

Проведено удосконалення несучої конструкції вагона-платформи для перевезення військової техніки та ведення вогняної дії. Особливістю вагона-платформи є наявність поворотних секторів з композитного матеріалу з в'язкими або пружно-в'язким зв'язками, що дозволяє поглинати кінетичну енергію, яка передається на раму при веденні вогню з вагону, а також дає можливість здійснювати бокове завантаження/вивантаження військової техніки.

Досліджено динамічну навантаженість несучої конструкції вагона-платформи для перевезення військової техніки та ведення бойової дії. Складено математичну модель, яка враховує переміщення несучої конструкції вагона-платформи при веденні з нього вогняної дії. Враховано, що вагон-платформа завантажений двома зенітними установками. Розв'язок математичної моделі здійснений в програмному середовищі MathCad.

Дослідження проведені у плоскій системі координат. Визначено прискорення, які діють на несучу конструкцію вагона-платформи. Максимальна величина прискорення при цьому складає близько $3,6 \text{ м/с}^2$ при коливаннях підскакування та $4,0 \text{ м/с}^2$ при коливаннях галопування. Тобто з урахуванням запропонованих технічних рішень динамічна навантаженість несучої конструкції вагона-платформи у вертикальній площині при пострілі зменшується майже на 30 %. При цьому величина прискорення майже не залежить від кута пострілу.

Отримані величини прискорень враховані при визначенні показників міцності несучої конструкції вагона-платформи. Розрахунок проведено за методом скінчених елементів в програмному середовищі Costos Works. Максимальні еквівалентні напруження в несучій конструкції вагона-платформи склали близько 285 МПа та зосереджені у зоні обтирання несучої конструкції на візки. Отже міцність несучої конструкції вагона-платформи забезпечується.

Проведений модальний аналіз несучої конструкції вагона-платформи. При цьому значення власних частот коливань знаходяться в межах допустимих.

Проведені дослідження сприятимуть створення інноваційних конструкцій вагонів-платформ

Ключові слова: вагон-платформа, несуча конструкція, динамічна навантаженість, модальний аналіз, комбіновані перевезення

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DETERMINING THE FEATURES OF LOADING THE IMPROVED BEARING STRUCTURE OF A PLATFORM WAGON FOR THE TRANSPORTATION OF MILITARY EQUIPMENT

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1. Introduction

Railroad transportation is a strategic component of the transport industry, which enables not only the process of transportation but can also help improve the civil defense of the country. It is known that during World War II railroad transport played an important role in carrying out military strategic operations.

The most common type of railroad car used to transport military equipment is the platform wagons. For the most part, universal platform wagons are employed, equipped with the means to fix military equipment when transporting by rail.

To ensure the country's civil defense at the present stage of development, it is important to introduce innovative rolling stock into operation. The design of such rolling stock

should provide an opportunity not only for the transportation of military equipment but also to ensure the possibility of firing from a car if such necessity arises.

It is important when designing such rolling stock to account for the dynamic loading of bearing structures when moving over a rail track and when firing. Normative documents underlying the design of rolling stock does not cover such issues. Therefore, a comprehensive approach to constructing specialized rolling stock would help improve the efficiency of its functioning and strengthen the country's civil defense.

2. Literature review and problem statement

Measures for upgrading the rolling stock to improve the efficiency of its utilization were considered in [1]. The

authors carried out an analysis of structures in the specialized and universal rolling stock. They considered the issue of modernization of universal wagons. The strength of the bearing structure of a platform was determined on the basis of a set of estimation and experimental studies. However, they did not consider the issue of upgrading wagons for the possibility of transporting military equipment.

Strength indicators of the long-base structure of a platform wagon were determined in [2]. The calculation was made for two variants of loading at which the largest bending momenta were obtained. The maximum equivalent stresses in the main bearing elements of a frame were determined according to the method of finite elements. The authors did not determine the strength indicators of the long-base bearing structure of a platform wagon in the transportation of military equipment and when firing from a car.

The issues on the possibility of applying methods of theoretical and experimental studies into the strength of the main bearing elements of structures of long-base platform wagons were considered in [3]. The authors report the results of calculating the bearing structural elements for fatigue using a computing complex, which implements a finite-element method based on the IBM-PC standard. The authors did not set the task of studying the possibility of transporting military equipment on a platform wagon.

The features of designing a railroad car for intermodal transportation, equipped with an adapted loading platform, were examined in [4]. The adopted structural solutions were substantiated by the static and dynamic studies in the ANSYS and ADAMS/Rail software packages. However, the cited paper does not highlight the issue of transporting military equipment by the developed structure of the platform wagon.

An analysis of the design of an innovative wagon for intermodal transportations was carried out in [5]. The wagon is intended for transporting trucks by railroad. Vehicles can be loaded by a special rotating platform using a truck tractor. However, the cited work does not specify whether it is possible to transport military equipment on a platform wagon and firing from it.

Paper [6] examined the rolling stock dynamics using a pilot laboratory wagon while moving over irregular track sections. The authors proposed measures for the safe operation of rolling stock. They studied the influence of track irregularities on the rolling stock dynamics indicators. However, the impact of military equipment carried by a platform wagon on the dynamic loading of the bearing structure was not considered in the cited paper.

The structural features of a wagon for the transportation of heavy cargoes were examined in [7]. The authors reported the results of calculating the strength of the wagons' bearing structure. The technical solutions proposed in the design of a given wagon were substantiated. At the same time, the cited article did not consider the dynamics of the bearing structure of a wagon during the transportation of military equipment.

Study [8] describes the features of running the strength and dynamic tests involving a platform wagon of model 13-9975. It was taken into consideration that a platform wagon is load-

ed with 20- and 40-foot containers. The main indicators of the platform wagon dynamics were defined. During the research, the authors did not set the task of determining the dynamic indicators of a platform wagon when transporting military equipment.

It is important to note that the process of transporting military equipment and firing from a car when it is moving is accompanied by the action of additional dynamic loads on the bearing structure. Normative documents underlying the railroad car design do not cover the issues of the dynamic loading of the bearing structures of wagons when firing from them. That is why, when designing platform wagons, these loads are not taken into consideration. The use of standard platform wagons when firing may cause damage to their bearing structures as they are not designed to perceive such loads. This limits the application of rail transport in military-strategic activities.

Our analysis of the scientific literature [1–8] makes it possible to conclude that the issues related to loading the bearing structures of wagons when transporting military equipment and when firing from them during motion have not been addressed up to now. Therefore, it is an important task to undertake relevant studies in this field aimed at improving the efficiency of using wagons for military strategic activities.

3. The aim and objectives of the study

The aim of this study is to define special features related to loading the bearing structure of a platform wagon for the transportation of military equipment, as well as to the possibility of firing from it.

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

- to build a bearing structure of a platform wagon for transporting military equipment and for firing from it during motion;

- to explore the dynamics of the platform wagon when firing from it;

- to define the basic strength indicators for the bearing structure of a platform wagon when firing from it.

4. Building the bearing structure of a platform wagon for the transportation of military equipment and firing from it during motion

To ensure the strength of a platform wagon when firing from it, we suggest the improvement to the bearing structure. In our case, the prototype chosen is a platform wagon of model 13-401 made at the Dneprodzerzhinsk wagon plant (Ukraine) (Fig. 1).

It is proposed to mount rotary sectors made from a composite material, with viscous or elastic-viscous links, on the bearing structure of the platform wagon, which makes it possible to absorb the kinetic energy transmitted to the frame when firing from the wagon (Fig. 2).

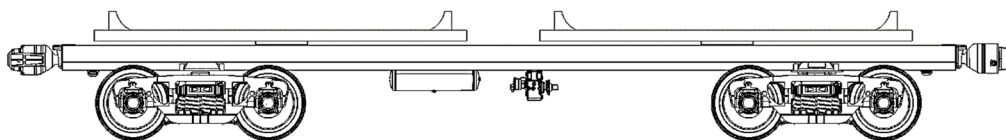


Fig. 1. A platform wagon for transporting military equipment and for firing from it

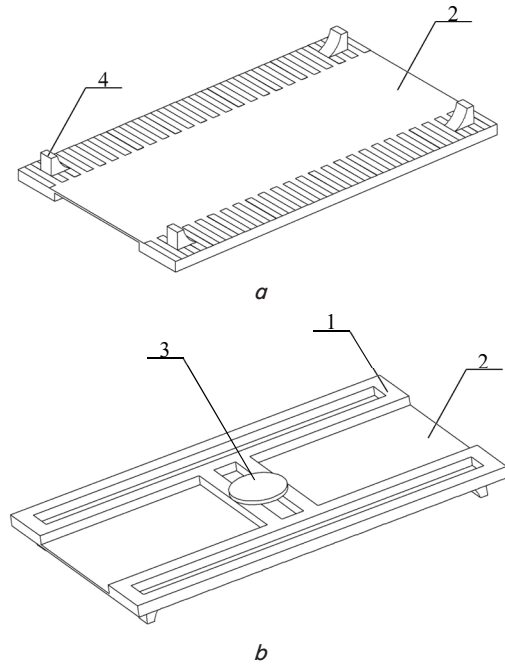


Fig. 2. A rotary sector of the platform wagon: *a* – side view; *b* – view from the bottom; 1 – frame; 2 – metal flooring; 3 – rotary element; 4 – removable wheeled stops

In addition, the presence of rotary sectors makes it possible to load/unload military equipment from the wagon's side, similar to the ACTS system.

5. Studying the dynamics of a platform wagon when firing from it

To determine the dynamic loading of the bearing structure of a platform wagon considering the proposed technical solutions, we performed mathematical modeling.

To this end, a mathematical model given in [9] was used. A given model was refined by taking into consideration an additional degree of freedom – the twitch oscillations.

It was taken into consideration that the platform wagon is loaded with two anti-aircraft guns, each with a muzzle energy of 89 kJ. It is assumed that the anti-aircraft guns do not move at firing.

The estimated scheme of the platform wagon, loaded with two anti-aircraft guns, is shown in Fig. 3.

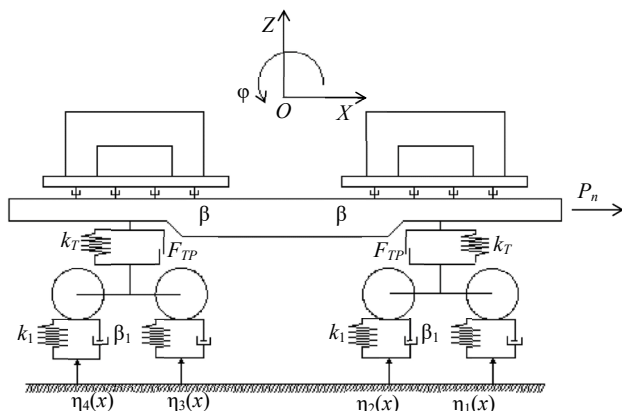


Fig. 3. Estimated scheme of the platform wagon loaded with two anti-aircraft guns

The study was conducted in a flat coordinate system. It was taken into consideration that a shot is fired when a wagon runs over a butt irregularity. This is accompanied by the longitudinal loading of the auto-coupling device (jerk-stretching). The shots are simultaneously fired from two anti-aircraft guns.

The estimated model's motion equation takes the following form:

$$M_1 \cdot \frac{d^2}{dt^2} q_1 + M' \cdot \frac{d}{dt} q_3 = P_l + P'_h, \tag{1}$$

$$M_1 \cdot \frac{d^2}{dt^2} q_2 + C_{2,2} \cdot q_2 + C_{2,5} \cdot q_5 + C_{2,8} \cdot q_8 = P_z - \beta \cdot \dot{q}_2, \tag{2}$$

$$M_2 \cdot \frac{d^2}{dt^2} q_3 + C_{3,3} \cdot q_3 + C_{3,5} \cdot q_5 + C_{3,8} \cdot q_8 = P_\phi - \beta \cdot \dot{q}_3, \tag{3}$$

$$M_3 \cdot \frac{d^2}{dt^2} q_4 = 0, \tag{4}$$

$$M_3 \cdot \frac{d^2}{dt^2} q_5 + C_{5,2} \cdot q_2 + C_{5,3} \cdot q_3 + C_{5,5} \cdot q_5 + B_{5,5} \cdot \frac{d}{dt} q_5 = P_z^{T_1}, \tag{5}$$

$$M_4 \cdot \frac{d^2}{dt^2} q_6 + C_{6,6} \cdot q_6 + B_{6,6} \cdot \frac{d}{dt} q_6 = P_\phi^{T_1}, \tag{6}$$

$$M_5 \cdot \frac{d^2}{dt^2} q_7 = 0, \tag{7}$$

$$M_5 \cdot \frac{d^2}{dt^2} q_8 + C_{8,2} \cdot q_2 + C_{8,3} \cdot q_3 + C_{8,8} \cdot q_8 + B_{8,8} \cdot \frac{d}{dt} q_8 = P_z^{T_2}, \tag{8}$$

$$M_6 \cdot \frac{d^2}{dt^2} q_9 + C_{9,9} \cdot q_9 + B_{9,9} \cdot \frac{d}{dt} q_9 = P_\phi^{T_2}, \tag{9}$$

$$P_z = -F_{FR} \cdot \left(\text{sign} \left(\frac{d}{dt} \delta_1 \right) + \text{sign} \left(\frac{d}{dt} \delta_2 \right) \right) + P'_v, \tag{10}$$

$$P_\phi = F_{FR} \cdot l \cdot \left(\text{sign} \left(\frac{d}{dt} \delta_1 \right) + \text{sign} \left(\frac{d}{dt} \delta_2 \right) \right) + M'_f, \tag{11}$$

$$P_z^{T_1} = F_{FR} \cdot \text{sign} \left(\frac{d}{dt} \delta_1 \right) + k_1 (\eta_1 + \eta_2) + \beta_1 \left(\frac{d}{dt} \eta_1 + \frac{d}{dt} \eta_2 \right), \tag{12}$$

$$P_\phi^{T_1} = -k_1 (\eta_1 - \eta_2) - \beta_1 \cdot a \cdot \left(\frac{d}{dt} \eta_1 - \frac{d}{dt} \eta_2 \right), \tag{13}$$

$$P_z^{T_2} = F_{FR} \cdot \text{sign} \left(\frac{d}{dt} \delta_2 \right) + k_1 (\eta_3 + \eta_4) + \beta_1 \left(\frac{d}{dt} \eta_3 + \frac{d}{dt} \eta_4 \right), \tag{14}$$

$$P_\phi^{T_2} = -k_1 \cdot a \cdot (\eta_3 - \eta_4) - \beta_1 \cdot a \cdot \left(\frac{d}{dt} \eta_3 - \frac{d}{dt} \eta_4 \right), \tag{15}$$

where M_i are the inertial coefficients of the elements in an oscillatory system; C_i is the characteristic of elasticity of the elements in an oscillatory system; B_i is the scatter function; a is the half of a trolley base; q_i are the generalized coordinates corresponding to the translational movement relative to the longitudinal and vertical axes and the angular movements around the vertical axis; k_i is the rigidity of a spring suspen-

sion; β_i is the damping coefficient; F_{FR} is the force of absolute friction in a spring set; P_l is the longitudinal load acting on an auto-coupling device's stops; P'_h , P'_v are, accordingly, the loading transmitted to the bearing structure when firing in the horizontal and vertical planes; M'_f is the moment that acts on the bearing structure of a platform wagon when firing; β is the coefficient of viscous resistance between a rotary sector and the bearing structure of a platform wagon.

The input parameters of the model are the technical characteristics of the bearing structure of the platform wagon, the spring suspension of trolleys (the trolley of model 18-100), perturbing action, as well as the technical characteristics of anti-aircraft guns.

To solve differential equations (1) to (9), we reduced them to the normal Cauchy form. Next, they were integrated using the Runge-Kutta method [10, 11].

The standard function $rkfixed(Y0, tn, tk, n', Q)$ was used. The $Y0$ vector includes initial conditions (16). The quantities tn and tk determine the starting and final integration variable, n' is the fixed number of steps, Q is the symbol vector.

$$Y0 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (16)$$

In other words, the initial displacement and speed were taken equal to zero [12–14].

Results from solving the differential equations allowed us to derive the accelerations, which act on a platform wagon when firing from anti-aircraft guns at different shooting angles.

The maximum value of acceleration, in this case, is about 3.6 m/s^2 at bouncing oscillations (Fig. 4) and 4.0 m/s^2 at galloping oscillations (Fig. 5). The rate of acceleration is almost independent of the shooting angle.

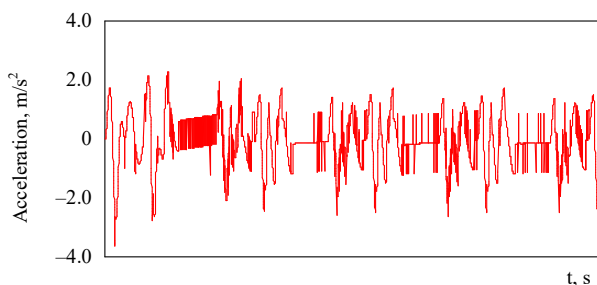


Fig. 4. Accelerations acting in the center of mass of the bearing structure of a platform wagon (the gun is directed at an angle of 30° to the longitudinal axis of the wagon) at bouncing oscillations

It was taken into consideration that the coefficient of viscous resistance between a rotary sector and the bearing structure of a platform wagon is $150 \text{ kN}\cdot\text{s/m}$.

Thus, given the installation of a viscous link between a rotary sector and the bearing structure of a platform wagon,

it becomes possible to reduce the dynamic load when shooting from anti-aircraft guns in a vertical plane by almost 30 % compared to the standard design.

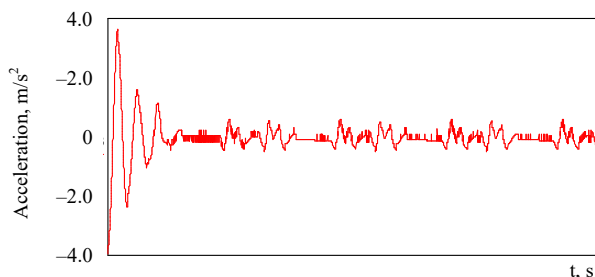


Fig. 5. Accelerations acting in the center of mass of the bearing structure of a platform wagon (the gun is directed at an angle of 30° to the longitudinal axis of the wagon) at galloping oscillations

6. Determining the main strength indicators for the bearing structure of a platform wagon when firing from it

To study the strength of the improved bearing structure of the platform wagon, we performed calculations. The spatial model of the bearing structure of a platform wagon was built in the SolidWorks programming environment (Fig. 6).

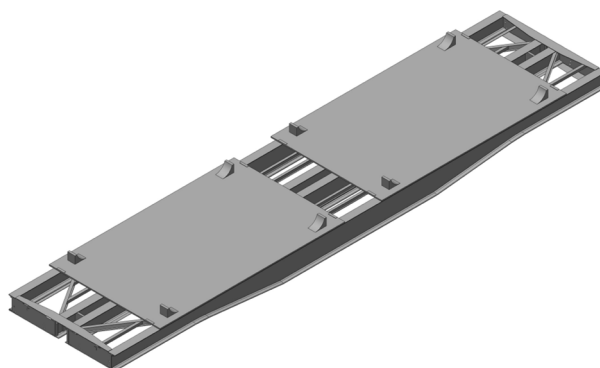


Fig. 6. A spatial model of the bearing structure of a platform wagon

The calculation for durability was implemented in the CosmosWorks programming environment [15–18] according to the method of finite elements. The finite element model of the bearing structure of a platform wagon is shown in Fig. 7.

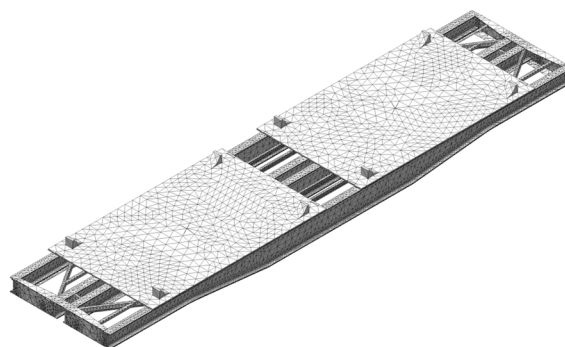


Fig. 7. A finite-element model of the bearing structure of a platform wagon

The spatial tetrahedra were used as finite elements. To determine the optimal number of the elements, we applied a graphic-analytical method.

The number of the model nodes was 122,715, elements – 381,831. The maximum element size was 200 mm, minimum – 40 mm. The percentage of elements with a side-ratio of less than three – 12.5, exceeding ten – 30.4. The minimum number of elements in the circle was 10, the ratio of an increase in the size of elements – 1.9. The material of the bearing structure of the platform wagon was the steel of grade 09G2S with the value of tensile strength $\sigma_s = 490$ MPa and a yield limit of $\sigma_y = 345$ MPa [19, 20].

The estimated scheme of the bearing structure of a platform wagon is shown in Fig. 8.

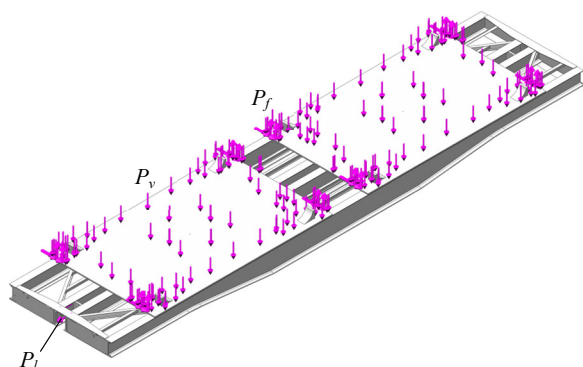


Fig. 8. Estimated scheme of the bearing structure of a platform wagon

When building the estimated scheme, it was taken into consideration that the front stops of the auto-coupling device are exposed to longitudinal load P_t , which is equal to 2.5 MN [19, 20]. The bearing structure of the platform wagon is exposed to vertical load P_v exerted by the gross weight of anti-aircraft guns, as well as the loads that occur in the regions P_f where the guns are fixed. As a result of the angular arrangement of fastening tools, the load P_f was decomposed into components. The model was fixed in the regions of resting on the chassis.

A viscous link was enabled between the supporting sectors and the bearing structure of the platform wagon.

Calculation results are shown in Fig. 9, 10.

Our calculations make it possible to conclude that the maximum equivalent stresses in the bearing structure of the platform wagon are about 285 MPa and occur in the region where a bearing structure rests on trolleys. The maximum equivalent stresses amounted to 165 MPa in the main beams (the upper shelf of the I-beam). On the lower shelf of the I-beam of the main longitudinal beam of the frame, the stresses are 130 MPa. In the middle of the girde beam, stresses are 205 MPa, and in the regions of resting on the trolley – about 260 MPa.

To determine the natural oscillation frequencies of the bearing structure of a platform wagon, we ran a modal analysis in the CosmosWorks programming environment. Calculation results are given in Table 1.

Certain oscillation shapes of the bearing structure of a platform wagon are shown in Fig. 11.

Our calculations indicate that the values of the natural oscillation frequencies are within admissible ones [19–21], that is, not less than 8 Hz.

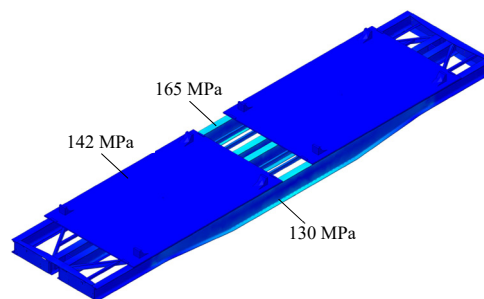


Fig. 9. The stressed state of the bearing structure of a platform wagon (side view)

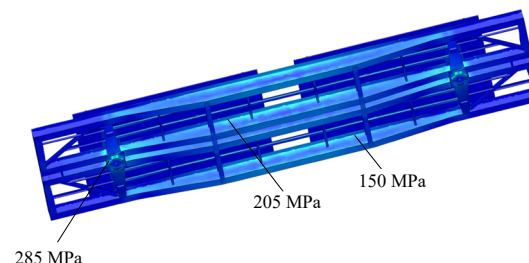


Fig. 10. The stressed state of the bearing structure of a platform wagon (view from below)

Table 1

Natural oscillation frequencies of the bearing structure of a platform wagon

Oscillation shape	Frequency, Hz	Period, s
1	19.52	0.051
2	23.95	0.041
3	25.8	0.038
4	30.27	0.034
5	30.63	0.033
6	31.1	0.032
7	31.18	0.031
8	31.44	0.030
9	37.3	0.027
10	39.36	0.025

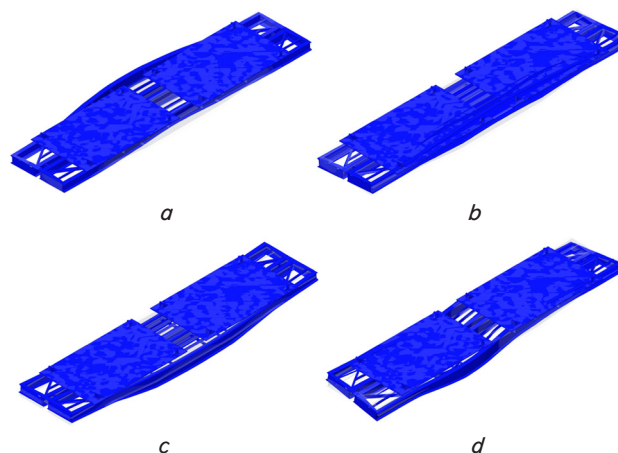


Fig. 11. Oscillation shapes of the bearing structure of a platform wagon: *a* – first natural frequency (deformation scale – 25:1); *b* – second natural frequency (deformation scale – 15:1); *c* – third natural frequency (deformation scale – 15:1); *d* – ninth natural frequency (deformation scale – 15:1)

7. Discussion of results of determining the features in loading the improved bearing structure of a platform wagon for the transportation of military equipment

A special feature of the platform wagon proposed in this paper is the existence of rotary sectors to enable the loading/unloading of military equipment from its side. The rotary sectors are made from a composite material with viscous or elastic-viscous links, which makes it possible to absorb the kinetic energy transmitted to the frame when firing from the wagon (Fig. 1).

We have mathematically modeled the dynamic loading of the bearing structure of the platform wagon when firing from it. It is assumed that two anti-aircraft guns fire simultaneously.

It has been established that the presence of a viscous link between the rotary sectors and a platform wagon reduces the dynamic loading of the bearing structure by almost 30 % in the vertical plane compared to a rigid link (Fig. 4, 5).

The proposed technical solutions could reduce the dynamic loading of the platform cars when firing from them. In addition, research results would contribute to the construction of innovative designs of platform wagons.

To ensure the strength of the bearing structure of a platform wagon when firing from it, we performed the calculation of durability. It has been determined that the maximum equivalent stresses in the frame's bearing elements do not exceed those permissible for steel 09G2S (Fig. 9, 10).

The issue that this study has not addressed is that the current stage does not consider the possibility of firing from military equipment that has greater muzzle energy than anti-aircraft guns. In addition, it does not account for the influence of the stochasticity of shots from anti-aircraft guns on the dynamic loading of the bearing structure of a wagon.

It is important to note that in the course of further studies it is necessary to account for the randomness of the oscillatory process caused by the track irregularity. It is also important to investigate the influence of transitional processes of a platform wagon's motion on dynamic loading.

8. Conclusions

1. We have designed the bearing structure of a platform wagon for transporting military equipment and for firing from it during motion. A special feature of the bearing structure of a platform wagon is the existence of rotary

sectors made from a composite material with viscous or elastic-viscous links, which makes it possible to absorb the kinetic energy transmitted to the frame when firing from the wagon, as well as enables the loading/unloading of military equipment from its side.

2. The dynamics of a platform wagon when firing from it have been investigated. It was taken into consideration that the platform wagon is loaded with two anti-aircraft guns, each with a muzzle energy of 89 kJ.

The study was conducted in a flat coordinate system. It was taken into consideration that a shot is fired when a wagon runs over a butt irregularity. That implies the longitudinal loading of the auto-coupling device. It is assumed that the coefficient of viscous resistance between the rotary sector and the bearing structure of the platform wagon is 150 kN·s/m.

The accelerations that act in the center of mass of the bearing structure of a platform wagon at bouncing oscillations amounted to 3.6 m/s², at galloping oscillations – 4.0 m/s².

Thus, given the installation of a viscous link between a rotary sector and the bearing structure of a platform wagon, it becomes possible to reduce the dynamic loading when shooting from anti-aircraft guns in a vertical plane by almost 30 % compared to the standard design.

3. The basic indicators of strength for the bearing structure of a platform wagon when firing from it have been defined. The maximum equivalent stresses in the bearing structure of the platform wagon are about 285 MPa; they occur in the region where the bearing structure rests on the trolley. In other words, the strength of the bearing structure of the platform wagon is ensured.

The natural oscillation frequencies of the bearing structure of a platform wagon have been determined. It has been established that the values of the natural oscillation frequencies are within allowable limits.

Our study could contribute to constructing innovative structures of platform wagons.

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