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IDENTIFYING POSSIBLE WAYS FOR ADAPTING AN OPEN WAGON FOR TRANSPORTING CONTAINERS

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The object of this study is the processes of perception and redistribution of loads in the supporting structure of a open wagon loaded with containers, taking into account the new scheme of their fastening.

For safe transportation of containers in an open wagon, it is suggested to use a removable module. This module works according to the principle of an intermediate adapter between the container and the open wagon body. Fastening of the module itself in the open wagon is carried out through the fitting stops, which are placed on the floor of the open wagon.

Mathematical modeling was carried out to determine the longitudinal dynamic load acting on the container fixed according to the new scheme in the open wagon. To this end, a mathematical model was built that characterizes the longitudinal movements of the "open wagon-removable module-container" system. Determination of the accelerations that act on the supporting structure of the open wagon loaded with containers was also carried out by means of computer simulation. Verification of the formed model of the dynamic load of the open wagon was carried out according to the F-criterion. Also, as part of the study, a modal analysis of the load-bearing structure of a open wagon loaded with containers was carried out, which made it possible to assess its traffic safety.

A feature of the results obtained as part of the research is that the proposed design of the removable module could be used not only for fastening containers but also for transportation of other types of cargo.

The field of practical application of the results is railroad transport, including other transportation industries. The conditions for the practical use of the results are a symmetrical scheme of loading the body of a open wagon with containers.

The results of this study will contribute to increasing the efficiency of container transportation and the profitability of railroad transport

Keywords: railroad transport, open wagon, structure adaptation, loading of a open wagon, longitudinal dynamics, container transportation

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1. Introduction

The increase in the operational efficiency of the transport industry led to the introduction of modular vehicles. One of the most common among these are containers. This is explained by the possibility of their transportation by almost all types of transport: railroad, road, water, aviation, even pipeline. Therefore, a container is a multimodal type of transport unit, which predetermines its wide demand not only in the internal communication of countries but also in the international one [1, 2].

A significant share of container transportation is accounted for by rail transport. Transportation of containers by railroad is carried out on platform cars. Fastening of containers on platform cars is ensured by means of fitting stops, which are placed on the longitudinal beams of the frame of platform cars. The spread of container transportation led to the modernization of universal platform cars for container transportation. Such modernization involved placing fitting stops on the frame. At the same time, this decision did not fully resolve the issue of technical support for container transportation by rail.

The lack of platform cars in operation makes it necessary to use other types of cars for container transportation, for example, open wagons. This is justified by the lack of a roof on the open wagon, which allows it to be loaded with containers. However, the use of open wagons for the transportation of containers requires ensuring a reliable scheme of their interaction because the open wagon is not adapted for these purposes. Due to the flexibility of the container in the open wagon, damage may occur not only to the container itself, the cargo transported in it, but also to the body of the open wagon. This not only causes the need for unscheduled types of vehicle repairs but can also contribute to accidents. In the case of transportation of dangerous goods, this additionally threatens environmental danger. Therefore, the issues of situational adaptation of open wagons for container transportation are quite relevant and require research.

2. Literature review and problem statement

The issues of constructing railroad rolling stock for transporting containers, as well as improving the schemes of their fastenings during transportation, are quite urgent. For example, in work [3], the issue of the safety of container transportation in the RgS car was considered. Fastening of containers on this car is carried out with the help of special bolts. The results of calculations carried out by the authors made it possible to determine the most rational type of bolts for fastening containers. However, the authors did not pay attention to the issue of determining the possibility of fastening containers in open wagons using such a scheme. This may be due to the fact that the most used type of car for transporting containers was considered during the research.

In work [4], for the adaptation of vehicles to the transportation of containers, the design of a removable module of the FLAT RACK type is proposed. The results of the strength calculation of the removable module under the condition of its use on the platform car are highlighted. The calculation results proved the feasibility of the proposed design of the removable module. Along with this, the authors did not investigate the possibility of its use for fastening containers in open wagons.

Features of the modernization of the supporting structure of the car for the possibility of transporting containers in it are highlighted in paper [5]. The authors report the results of experimental studies into the strength of the car frame during a shunting collision. It was established that the proposed modernization is expedient. But the studies were conducted in relation to the platform car. That is, the authors did not investigate the expediency of such modernization of the open wagon.

In paper [6], the issue of modernization of the freight car for the transportation of containers is also considered. The authors of the work proposed the introduction of a removable frame. Such a frame is designed to accommodate 20-foot and 40-foot containers and is attached to the car frame. It has been proven that the proposed solutions for using the specified frame are effective. However, the authors limited themselves to justifying the use of the proposed frame on a platform car.

Work [7] provides solutions for the situational adaptation of open wagons to the transportation of containers. A special removable module for securing containers in a open wagon is proposed. Such a module is multifunctional and can be used for transportation of other types of cargo. The paper provides an example of its application for the transportation of long cargo. However, the authors did not pay attention to the study of the strength of the load-bearing structure of the open wagon and container, taking into account the use of such a module.

Features of calculating the strength of the floor of a 40-foot container during its transportation by water transport are considered in work [8]. This work is of practical importance since the authors investigated a certain route of container transportation. They recommended safe operation of this type of container along this route. However, these solutions are not effective when transporting it by rail, in particular in open wagons.

In [9], the justification for the introduction of innovative multimodal systems into operation is given. These systems are considered as an alternative to existing types of transportation. The rationale for the use of such systems from an economic point of view is presented. However, the authors of the work did not pay attention to the issue of situational adaptation of vehicles to increase the efficiency of container transportation. This would contribute to the further development and profitability of the transport industry as a whole.

Analysis of the dynamic load of a car loaded with containers during coupling (maneuvering collision) is carried out in work [10]. The case of the container having its own degree of freedom on the car is considered. A mathematical model has been built that allows one to determine the dynamic loads acting on the car and the container during coupling. But the authors did not use this model to determine the load of containers in a open wagon.

Work [11] reports determining the load of a open wagon when transporting containers in it. The calculation of the strength of the car body when it receives longitudinal loads from containers through fitting stops welded to the floor is given. A solution for improving the scheme of fixing containers in a open wagon is proposed. However, these solutions are proposed as concepts. Examples of the implementation of these solutions are not given in the work.

Our review of the literature [3–11] proves that the issues of increasing the efficiency of container transportation are quite relevant. At the same time, it can be concluded that the situational adaptation of open wagons for container transportation has not yet been given due attention. This makes it necessary to carry out research in the specified area.

3. The aim and objectives of the study

The purpose of our study is to determine the dynamic load of a open wagon loaded with containers, taking into account the new scheme of their fastening in the body. This will contribute to recommendations for the involvement of open wagons in container transportation, and therefore to increasing the efficiency of railroad transport operation.

To achieve the goal, the following tasks were set:

– to carry out mathematical modeling of the longitudinal dynamic loading of the load-bearing structure of a open wagon loaded with containers;

– to conduct a computer simulation of the longitudinal dynamic loading of the load-bearing structure of a open wagon loaded with containers.

4. The study materials and methods

The object of our research is the processes of perception and redistribution of loads in the supporting structure of a open wagon loaded with containers, taking into account the new scheme of their fastening.

The main hypothesis of this study assumes that the use of a removable module for fastening containers in a open wagon will contribute to reducing its load under the conditions of operational modes.

For safe transportation of containers in a open wagon, it is suggested to use a removable module. This module works on the principle of an intermediate adapter between the container and the body of the open wagon (Fig. 1). The module consists of a frame formed by transverse beams, end beams, longitudinal beams, end superstructures, and braces. It is equipped with corner fittings for mounting the module in a open wagon. Fastening of containers in the module is carried out through fitting stops. The location of the container in the module is shown in Fig. 2.

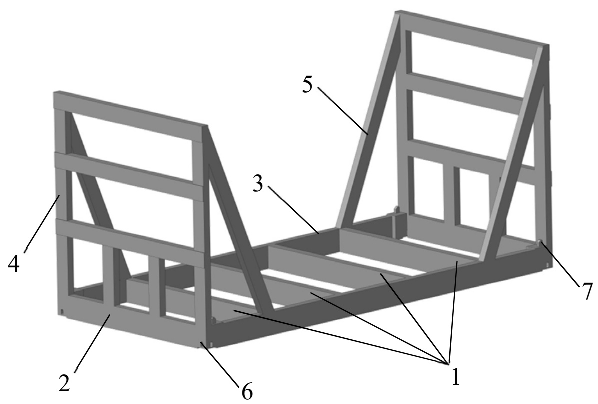

Fig. 1. Module for fastening containers in a open wagon: 1 – transverse beams; 2 – end beams; 3 – longitudinal beams; 4 – end superstructures; 5 – braces; 6 – corner fittings; 7 – fitting stops

Fastening of the module itself in the open wagon is carried out through the fitting stops, which are placed on the floor of the open wagon. At the same time, the fittings of the removable module have a recess (Fig. 3, 4), which provides the possibility of transferring the load from the removable module over the entire area of the frame.

Placement of containers in a open wagon, fixed according to the new scheme, is shown in Fig. 5.

Mathematical modeling was carried out to determine the longitudinal dynamic load acting on the container fixed according to the new scheme in the open wagon. The mathematical model, which characterizes the movement of a open wagon loaded with containers, was formed according to the La Grange II type method [12, 13]. It is taken into account that the removable modules are fixed relative to the floor of the open wagon through fittings. Their movement relative to the floor is limited by fitting stops. The container is fixed in the removable module and has its own degree of freedom in the longitudinal plane, which is limited by the size of the technological gap between the fittings and fitting stops. The connection between fitting stops and fittings, respectively open wagon and removable modules, removable modules, and containers, is accepted as rigid.

The mathematical model was resolved in Mathcad (USA) [14, 15]. The initial conditions were assumed to be close to zero [16, 17].

In order to determine the distribution fields of accelerations acting on the containers, taking into account the new scheme of their fastening, computer simulation was carried out. At the same time, the finite element method, which is implemented in SolidWorks Simulation (France) [18], was applied.

Fig. 2. Placement of the container in the module

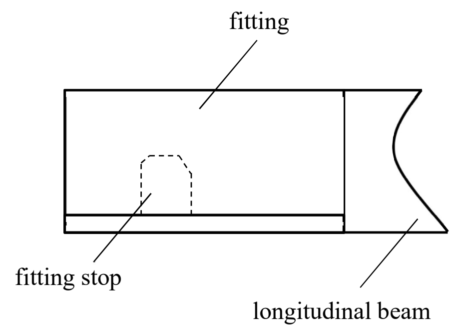

Fig. 3. Scheme of interaction of the open wagon fitting stop with the fitting of the removable module

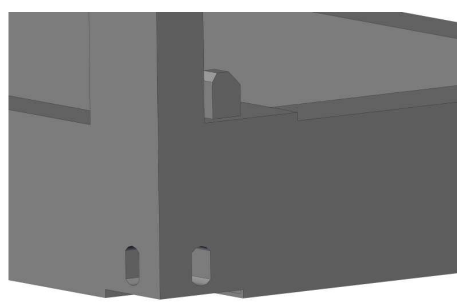

Fig. 4. Fitting of the removable module

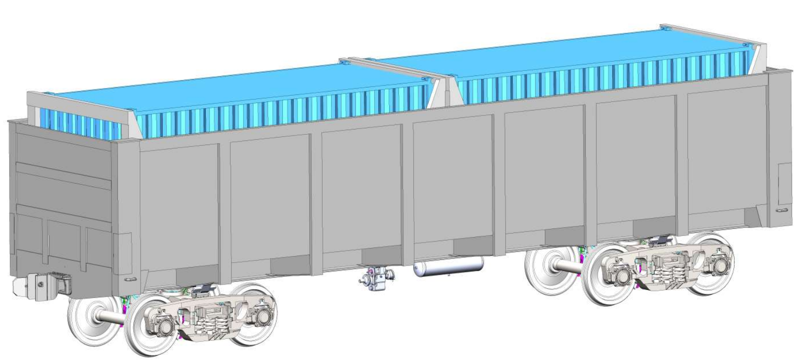

Fig. 5. Placement of containers in a open wagon

The construction of the finite-element model is carried out by tetrahedra (Fig. 10). Their optimal number was determined graph-analytically [19–22].

The results were used to verify the formed mathematical model. In this case, the F-test was applied [23, 24]. The verification was carried out by comparing two samples obtained by mathematical modeling and the finite element method. The optimal number of measurements was determined according to the Student criterion [25].

Also, as part of the study, a modal analysis of the load-bearing structure of a open wagon loaded with containers was carried out. At the same time, options of the SolidWorks Simulation software package were used. The purpose of this analysis was to determine natural frequencies and forms of oscillations. Based on the first natural frequency of oscillations, the safety of the open wagon was evaluated.

5. Results of determining the longitudinal dynamic load of the supporting structure of an open wagon loaded with containers

5. 1. Mathematical modeling of longitudinal dynamic loading of the supporting structure of an open wagon loaded with containers

To determine the longitudinal dynamic load of the load-bearing structure of an open wagon loaded with containers, the calculation scheme shown in Fig. 6 was built.

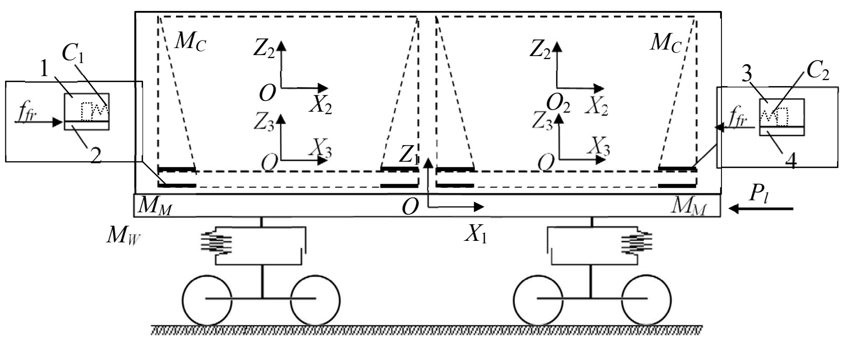

Fig. 6. Calculation diagram of an open wagon loaded with containers: 1 — fitting of the removable module; 2 — open wagon fitting stop; 3 — container fitting; 4 — fitting stop of the removable module

The mathematical model that describes the movement in the "open wagon - removable module - container" system takes the following form:

$$\begin{cases} M_W \cdot \ddot{q}_1 = P_l - \left(\sum_{i=1}^{n} f_{fr} \cdot \operatorname{sign}(\dot{q}_1 - \dot{q}_2) + C_1(q_1 - q_2) \right), \\ M_M \cdot \ddot{q}_2 = \left(f_{fr} \cdot \operatorname{sign}(\dot{q}_1 - \dot{q}_2) + C_1(q_1 - q_2) \right) - \\ -\left(f_{fr} \cdot \operatorname{sign}(\dot{q}_2 - \dot{q}_3) + C_2 \cdot (q_2 - q_3) \right), \\ M_C \cdot \ddot{q}_3 = f_{fr} \cdot \operatorname{sign}(\dot{q}_2 - \dot{q}_3) - C_2 \cdot (q_2 - q_3), \end{cases} \tag{1}$$

where M_W is the gross mass of the open wagon; P_l – the value of the longitudinal force acting on the auto coupler (3.5 MN); n is the number of containers placed in an open wagon; f_{fr} – friction force between fitting stops and fittings; C_1, C_2 – stiffness of the connection between fitting stops and fittings, respectively, of the open wagon and removable module, removable module and container; M_C – mass of the container; q_1, q_2, q_3 – coordinates defining the movement of the open wagon, the removable module and the container, respectively, relative to the longitudinal axis.

Generalized accelerations were calculated in the corresponding arrays $ddq_{j,i}$:

$$ddq_{j,1} = \frac{P_l - \left(\sum_{i=1}^{n} f_{fr} \cdot \operatorname{sign}(\dot{y}_1 - \dot{y}_2) + C_1(y_1 - y_2) \right)}{M_W}, \tag{2}$$

$$ddq_{j,2} = \frac{\left(f_{fr} \cdot \operatorname{sign}(\dot{y}_1 - \dot{y}_2) + C_1(y_1 - y_2) \right) - \left(f_{fr} \cdot \operatorname{sign}(\dot{y}_2 - \dot{y}_3) + C_2 \cdot (y_2 - y_3) \right)}{M_M}, \tag{3}$$

$$ddq_{j,3} = \frac{f_{fr} \cdot \operatorname{sign}(\dot{y}_2 - \dot{y}_3) - C_2 \cdot (y_2 - y_3)}{M_C}, \tag{4}$$

where $y_1=q_1$, $y_2=q_2$, $y_3=q_3$, $y_4=\dot{y}_1$, $y_5=\dot{y}_2$, $y_6=\dot{y}_3$.

Based on the calculations, it was established that the maximum accelerations acting on the open wagon are 40.6 m/s^2, on the loading module – 33.4 m/s^2, and on the container – about 33.7 m/s^2 (Fig. 7).

At the moment of "impact", these accelerations have a negative value. Since it is taken into account that the connection between the container and the module is elastic, the accelerations have a sign-changing character.

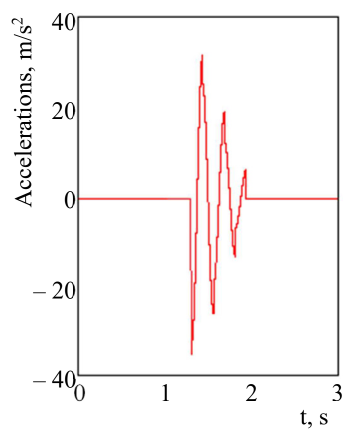

Fig. 7. Accelerations acting on the container

5. 2. Computer simulation of longitudinal dynamic loading of the supporting structure of an open wagon loaded with containers

To determine the distribution fields of accelerations acting on an open wagon loaded with containers, its spatial model was constructed (Fig. 8).

When drawing up the calculation scheme, it was taken into account that a longitudinal force of 3.5 MN acts on the back stop of the auto coupling (Fig. 9). On the opposite side, this force is balanced by the forces of inertia of the car masses.

Fixation of the model was carried out by heels. At the same time, a rigid connection was applied, that is, possible movements of the heel relative to the heel support were not taken into account. An elastic connection was established between fittings and fitting stops (Fig. 10).

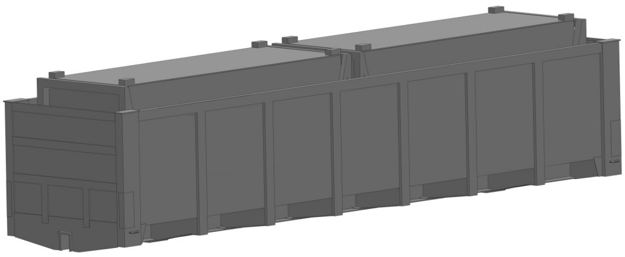

Fig. 8. Spatial model of the supporting structure of an open wagon loaded with containers, taking into account the new scheme of their fastening

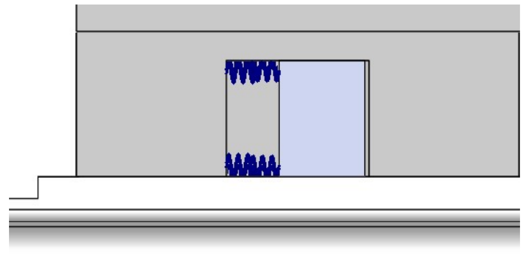

Fig. 10. Modeling the elastic connection between the fitting and the fitting stop

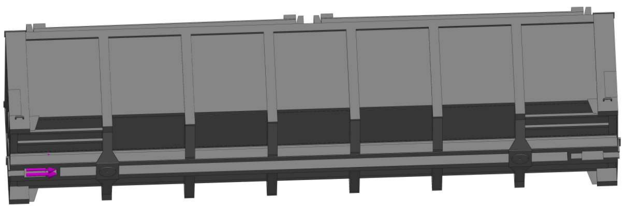

Fig. 9. Calculation diagram for the supporting structure of an open wagon loaded with containers

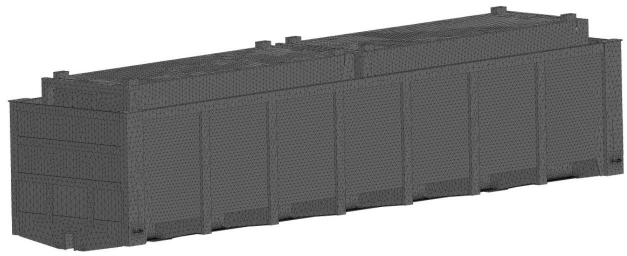

Fig. 11. Finite-element model of the supporting structure of an open wagon, loaded with containers

The number of nodes of the finite-element model (Fig. 11) was 154,524, and the number of elements was 469,389 with a maximum size of 100 mm and a minimum size of 20 mm.

The construction material is 09G2S steel, which is typical for the production of load-bearing structures of cars and containers. The calculation results are shown in Fig. 12. The maximum accelerations acting on the supporting structure of the open wagon are concentrated in the middle part of its frame and amount to 39.1 m/s^2. The minimum value of the acceleration is observed in the areas where the body is secured.

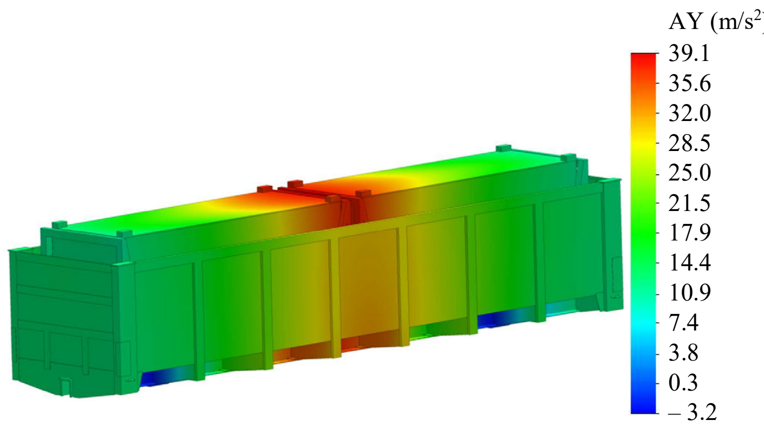

Fig. 12. Fields of acceleration distributions acting on the supporting structure of an open wagon loaded with containers

The maximum acceleration acting on the removable modules was 35.2 m/s^2. This acceleration is distributed over the end parts of the removable modules, which are located behind the center of the open wagon body.

The maximum acceleration acting on the containers was 36.2 m/s^2. This acceleration is also distributed over the end parts of the containers placed behind the center of the open wagon body.

Taking into account our variational calculations, the dependence of the container acceleration on the impact force of the open wagon on the coupling was obtained (Table 1). In this case, the number of trials was 10.

Table 1

Results of simulating the load of a container fixed in an open wagon according to the new scheme

Model	Impact force, MN									
	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5
Mathematical	25.2	25.7	26.7	27.8	28.7	29.7	30.6	31.7	32.8	33.7
Computer	26.7	27.8	28.4	30.2	31.3	32.2	33.1	34.4	35.1	36.2

The calculations showed that the dependence of the container's acceleration on the impact force of the open wagon is linear (Fig. 13).

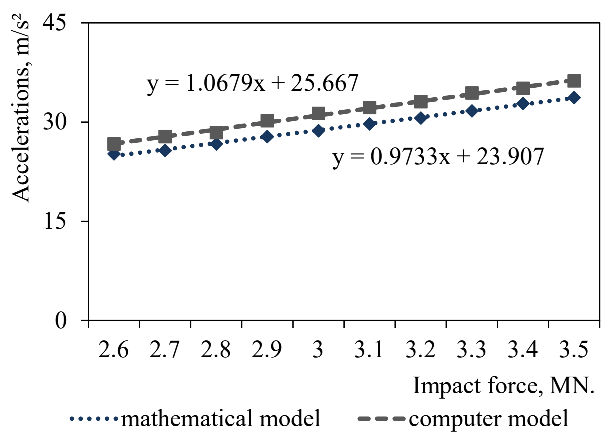

Fig. 13. Dependence of the accelerations acting on the container on the impact force of the open wagon on the coupling

The maximum discrepancy between the simulation results was 8.3 % and occurs at an impact force of 3.0 MN (Fig. 14).

Based on our calculations in accordance with the data given in Table 1, it was established that the calculated value of the criterion is F_p=1.2. At the same time, the dispersion of reproducibility is equal to $S_r^2 = 8.7$ and the variance of adequacy – $S_{ad}^2 = 10.5$. This value of the criterion is less than the tabular one, which is F_t=3.07. Therefore, the hypothesis about the adequacy of the model is not rejected.

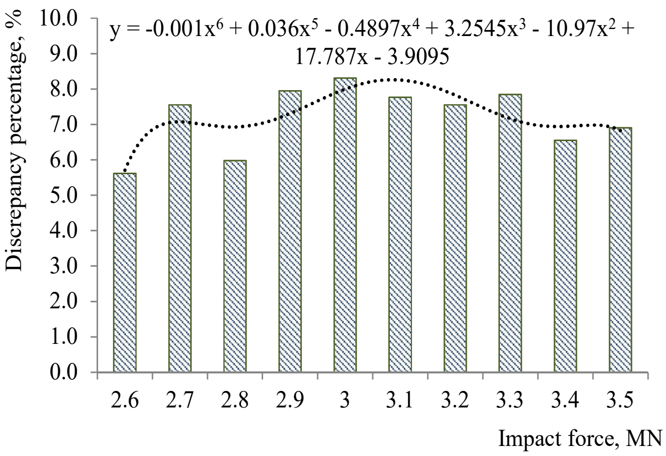

Fig. 14. Discrepancy between simulation results

According to the calculation scheme shown in Fig. 9, a modal analysis of the supporting structure of an open wagon loaded with containers was carried out. Table 2 gives the numerical values of natural frequencies of vibrations of the supporting structure of an open wagon loaded with containers.

Analyzing the data given in Table 2, it can be concluded that the safety of the open wagon movement from the point of view of modal analysis is ensured, since the value of the first natural frequency of oscillations is greater than 8 Hz [DSTU 7598:2014. Freight cars. General requirements for calculations and design of new and modernized cars of 1520 mm gauge (non-self-propelled)]. The foreign analog of this standard is "EN 12663-2. Railroad applications – structural requirements of railroad vehicle bodies – Part 2: Freight cars. B., 2010. 54 p.".

In Fig. 15, as an example, the first six forms of oscillations of the supporting structure of the open wagon are given.

Table 2

Values of the natural frequencies of open wagon oscillations

Mode	Frequency, Hz
1	21.77
2	25.25
3	34.47
4	35.58
5	41.01
6	41.7
7	44.12
8	57.59
9	65.21
10	65.53

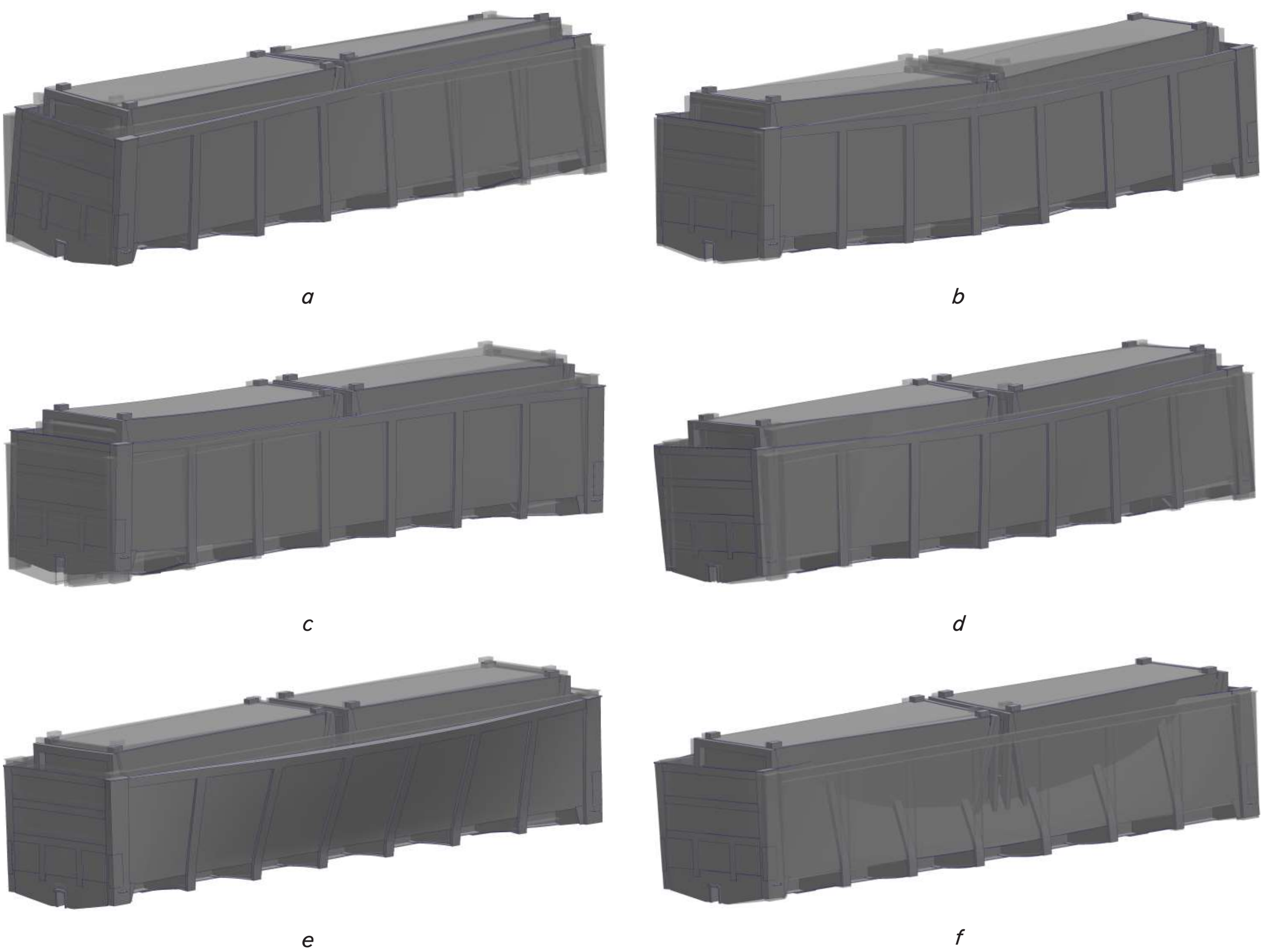

Fig. 15. Forms of oscillations of the supporting structure of an open wagon loaded with containers: *a* — mode I; *b* — mode II; *c* — mode III; *d* — mode IV; *d* — mode V; *f* — mode VI

In this case, the stationary position of the supporting structure of the open wagon loaded with containers is shown in matte color, and the deformed state in a 30:1 magnification scale is shown in transparent.

6. Discussion of results related to determining the longitudinal dynamic load of the supporting structure of an open wagon loaded with containers

To adapt open wagons to the reliable transportation of containers, the structure of a removable module has been proposed (Fig. 1). This module acts as an intermediate adapter between the car body and the container. The peculiarity of this module is that the fittings, by which it interacts with the fitting stops, are made with recesses (Fig. 3). This contributes to the transfer of the load from the removable module to the car body not along the horizontal area of the fitting stop but as distributed over the area of the module's contact with the floor. In addition, such a decision helps limit the degree of freedom of the removable module relative to the body since the vertical parts of the fittings will interact with the vertical parts of the fitting stops.

Mathematical modeling was carried out to justify the use of a removable module for fastening containers in an open wagon. To this end, a mathematical model (1) was formed. The results of its solution established that the maximum accelerations acting on the container, taking into account the new fastening scheme in the open wagon, are about 33.7 m/s^2 (Fig. 7). These accelerations are almost 10 % lower than those acting on a container with a typical anchoring scheme. In the case of over-normalized operating modes, the value of this discrepancy is even greater.

Our results were verified by computer simulation. To this end, a spatial model of a half-car was built (Fig. 8) and the corresponding calculations were performed. It was established that the maximum value of the acceleration acting on the containers was 36.2 m/s^2 (Fig. 12). This acceleration is distributed over the end parts of the containers placed behind the center of the open wagon body. To verify the formed model, variational calculations were carried out (Table 1). At the same time, as a variation parameter, the impact force of the open wagon on the coupling is taken into account. The calculations showed that the dependence of the container's acceleration on the impact force of the open wagon is linear (Fig. 13). The maximum discrepancy between the results of mathematical and computer simulation was 8.3 % at an impact force of 3.0 MN, and the smallest was 5.6 % at an impact force of 2.6 MN (Fig. 14). Using the F-criterion, it was established that the hypothesis of adequacy is not rejected.

This study has certain advantages in comparison with known ones. For example, in contrast to works [3, 5, 6], we proposed a solution that facilitates the possibility of transporting containers not only on platform cars but also in open wagons. In comparison with the results reported in [4], the justification of the use of a removable module for fastening containers in open wagons, which increases their demand in operation, was carried out. In contrast to work [7], we proposed not only a removable module for transporting containers but also investigated the dynamic loading of vehicles with such a scheme of their interaction. The advantage of this study in comparison with [8] is that the proposed solutions are effective when transporting containers by various modes of transport. In contrast to work [9], we considered the possibility of situational adaptation of existing vehicles for container transportation. The results of work [10] do not provide the possibility of situational adaptation of open wagons to container transportation. In contrast to the results of [11], we proposed specific solutions that could facilitate the possibility of transporting containers in open wagons.

However, this study has a certain limitation, which is that its results can be applied to open wagons with a dead bottom. That is, at present, no attention was paid to justifying the application of such a fastening scheme on an open wagon, the floor of which is formed by the covers of the unloading hatches.

One of the main shortcomings of this study is that at this stage, during the mathematical modeling of the longitudinal loading of the open wagon, its angular movements were not taken into account. Such movements are due to an asymmetric impact on the car coupling relative to the longitudinal axis of the car.

At the same time, these questions can be considered as a further development of research into the specified area.

The results of our study will contribute to increasing the efficiency of container transportation and the profitability of railroad transport.

7. Conclusions

1. Mathematical modeling of the longitudinal dynamic loading of the load-bearing structure of an open wagon loaded with containers has been carried out. To this end, a mathematical model was built that characterizes the longitudinal movements of the "open wagon - removable module - container" system. The results of the calculations established that the maximum accelerations acting on the open wagon are 40.6 m/s^2, on the loading module – 33.4 m/s^2, and on the container – about 33.7 m/s^2.

2. Computer simulation of the longitudinal dynamic loading of the load-bearing structure of an open wagon loaded with containers has been carried out. It was established that the maximum accelerations acting on the supporting structure of the open wagon are concentrated in the middle part of its frame and amount to 39.1 m/s^2. The maximum acceleration acting on removable modules was 35.2 m/s^2, and on containers – 36.2 m/s^2.

Verification of the formed model of the dynamic load of the load-bearing structure of the open wagon loaded with containers was carried out. Our calculations showed that the adequacy hypothesis is not rejected.

A modal analysis of the load-bearing structure of an open wagon loaded with containers was carried out, taking into account the new scheme of their interaction. It was established that the safety of the open wagon movement from the point of view of modal analysis is ensured, since the value of the first natural frequency of oscillations is greater than 8 Hz.

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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, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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