of dynamic loads acting on it, and, accordingly, to the improvement of strength.

7. Conclusions

1. The vertical dynamics of the body of a gondola car with unloading hoppers were studied. The acceleration acting in the center of mass of the car body when moving in an empty state was about 0.5 g. The acceleration of the body in the areas of support on the bogies was about 0.6 g.

When the car is moving in a loaded state, the accelerations acting at the center of mass are equal to 0.17 g. Accelerations that act at the points of support of the body on the bogies amounted to 0.22 g. The obtained indicators correspond to the "excellent" movement of the car. This is explained by the fact that the carrying capacity of the body has been increased and, accordingly, its center of gravity has been lowered.

2. The main indicators of strength of the body of a gondola car with unloading hoppers were determined. It was established that the maximum stresses in the body of the gondola car occur in the I calculation mode and correspond to the impact. In this case, these stresses are equal to

305.2 MPa and are lower than permissible. The maximum movements in the car body occur in the middle part of the girder beam and amount to 4.4 mm. The calculation of the gondola car body under other load schemes showed that its strength is ensured.

3. The coefficient of stability of the car body against overturning was determined. It was established that the balance stability of the car body with unloading hoppers is 7 % better than that of a typical design. This can be explained by the fact that its center of gravity decreases compared to a typical gondola car structure.

A modal analysis of the car body was carried out. The results of the calculation allowed us to conclude that the first natural frequency of oscillations takes a value of 14.07 Hz. This allows us to conclude that traffic safety from the point of view of frequency analysis is ensured.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

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