UDC 629.463.5
DOI: 10.15587/1729-4061.2020.208407

DETERMINING THE DYNAMIC LOADING AND STRENGTH OF THE BEARING STRUCTURE OF A COVERED WAGON WHEN FIRING FROM IT

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The bearing structure of a covered rail wagon has been improved to enable firing from it at motion. The covered wagon of model 11–217 was chosen as a prototype. To enable firing in the vertical plane, it has been proposed to use a sliding roof, which consists of shutters that move by means of a pneumatic or hydraulic drive. To accommodate military equipment inside the covered wagon, its frame is equipped with supporting sectors.

Mathematical modeling was performed in order to determine the dynamic load on a covered rail wagon when firing from it. The mathematical model was solved in the Mathcad software package. We have established the dependence of the accelerations of the bearing structure of a covered rail wagon on the recoil force induced by the combat equipment that it hosts. It has been found that in order to maintain the dynamics indicators within acceptable limits, combat equipment should have a maximum recoil at a shot of about 3.2 kN. The maximum accelerations that act on the bearing structure of a covered wagon in a vertical plane are about 6 m/s^2. In the zones of interaction between the body and bogies, the maximum accelerations are about 9.5 m/s^2 and the accelerations of bogies are 10 m/s^2. To reduce the dynamic load on the bearing structure of a covered rail wagon, it has been proposed to use a viscous connection between the supporting sectors and frame. We have determined the dependence of accelerations on the coefficient of viscous resistance between the supporting sectors and the bearing structure of a wagon. It has been established that taking into consideration the use of a viscous connection between the supporting sectors and frame makes it possible to reduce the dynamic load on a wagon at least by 15 %. The basic indicators of strength for the bearing structure of a covered rail wagon when firing from it have been determined. We have derived the dependence of the maximum equivalent stresses in the bearing structure of a covered wagon on the recoil force of combat equipment. The maximum equivalent stresses at a recoil force of 3.2 kN arise in the console part of the girder of a covered wagon and are about 300 MPa. The maximum displacements were registered in the area where the front stops of the auto-coupling are arranged; they are equal to 2.9 mm. The maximum deformations amounted to $6.98\cdot10^{-3}$.

Modal analysis of the bearing structures of a covered rail wagon has been carried out. It has been determined that the values of the oscillation natural frequencies are within the permissible limits.

Our study will contribute to the construction of innovative rolling stock for the transportation of military equipment and for firing at motion

Keywords: covered wagon, bearing structure, dynamic load, structural strength, modal analysis, transport mechanics

Received date 10.06.2020
Accepted date 14.07.2020
Published date 27.08.2020

1. Introduction

Increasing the efficiency of use and competitiveness of railroad transportation predetermines its involvement in military-strategic objectives. This necessitates the improvement of the load-bearing structures of wagons to ensure not only the transportation of military equipment but also firing from them at motion.

It is important to note that the railroad industry engagement in military-strategic issues is not a novelty. In the middle of the XIX century, a 32-pound cannon was used between North and South America, which fired from a railroad platform wagon. There are known historical facts about the world wars when railroad transport repeatedly contributed to the successful implementation of military activities.

Today, one of the most used types of carriages for transporting military equipment is the platform wagons. A feature of these cars is that the bearing structure is represented by a frame. For the most part, these wagons are used to transport cargoes that do not require protection from the atmospheric precipitation. To transport military equipment that requires protection from the atmospheric precipitation, it is possible to use covered rail wagons.

In order to improve the efficiency of railroad transport in military-strategic aims, the construction of rolling stock for firing at motion is important. It is necessary to determine patterns in the dynamic loading and strength of the load-bearing structures of rolling stock depending on the disturbance action, which is transmitted to it while firing. That would help devise recommendations and requirements for the design of the specialized rolling stock, which could be used for military-strategic purposes. In addition, our study will contribute to forming the requirements for the modernization of the existing railroad fleet to transport military equipment and to fire at motion.

2. Literature review and problem statement

The prospects for the use of new generation materials during the production of railroad cars were previously outlined in [1]. The advantages of using magnesium alloys in the carrying systems of wagons were indicated.

The analysis and selection of materials for designing low-weight rail vehicles were reported in [2]. The authors devised a methodology that was proposed for the evaluation and selection of vehicle construction materials. This methodology consists of two stages, taking into consideration various categories of key criteria.

However, the authors of the cited works did not specify the peculiarities of the dynamic loading on the wagons made from such materials, including the structures of specialized wagons for transporting military equipment.

The features of a specialized wagon with a low turning loading platform are covered in work [3]. The wagon is intended for the transportation of trucks by railroad. In addition, the wagon can be used for the transportation of military equipment. Paper [4] calculated the dynamics indicators of a given wagon. At the same time, the authors studied the wagon's stability against derailing at its movement along the curve of a radius of 250 meters, taking into consideration the varying speed of movement.

It is important to note that the design of a given wagon can also be used for the transportation of military equipment. However, it is not adapted to firing at motion because the design of this wagon does not take into consideration the accelerations that could act on it while firing. That would contribute to disrupting the wagon movement stability, as well as damaging the bearing structure.

The static and modal numerical analysis of the structure of a covered rail wagon is reported in [5]. The strength was calculated using a method of finite elements. The authors determined the natural oscillation frequencies of the elements of the bearing structure of a wagon. However, in the design of the wagon, they took into consideration the basic normative values of loads that could act on it in operation. That is, when using a given design of the wagon for firing from it at motion, there may occur, as a result of impact loads caused by shots from combat equipment, the damage to the bearing structure of the wagon.

A covered rail wagon's design was improved in [6]. The authors considered the structural features of the main models of covered wagons by different manufacturers from the CIS countries. They suggested measures to improve the efficiency of the use of covered wagons in operation. Such a modernization did not take into consideration the patterns of the force influence on the bearing structure of the wagon when firing from it. This restricts the possibility of using the wagon under the assigned operating modes. In particular, the transportation of military equipment and firing at motion.

The structural-optimization concept of the wagon body made from aluminum panels of the "sandwich" type is given in [7]. The characteristic function in the search for the optimal combination was determined through maximum stresses and displacements.

However, the cited paper does not specify how the longitudinal dynamic load on the wagon is reduced taking into consideration the use of the proposed panels.

A study into the structural features of BCNHL freight wagons is reported in [8]. The authors defined possible ways to improve the technical and economic performance indicators of wagons in order to improve the efficiency of their operation.

However, they did not focus on measures related to using the wagon for military-strategic purposes.

An analysis of references [1–8] allows us to conclude that up to now the issue of determining the patterns in the dynamic load and durability of the load-bearing structures of covered wagons while firing from them has not been paid proper attention to. This may cause damage to the typical load-bearing structures of wagons when they are used for military strategic purposes. Therefore, it is necessary to establish patterns in the dynamic loading and durability of the bearing structure of a wagon when firing from it at motion. The results to be obtained would contribute to the construction of specialized wagon fleet, which could be used for the country's military-strategic purposes.

3. The aim and objectives of the study

The aim of this study is to determine patterns in the dynamic loading and durability of the bearing structure of a covered rail wagon for the transportation of military equipment and firing from it while moving.

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

– to determine the dynamic load on the bearing structure of a covered rail wagon when firing from it;

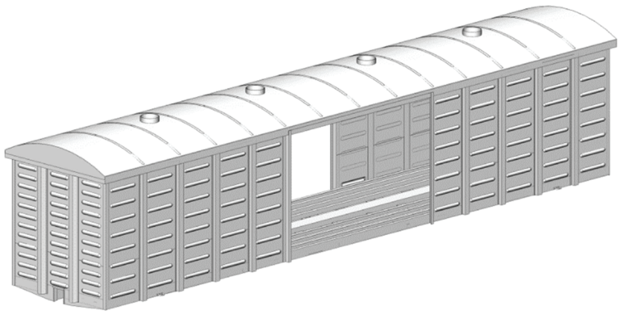
– to define the basic strength indicators of the bearing structure of a covered rail wagon when firing from it;

– to conduct a modal analysis of the bearing structure of a covered rail wagon when firing from it.

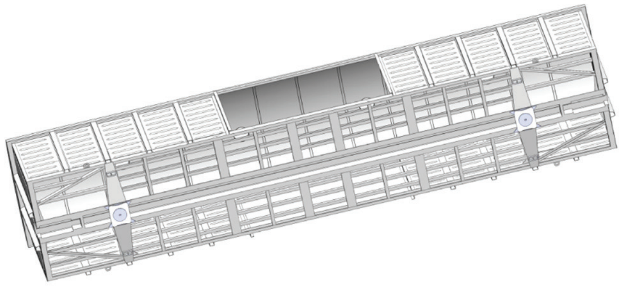
4. The study materials and methods

To enable firing from covered cars at motion, it has been proposed to improve their bearing structures. A covered rail wagon of model 11-217 (JSC "Altaiwagon", Russia) was selected as the prototype. This wagon model was chosen to be studied because it is the most common one on the CIS railroads. In addition, the covered cars produced by Ukrainian wagon building enterprises have a similar structure. Based on the album of drawings for the wagon, we built its spatial model in the SolidWorks programming environment (Fig. 1). When constructing the model, attention was paid to those design elements that rigidly interact through welding or riveting. The movable sealed doors were not taken into consideration as they are connected via hinges to the carrying structure.

To enable firing in the vertical plane, it is proposed to use a sliding roof, which consists of shutters that move by means of a pneumatic or hydraulic drive (Fig. 2).

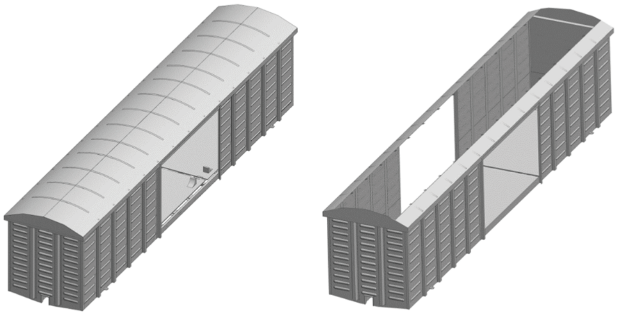


a



b

Fig. 1. The bearing structure of a covered rail wagon: *a* – side view; *b* – view from below



a *b*

Fig. 2. The improved bearing structure of a covered rail wagon with a sliding roof: *a* –the roof in the closed position; *b* – the roof in the open position

To arrange military equipment inside a covered wagon, its frame is equipped with supporting sectors (Fig. 3).

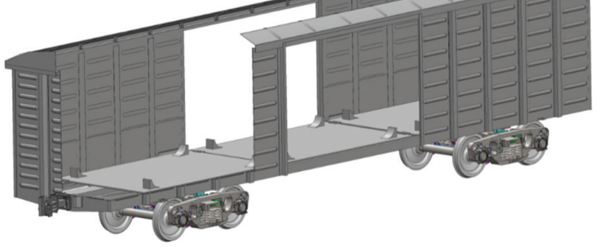


Fig. 3. Arrangement of supporting sectors for military equipment in a covered wagon

It is also possible to use, at the supporting sectors, removable stops for attaching wheeled military equipment.

To study patterns in the dynamic loading and durability of the bearing structure of a covered rail wagon depending on the disturbance action, which is transmitted to it when firing, we used classical methods of mathematical modeling. When building the differential equations of the displacements of the bearing structure of a covered rail wagon, a Lagrange method of the second kind was applied, as one of the most common ones in transport mechanics. While studying the dynamic load on a wagon, we accounted for the parameters of the spring suspension of bogies since a shot is accompanied by the recoil force, which exerts an additional force effect not only on the carrying structure but also on bogies. When solving the equations of motion, the initial movements and speeds were taken to equal zero. The boundary conditions, which are accepted at modeling, are the absence of wear in the bearing structure of a wagon. That is, it is assumed that all components of the wagon have its album's dimensions. The equations of motion were solved in the Mathcad software package [9, 10]. The Runge-Kutta method [11–14] was used as an estimation method.

The accelerations, derived from mathematical modeling, were accounted for as the components of the dynamic load, which acts on the bearing structure at firing, in the calculation of strength. The calculation was carried out in the CosmosWorks programming environment [15, 16], which employs the method of finite elements. When constructing a finite-element model, we used spatial isoparametric tetrahedra. The optimal number of elements was determined by the graph-analytical method [17–20].

The number of the model nodes was 309,127, elements – 863,831. The maximum element size was 80 *mm* and the minimum size was 16 *mm*. The percentage of elements with a side-ratio of less than three is 17.1, exceeding ten – 35.7. The minimum number of elements in the circle was 22, the ratio of increase in size is 1.8. A material of the bearing structure of a platform wagon is the steel of grade 09G2S. The model was fixed in the areas resting on bogies.

Based on the developed estimation scheme for strength determination, a modal analysis was performed, which made it possible to determine the shape and natural oscillation frequencies of the bearing structure of the wagon when firing from it.

At this stage of our study, the possibility of designing a new wagon structure was considered; in the future, however, it is possible to build the modernized structures of specialized wagons for firing from them at motion.

5. Determining the dynamic loading on the bearing structure of a covered rail wagon when firing from it

5. 1. Determining the dynamic loading taking into consideration the rigid interaction between the supporting sectors and frame

Mathematical modeling was performed in order to determine patterns in the dynamic load on a wagon when firing from it. In this case, we applied a mathematical model given in [21] and represented by equations (1) to (12). However, the specified model was built for an empty semi-wagon, which moves over a butt rail irregularity. Therefore, as part of the current study, the model was refined, in particular taking into consideration the disturbing components, which act on the bearing structure at firing from combat equipment. The estimation scheme of the wagon is shown in Fig. 4.

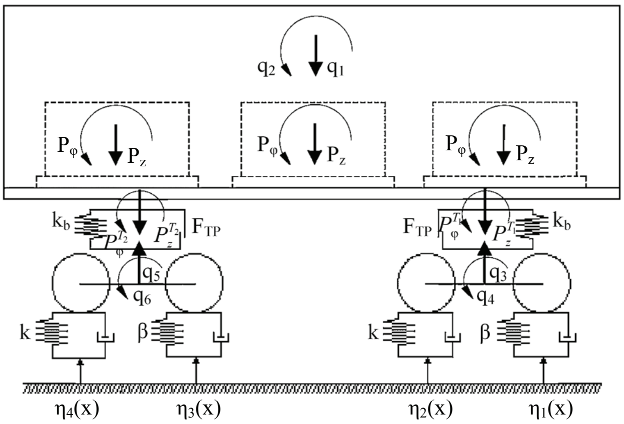


Fig. 4. The estimation scheme of a covered rail wagon

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

$$M_1\cdot\frac{\mathrm{d}^2}{\mathrm{d}t^2}q_1+C_{1,1}\cdot q_1+C_{1,3}\cdot q_3+C_{1,5}\cdot q_5=P_z, \tag{1}$$

$$M_2\cdot\frac{\mathrm{d}^2}{\mathrm{d}t^2}q_2+C_{2,2}\cdot q_2+C_{2,3}\cdot q_3+C_{2,5}\cdot q_5=P_\varphi, \tag{2}$$

$$M_3\cdot\frac{\mathrm{d}^2}{\mathrm{d}t^2}q_3+C_{3,1}\cdot q_1+C_{3,2}\cdot q_2+$$

$$+C_{3,3}\cdot q_3+B_{3,3}\cdot\frac{\mathrm{d}}{\mathrm{d}t}q_3=P_z^{T_1}, \tag{3}$$

$$M_4\cdot\frac{\mathrm{d}^2}{\mathrm{d}t^2}q_4+C_{4,4}\cdot q_4+B_{4,4}\cdot\frac{d}{dt}q_4=P_\varphi^{T_1}, \tag{4}$$

$$M_5\cdot\frac{\mathrm{d}^2}{\mathrm{d}t^2}q_5+C_{5,1}\cdot q_1+C_{5,2}\cdot q_2+$$

$$+C_{5,5}\cdot q_5+B_{5,5}\cdot\frac{\mathrm{d}}{\mathrm{d}t}q_5=P_z^{T_2}, \tag{5}$$

$$M_6\cdot\frac{\mathrm{d}^2}{\mathrm{d}t^2}q_6+C_{6,6}\cdot q_6+B_{6,6}\cdot\frac{\mathrm{d}}{\mathrm{d}t}q_6=P_\varphi^{T_2}, \tag{6}$$

$$P_z=-F_{TP}\cdot\left(\operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t}\delta_1\right)+\operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t}\delta_2\right)\right)+P_v, \tag{7}$$

$$P_\varphi=F_{TP}\cdot l\cdot\left(\operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t}\delta_1\right)+\operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t}\delta_2\right)\right)+M_w, \tag{8}$$

$$P_z^{T_1}=F_{TP}\cdot\operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t}\delta_1\right)+k(\eta_1+\eta_2)+$$

$$+\beta\left(\frac{\mathrm{d}}{\mathrm{d}t}\eta_1+\frac{\mathrm{d}}{\mathrm{d}t}\eta_2\right), \tag{9}$$

$$P_\varphi^{T_1}=-k(\eta_1-\eta_2)-\beta\cdot a\cdot\left(\frac{\mathrm{d}}{\mathrm{d}t}\eta_1-\frac{\mathrm{d}}{\mathrm{d}t}\eta_2\right), \tag{10}$$

$$P_z^{T_2}=F_{TP}\cdot\operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t}\delta_2\right)+k(\eta_3+\eta_4)+\beta\left(\frac{\mathrm{d}}{\mathrm{d}t}\eta_3+\frac{\mathrm{d}}{\mathrm{d}t}\eta_4\right), \tag{11}$$

$$P_\varphi^{T_2}=-k\cdot a\cdot(\eta_3-\eta_4)-\beta\cdot a\cdot\left(\frac{\mathrm{d}}{\mathrm{d}t}\eta_3-\frac{\mathrm{d}}{\mathrm{d}t}\eta_4\right), \tag{12}$$

where M_1, M_2 is, respectively, the mass and moment of inertia of the bearing structure of a wagon; M_3, M_4 is, respectively, the mass and moment of inertia of the first bogie in the wagon's motion direction; M_5, M_6 is, respectively, the mass and moment of inertia of the second bogie in the wagon's motion direction; C_{ii} is the elasticity characteristic of the elements of an oscillatory system; B_{ii} is the dispersion function; a is the half of a bogie base; k_b is the rigidity of spring suspension; k is the track rigidity; β is the damping coefficient; $\eta_i(x)$ is the function that describes the track irregularity; δ_i are the deformations of the elastic elements of a spring suspension; F_{TP} is the force of absolute friction in a spring kit; P_v is the load, which is transmitted to the bearing structure at firing in the vertical plane; M_w is the momentum, which acts on the bearing structure of a wagon at firing.

The input parameters of the mathematical model are the technical characteristics of a wagon, a rail track, as well as the military equipment from which firing is performed. In our calculations, the following input parameters were accepted: the mass and moment of inertia of the bearing structure of the wagon are, respectively, 18.5 t, 348 t m^2; the mass and moment of inertia of a bogie are, respectively, 4.3 tons, 3.0 t m^2; the half of bogie base is 0.93 m; the spring suspension rigidity is 8,000 kN/m; the rigidity of the track is 100·10^2 kN/m; the damping coefficient is 200 kN·c/m; the absolute friction force in a spring set is 7.0 kN.

It is known that, in addition to the energy and momentum, the recoil can also be characterized by power as well as strength. In the current study, attention is paid to the recoil force since, as is known, during translational movements every term in the system of a differential equation must have the dimensionality of force. Since firing is performed in the vertical plane, the translational movements are meant. At angular movements, attention is paid to the momentum, caused by the effect of a recoil force.

The recoil force, which is transmitted to the bearing structure at firing, varied in the range of 0.5–5 kN. The momentum that acts on the bearing structure of a wagon at firing was defined taking into consideration the specified range of variation in the recoil force.

The calculation is carried out for the case of firing from conditional combat equipment to determine the permissible recoil force at which the covered rail wagon's dynamics indicators [22, 23] are maintained.

Based on the calculations, we established the dependence of the vertical accelerations of the bearing structure of a covered rail wagon on recoil force (Fig. 5).

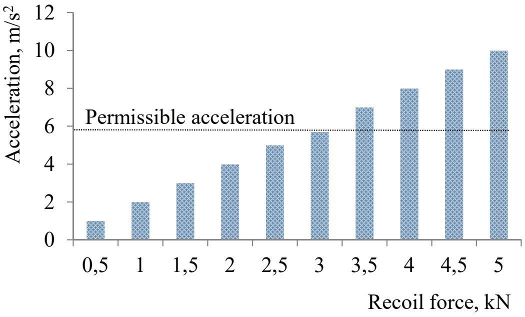


Fig. 5. The dependence of the vertical accelerations of the bearing structure of a covered rail wagon on recoil force

Fig. 6 shows that in order to maintain the vertical accelerations within the acceptable limits [22, 23], the combat equipment must have a maximum recoil force of about 3.2 kN.

The results of calculating the accelerations that act on the components of a wagon at firing at a recoil force of 3.2 kN are shown in Fig. 6–8.

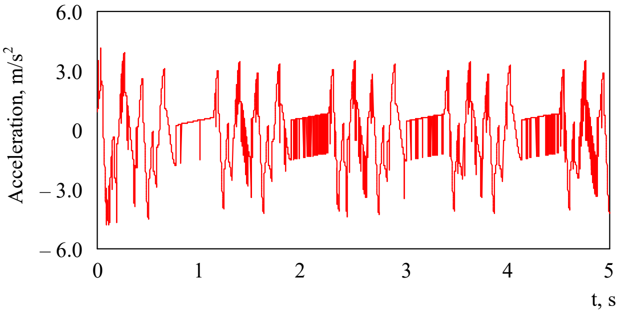


Fig. 6. Accelerations that act in the wagon's center of mass

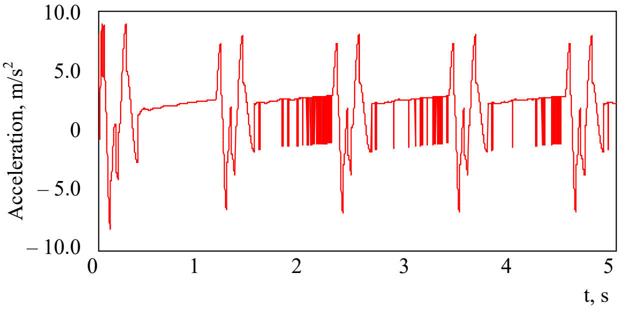


Fig. 7. Body accelerations at the points of resting on bogies

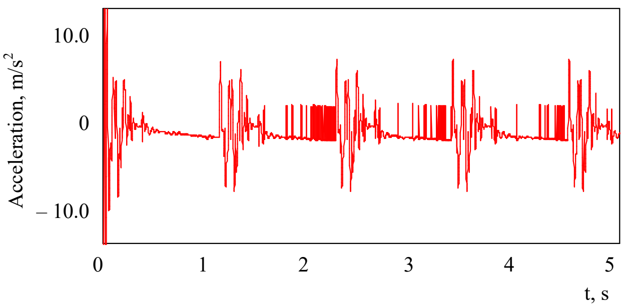


Fig. 8. Bogie accelerations

The maximum accelerations that act on the bearing structure of a covered rail wagon in the vertical plane are about 6 m/s^2 (Fig. 7). At the points where the body rests on bogies, the maximum accelerations are about 9.5 m/s^2 (Fig. 8), and the accelerations of the bogies are 10 m/s^2 (Fig. 9).

5. 2. Determining the dynamic loading taking into consideration the viscous interaction between the supporting sectors and frame

In order to use combat equipment with increased capacity, it is possible to install, between the supporting sectors for military equipment and a wagon's frame, a viscous connection. This solution is proposed at the level of the concept of the bearing structure of a covered rail wagon. It is possible to implement it through the use of damper components between the supporting sectors and the frame of a wagon.

Mathematical modeling was carried out to substantiate the proposed technical solution. The estimation scheme is shown in Fig. 9.

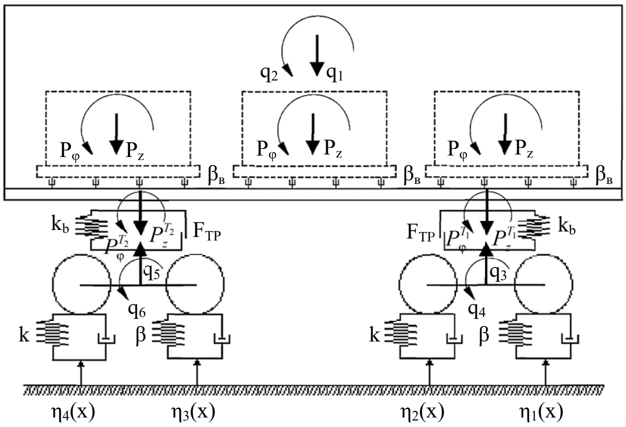


Fig. 9. The estimation scheme of a covered rail wagon

The above mathematical model is reduced to the form:

$$M_1 \cdot \frac{\mathrm{d}^2}{\mathrm{d}t^2} q_1 + C_{1,1} \cdot q_1 + C_{1,3} \cdot q_3 + C_{1,5} \cdot q_5 = P_z - \beta_b \frac{\mathrm{d}}{\mathrm{d}t} q_1, \tag{13}$$

$$M_2 \cdot \frac{\mathrm{d}^2}{\mathrm{d}t^2} q_2 + C_{2,2} \cdot q_2 + C_{2,3} \cdot q_3 + C_{2,5} \cdot q_5 =$$

$$= P_\varphi - \beta_{\text{в}} \cdot h \cdot \frac{\mathrm{d}}{\mathrm{d}t} q_2, \tag{14}$$

$$M_3 \cdot \frac{\mathrm{d}^2}{\mathrm{d}t^2} q_3 + C_{3,1} \cdot q_1 + C_{3,2} \cdot q_2 +$$

$$+ C_{3,3} \cdot q_3 + B_{3,3} \cdot \frac{\mathrm{d}}{\mathrm{d}t} q_3 = P_z^{T_1}, \tag{15}$$

$$M_4 \cdot \frac{\mathrm{d}^2}{\mathrm{d}t^2} q_4 + C_{4,4} \cdot q_4 + B_{4,4} \cdot \frac{\mathrm{d}}{\mathrm{d}t} q_4 = P_\varphi^{T_1}, \tag{16}$$

$$M_5 \cdot \frac{\mathrm{d}^2}{\mathrm{d}t^2} q_5 + C_{5,1} \cdot q_1 + C_{5,2} \cdot q_2 +$$

$$+ C_{5,5} \cdot q_5 + B_{5,5} \cdot \frac{\mathrm{d}}{\mathrm{d}t} q_5 = P_z^{T_2}, \tag{17}$$

$$M_6 \cdot \frac{\mathrm{d}^2}{\mathrm{d}t^2} q_6 + C_{6,6} \cdot q_6 + B_{6,6} \cdot \frac{\mathrm{d}}{\mathrm{d}t} q_6 = P_\varphi^{T_2}, \tag{18}$$

$$P_z = -F_{TP} \cdot \left(\operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t} \delta_1 \right) + \operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t} \delta_2 \right) \right) + P_v, \tag{19}$$

$$P_\varphi = F_{TP} \cdot l \cdot \left(\operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t} \delta_1 \right) + \operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t} \delta_2 \right) \right) + M_w, \tag{20}$$

$$P_z^{T_1} = F_{TP} \cdot \operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t} \delta_1 \right) + k_1 (\eta_1 + \eta_2) + \beta_1 \left(\frac{\mathrm{d}}{\mathrm{d}t} \eta_1 + \frac{\mathrm{d}}{\mathrm{d}t} \eta_2 \right), \tag{21}$$

$$P_\varphi^{T_1} = -k_1 (\eta_1 - \eta_2) - \beta_1 \cdot a \cdot \left(\frac{\mathrm{d}}{\mathrm{d}t} \eta_1 - \frac{\mathrm{d}}{\mathrm{d}t} \eta_2 \right), \tag{22}$$

$$P_z^{T_2} = F_{TP} \cdot \operatorname{sign}\left(\frac{\mathrm{d}}{\mathrm{d}t} \delta_2 \right) + k_1 (\eta_3 + \eta_4) +$$

$$+ \beta_1 \left(\frac{\mathrm{d}}{\mathrm{d}t} \eta_3 + \frac{\mathrm{d}}{\mathrm{d}t} \eta_4 \right), \tag{23}$$

$$P_\varphi^{T_2} = -k_1 \cdot a \cdot (\eta_3 - \eta_4) - \beta_1 \cdot a \cdot \left(\frac{\mathrm{d}}{\mathrm{d}t} \eta_3 - \frac{\mathrm{d}}{\mathrm{d}t} \eta_4 \right), \tag{24}$$

where $\beta_{в}$ is the coefficient of viscous resistance between the sectors and a covered rail wagon's frame; h is the height from the center of weight of combat equipment to the plane of resting on the frame of the wagon.

The value of the viscous resistance coefficient between the sectors and the covered rail wagon's frame varied in the range of 10–100 kN·s/m. The height from the center of weight of combat equipment to the plane of resting on the frame of the wagon was adopted equal to 1.2 m. This magnitude is averaged and was chosen based on the analysis of the parameters of combat equipment that can be used to fire from a wagon.

In this case, the right-hand part of differential equations (13) and (14) includes a viscous resistance coefficient between the sectors and the covered rail wagon's frame. By solving the differential equations, we determined those accelerations that act on a bearing structure at firing (Fig. 10).

By considering the coefficient of viscous resistance between the supporting sector and the frame of a wagon, 100 kN·s/m, we determined those accelerations that operate in the center of the wagon's mass (Fig. 11), at the points of resting on bogies (Fig. 12), and on the bogies (Fig. 13).

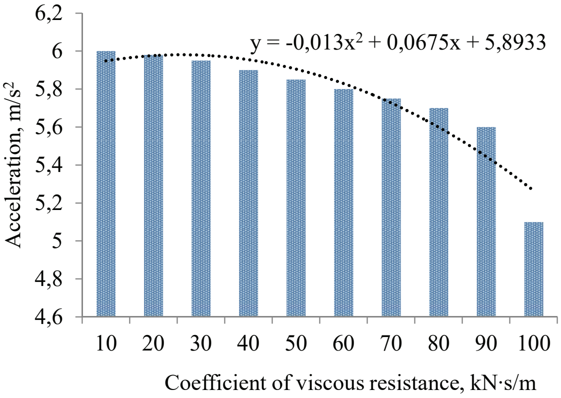


Fig. 10. The dependence of accelerations on the coefficient of viscous resistance between the supporting sectors and the bearing structure of a wagon

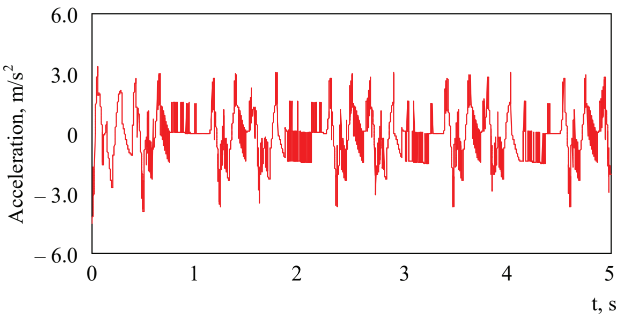


Fig. 11. Accelerations that act in the wagon's center of mass

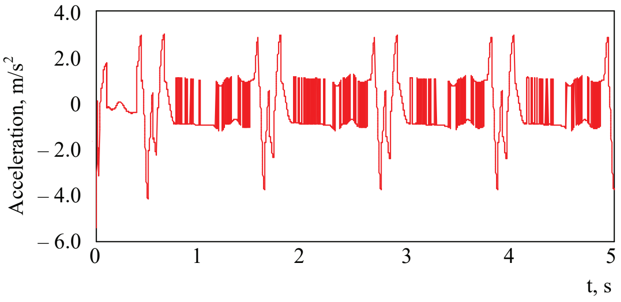


Fig. 12. Body accelerations at the points of resting on bogies

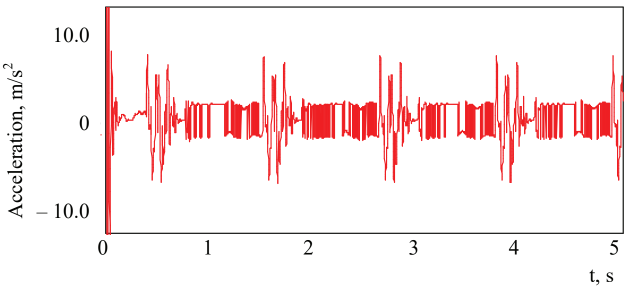


Fig. 13. Bogie accelerations

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

The estimation scheme of the bearing structure of a covered rail wagon is shown in Fig. 14. Attention was paid to the vertical static load P_v^{st}, the load that acts on the supporting sectors at firing, which was considered as remote P_R. We also took into consideration that the front stops of the auto-coupling are exposed to the longitudinal load P_l, which, in accordance with normative documentation [22, 23], was taken equal to 2.5 MN.

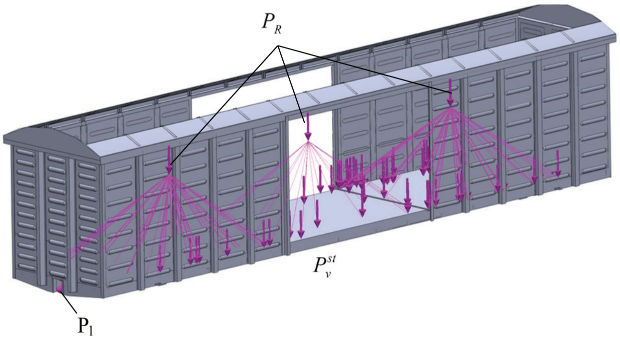


Fig. 14. The estimation scheme of the bearing structure of a covered rail wagon

The dependence of the maximum equivalent stresses σ_{eq} on the recoil force, which varied in the range of 0.5–5.0 kN, is shown in Fig. 15.

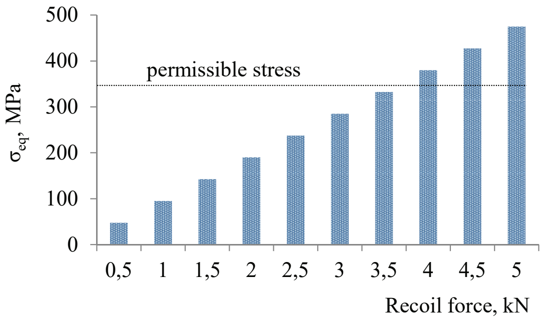


Fig. 15. The dependence of the maximum equivalent stresses in the bearing structure of a covered rail wagon on recoil force

Based on our calculations, it can be concluded that the maximum equivalent stresses are within the limits that are admissible at the recoil force of combat equipment at firing, about 3.7 kN. However, with such a recoil force, the permissible accelerations of the bearing structure of a covered rail wagon are not ensured (Fig. 5). Therefore, the strength calculation was conducted for the recoil force of 3.2 kN (Fig. 16, 17).

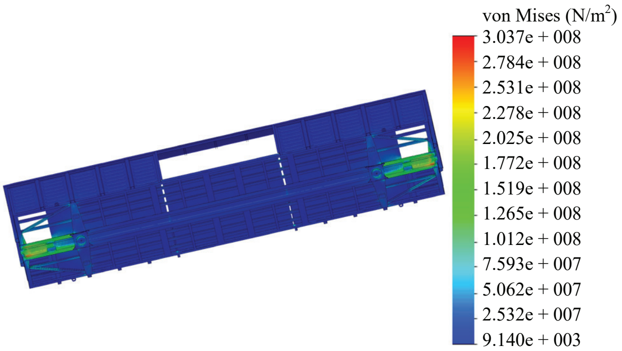


Fig. 16. The stressed state of the bearing structure of a covered rail wagon (bottom view)

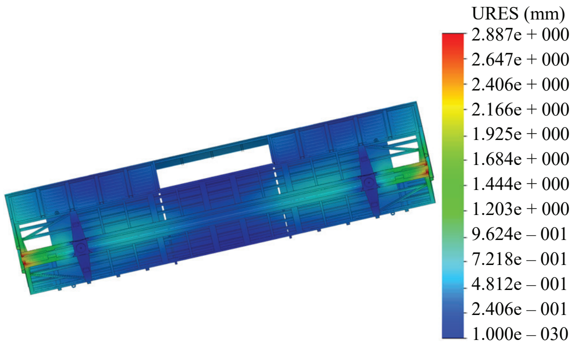


Fig. 17. Displacements in the nodes of the bearing structure of a covered rail wagon (bottom view)

The calculations allowed us to conclude that the maximum equivalent stresses arise in the console part of the girder of a covered wagon and reach about 300 MPa.

The maximum displacements were registered in the area of the arrangement of the front stops of the auto-coupling; they are equal to 2.9 mm. The maximum deformations amounted to $6.98 \cdot 10^{-3}$. Thus, the strength of the bearing structure of a covered rail wagon when firing from it in the vertical plane while moving along a rail track is ensured [22–24].

7. Modal analysis of the bearing structure of a covered rail wagon when firing from it

A modal analysis [25–29] was performed to determine the oscillation shapes of the bearing structure of a covered rail wagon. Fig. 18 shows several first oscillation shapes of the bearing structure of a covered rail wagon when firing from it.

The calculations were carried out based on the developed estimation scheme (Fig. 14) in the CosmosWorks programming environment according to the method of finite elements. The parameters of the finite-element model are identical to those used when calculating the strength of the bearing structure.

Table 1 shows that the values of the natural oscillation frequencies are within the permissible limits since the first natural frequency acquires a value greater than 8 Hz.

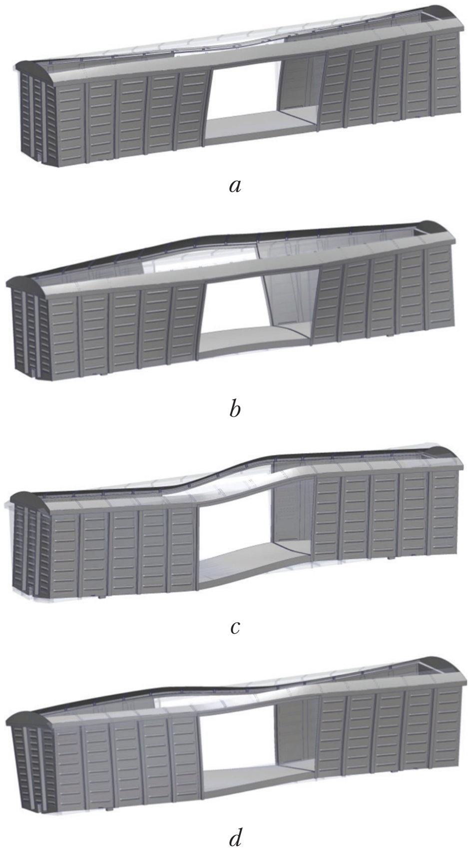


Fig. 18. The natural oscillation shapes of the bearing structure of a covered rail wagon: *a* – first shape (the scale of deformation is 30:1); *b* – second shape (the scale of deformation is 30:1); *c* – third shape (the scale of deformation is 20:1); *d* – fourth shape (deformation scale is 20:1)

Table 1

Values of the natural oscillation frequencies of the bearing structure of a covered rail wagon

Frequency number	1	2	3	4	5	6	7	8	9	10
Value, Hz	19.8	20.5	22.9	23.6	25.5	31.3	38.6	38.9	41.4	50.2

8. Discussion of results of determining the dynamics and strength of the bearing structure of a covered rail wagon when firing from it

In order to increase the military capabilities of this country, covered rail wagons have been proposed to transport military vehicles and to fire from them. The wagon has a sliding roof to enable firing in the vertical plane. At the same time, military equipment is placed in special supporting sectors (Fig. 3).

The mathematical modeling of the dynamic loading on the bearing structure of a covered rail wagon at firing was carried out. Our study was conducted in a flat coordinate system. The loading that is transmitted to the bearing structure at firing in the vertical plane varied in the range of 0.5 5 kN. It was established that the values of vertical accelerations, in this case, are in the interval of 1 10 m/s^2. In order to maintain the covered rail wagon's dynamics indicators within the permissible limits, the maximum recoil force from a shot should not exceed 3.2 kN. In this case, the maximum accelerations, which act on the bearing structure of a covered rail wagon in the vertical plane, are equal to about 6 m/s^2 (Fig. 6). In addition, the current paper proposes the use of a viscous connection between the supporting sector and a covered rail wagon's frame. When calculating, the values of the viscous resistance coefficient between the sectors and the covered rail wagon's frame changed in the range of 10–100 kN·s/m. It was established that at a value of the viscous resistance coefficient between the sector and the frame of 100 kN·s/m it becomes possible to reduce the dynamic loading on the bearing structure of a covered rail wagon at least by 15 %.

The results of calculating the strength of the bearing structure of a covered rail wagon are given. The dependence of the maximum equivalent stresses on the recoil force of military equipment was determined. The recoil force varied in the range of 0.5–5.0 kN. The maximum equivalent stresses, in this case, are within the permissible limits at a recoil force of combat equipment at firing of about 3.7 kN. However, since this recoil force does not ensure vertical accelerations in the permissible limits, the calculation was performed for the recoil force of 3.2 kN. It was established that the maximum equivalent stresses, in this case, occur in the console part of the girder of a covered rail wagon and reach about 300 MPa (Fig. 16), which is lower than the permissible stresses by 13 % (the steel of grade 09G2S). The maximum displacements were registered in the area where the front stops of the automatic coupling are arranged; they are equal to 2.9 mm (Fig. 17). The maximum deformations amounted to $6.98 \cdot 10^{-3}$.

To determine the natural frequencies and oscillation shapes of the bearing structure of a covered rail wagon, a modal analysis in the software package CosmosWorks was performed. For this purpose, we applied the estimation scheme, shown in Fig. 14. In this case, the first natural oscillation frequency acquires a value exceeding 8 Hz. Thus, the values of the natural oscillation frequencies are within the permissible limits.

The limitations of this study relate to that we calculated the case of firing from conditional combat equipment to determine the permissible recoil force. That is, there is no analysis of the use of existing combat equipment with the predefined recoil force. It is important in the future to determine the dynamic load on a wagon taking into consideration the use of existing combat equipment with the appropriate parameters of firing.

In the future, it is also important to take into consideration the randomness of a wagon oscillatory process, caused by the irregularities in a rail track. In addition, attention should be paid to the stochasticity of shots from combat equipment and their impact on the dynamic load on the bearing structure of a covered rail wagon.

8. Conclusions

1. We have determined the dynamic loading on the bearing structure of a covered rail wagon when firing from it in the vertical plane. This study was conducted in a flat coordinate system. Attention was paid to the fluctuations of bouncing and galloping. It was considered that a wagon moves over a butt elastic-viscous rail track. The calculation in the Mathcad software package involved a Runge-Kutta method. It was determined that the maximum vertical accelerations, which act on the bearing structure of a covered rail wagon, were about 6 m/s^2 (0.6 g). At the points when the body rests on bogies, the maximum accelerations are about 9.5 m/s^2 (0.95 g), and the accelerations of the bogies are 10 m/s^2 (1.0 g). At the same time, to maintain the permissible dynamic loading on a wagon, the recoil force from a shot from combat equipment should not exceed 3.2 kN.

We also considered the case of viscous interaction between the supporting sector and the frame of a wagon. The value of the viscous resistance coefficient between the sectors and a covered rail wagon's frame varied in the range of 10–100 kN·s/m. It was determined that in order to reduce the dynamic load on the bearing structure of a wagon when firing from it, the coefficient of viscous resistance must be at least 100 kN·s/m. Thus, it becomes possible to reduce the dynamic load on the bearing structure of a wagon by 15 %.

2. The basic indicators of strength for the bearing structure of a covered rail wagon when firing from it were determined. The calculation involved the method of finite elements in the programming environment CosmosWorks. We determined the maximum equivalent stresses depending on the recoil force of combat equipment, which varied in the range of 0.5–5.0 kN. It was determined that the maximum equivalent stresses are within the permissible limits at the recoil force of combat equipment at firing about 3.7 kN. However, this force of recoil does not guarantee vertical accelerations within the permissible limits. Therefore, the accepted estimation recoil force was 3.2 kN. In this case, the maximum equivalent stresses acting on the bearing structure of a covered rail wagon are about 300 MPa, which is lower than the permissible stresses by 13 % (at the value of material yield σ_T=345 MPa). The maximum displacements are 2.9 mm and are concentrated in the area where the front stops of the auto-coupling are arranged, the maximum deformations amounted to $6.98 \cdot 10^{-3}$.

3. Modal analysis of the bearing structure of a covered rail wagon was performed when firing from it. This study was carried out based on the estimated model, which was built to determine the main indicators of strength for the bearing structure of a covered rail wagon in the programming environment CosmosWorks by using a method of finite elements. We have determined the numerical values of natural frequencies and oscillation shapes of the bearing structure of a covered rail wagon. It has been established that the first natural frequency acquires a value greater than 8 Hz. Thus, the values of the natural oscillation frequencies are within the permissible limits.

This study will contribute to the construction of innovative structures for covered wagons.

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