The determination of the dynamic loading of the bearing structures of the main types of freight wagons with the actual dimensions under the main operating conditions is carried out. The inertial coefficients of the bearing structures of the wagons are determined by constructing their spatial models in the SolidWorks software package. Two cases of loading of the bearing structures of the wagons – in the vertical and longitudinal planes – have been taken into account. The studies were carried out in a flat coordinate system. When modeling the vertical loading of the bearing structures of wagons, it was taken into account that they move in the empty state with butt unevenness of the elastic-viscous track. The bearing structures of the wagons are supported by bogies of models 18-100. The solution of differential equations of motion was carried out by the Runge-Kutta method in the MathCad software package. When determining the longitudinal loading of the bearing structures of wagons, the calculation was made for the case of a shunting collision of wagons or a "jerk" (tank wagon). The accelerations acting on the bearing structures of the wagons are determined.

The research results will help to determine the possibility of extending the operation of the bearing structures of freight wagons that have exhausted their standard service life.

It has been established that the indicators of the dynamics of the load-carrying structures of freight wagons with the actual dimensions of the structural elements are within the permissible limits. So, for a gondola wagon, the vertical acceleration of the bearing structure is 4.87 m/s², for a covered wagon – 5.5 m/s², for a flat wagon – 5.8 m/s², for a tank wagon – 4.25 m/s², for a hopper wagon – 4.5 m/s². The longitudinal acceleration acting on the bearing structure of a gondola wagon is 38.25 m/s², for a covered wagon – 38.6 m/s², for a flat wagon – 38.9 m/s², for a tank wagon – 27.4 m/s², for a hopper wagon – 38.5 m/s². This makes it possible to develop a conceptual framework for restoring the effective functioning of outdated freight wagons.

The conducted research will be useful developments for clarifying the existing methods for extending the service life of the bearing structures of freight wagons that have exhausted their standard resource

Keywords: freight wagon, bearing structure, dynamic loading, modeling of loading, dynamic indicators, service life, railway transport, transport mechanics

DETERMINATION OF DYNAMIC LOADING OF BEARING STRUCTURES OF FREIGHT WAGONS WITH ACTUAL DIMENSIONS

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1. Introduction

Ensuring timely door-to-door delivery of goods primarily depends on the technical equipment of the transport fleet. It is known that railway transport is the leading industry in the road transport complex of many countries, which provides a significant volume of freight traffic carried out by all modes of transport.

One of the options for increasing the efficiency of the freight wagon fleet functioning is the restoration of the existing obsolete wagons with the improvement of technical and economic indicators to the corresponding competitive level. At the same time, the price of a new freight wagon is on average about 50,000 USD, and the volume of repairs sufficient for restoration (for example, overhaul and refurbishment) is from 20 % to 30 % of the indicated cost. At present, the assigned service life of the "wide gauge" freight wagons is around 23 years. However, in some European countries, technologies have been created and are being used, the use of which doubles this period (in countries with a developed system of freight transport, this period reaches 50 years).

Therefore, the issue of developing conceptual foundations for the restoration of obsolete freight wagons, which will allow to overcome the factors that reduce the efficiency of their functioning, becomes relevant. Such solutions will be of a general engineering nature and will also be appropriate for implementation in the designs of freight wagons in other countries.

2. Literature review and problem statement

In [1], a method is proposed for the calculation and experimental substantiation of the extension of the service life of gondola wagons. This technique allows to assign a new service life, based on data on the fluid technical condition and the calculated and experimental assessment of the residual life of the gondola wagon. The issues of technical diagnostics of tank wagons for the transport of dangerous goods are covered in [2]. Analysis of theoretical studies in the field of extending the service life of tank wagons for the transport of dangerous goods and accumulated rich experience in diagnosing the technical condition of such wagons has made it

possible to improve the algorithm for testing and diagnosing their technical condition.

However, in these works, the determination of the dynamic loading of the bearing structures of the wagons and its influence on the assigned service life is not carried out.

In work [3], the features of extending the service life of wagons for the transportation of pellets are considered; they have exhausted their standard resource. The presented results of the experimental determination of the level of loading and the stress state of the bearing structures of wagon bodies in operation.

The study of the possibility of extending the service life of universal gondola wagons that have exhausted their standard resource is carried out in [4]. Mathematical modeling was carried out to determine the refined dynamic loads. The calculation results were used to determine the stress state of the wagon bearing structure.

At the same time, no attention was paid to the study of the possibility of extending the service life of other types of wagons. Perhaps this is due to the fact that the gondola wagon is the widest type of wagon in operation.

The specifics of determining the dynamic loading of the wagon bearing structure are carried out in [5]. A feature of these studies is that the case of using various types of bogies under the wagons is taken into account. At the same time, the study did not study the influence of the technical characteristics of bogies on the fatigue strength of the bearing elements of the wagons and their service life. This can be explained by the fact that the authors limited themselves to the standard service life of the wagon.

The specifics of determining the strength of the bearing structure of a wagon for intermodal transportation is carried out in [6]. When drawing up the design scheme, PN-EN standards were used. The calculation was carried out using the finite element method. However, the work does not determine the fatigue strength of the wagon bearing structure, and also does not indicate its design life.

The work [7] considers methods and studies to extend the service life of the bearing structures of traction rolling stock for industrial transport. Technical solutions have been developed with measures that must be carried out during operation within the extended designated service life of traction and motor units of industrial rolling stock of enterprises that use diesel locomotives and traction units. However, the work lacks applied application of the proposed solutions.

Analysis of the literature [1–7] allows to conclude that the issue of determining the dynamic loading of the load-carrying structures of freight wagons with actual dimensions requires more attention.

3. The aim and objectives of research

The aim of research is to highlight the features of determining the dynamic loading of the bearing structures of freight wagons with the actual dimensions of the constituent elements in order to further determine the possibility of extending the service life.

To achieve this aim, the following objectives have been identified:

– to create spatial models of the bearing structures of the main types of freight wagons with their actual dimensions;

– determination of dynamic loading of bearing structures of freight wagons with actual dimensions in the vertical plane;

– determination of the dynamic loading of bearing structures of freight wagons with actual dimensions in the longitudinal plane.

4. Creation of spatial models of bearing structures of the main types of freight wagons with actual dimensions

To determine the masses and moments of inertia of the bearing structures of the main types of freight wagons with their actual dimensions, their spatial models were built in the SolidWorks software package [8–11]. The most widespread models of freight wagons have been taken into account, they have found application on the CIS railways:

– gondola wagon model 12-757 (Fig. 1, *a*);
– covered wagon model 11-217 (Fig. 1, *b*);
– flat wagon model 13-401 (Fig. 1, *c*);
– tank wagon model 15-1443-06 (Fig. 1, *d*);
– hopper wagon model 20-9749 (Fig. 1, *e*).
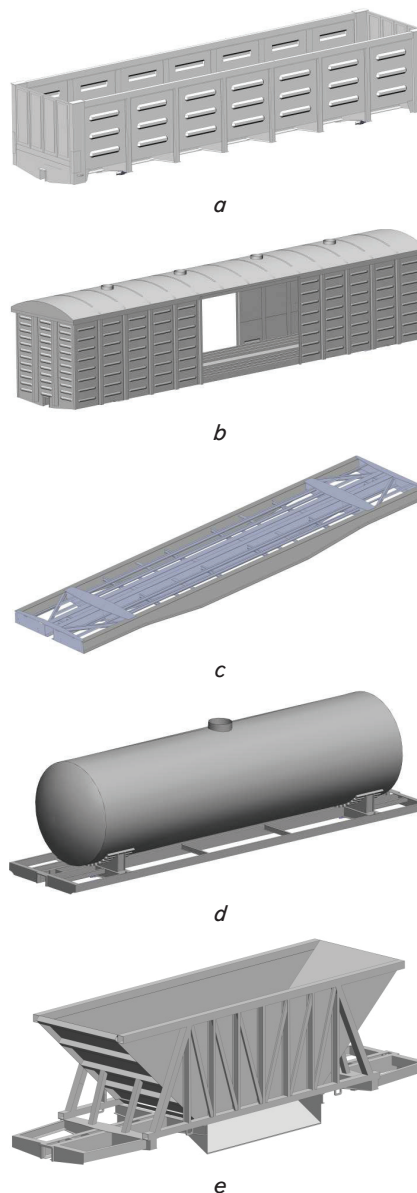

a

b

c

d

e

Fig. 1. Spatial models of bearing structures of freight wagons with actual dimensions: *a* — gondola wagon; *b* — covered wagon; *c* — flat wagon; *d* — tank wagon; *e* — hopper wagon

At the same time, the actual values of the demolition of the elements of the bearing structures of the wagons, recorded during field studies, were taken into account (Fig. 2–9). In this case, the upper index of the serial number of the structural element characterizes the nominal value of the thickness, and the lower one, indeed, was recorded during field studies.
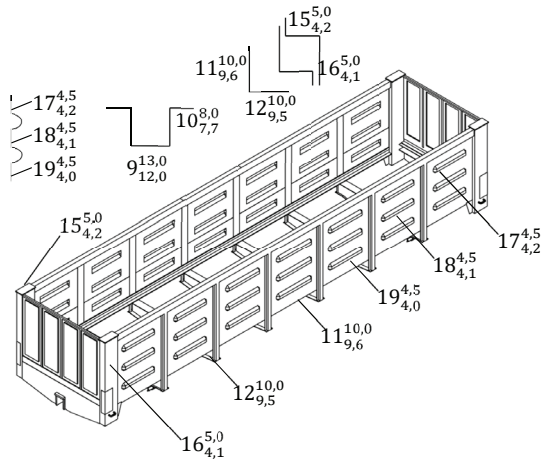

Fig. 2. Spatial model of the gondola wagon body with indication of the nominal and certain minimum actual average thicknesses of the elements of the bearing components
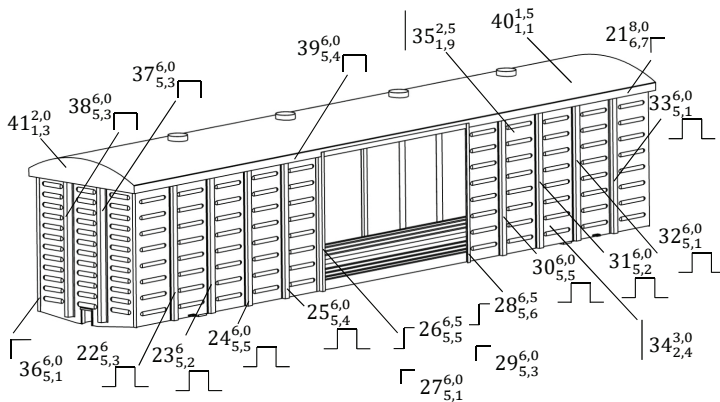

Fig. 3. Spatial model of the covered wagon body with indication of the nominal and certain minimum actual average thicknesses of the elements of the bearing components
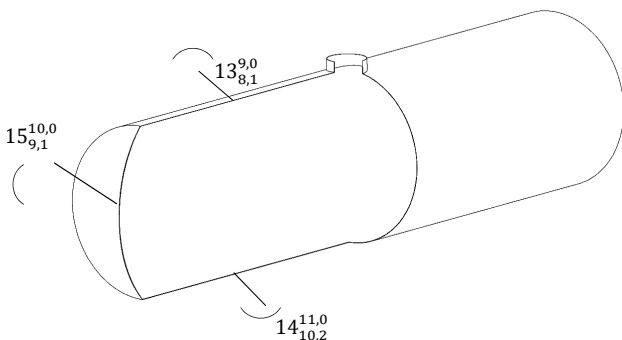

Fig. 4. Spatial model of the tank wagon body with indication of the nominal and certain minimum actual average thicknesses of the elements of the bearing components

When determining the actual dimensions of the elements of the bearing structures of platform wagons, the thicknesses of the I-beams of the vertebral beams and the main longitudinal beams were taken into account (Fig. 10).
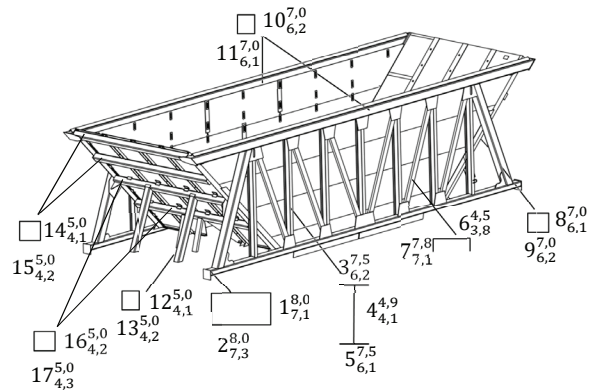

Fig. 5. Spatial model of the hopper wagon body with indication of the nominal and certain minimum actual average thicknesses of the elements of the bearing components

The number of measurements carried out is 20. In this case, the most unfavorable technical condition of these elements is taken into account, when the thickness of the rack was 11.69 mm.

The inertial coefficients of the bearing structures of the main types of freight wagons, which are taken into account when determining the dynamic loading in the vertical and longitudinal planes, are given, respectively, in Tables 1, 2. These coefficients are determined using the options of the SolidWorks software package.

Table 1

Inertial coefficients of bearing structures of wagons for determining dynamic loading in the vertical plane

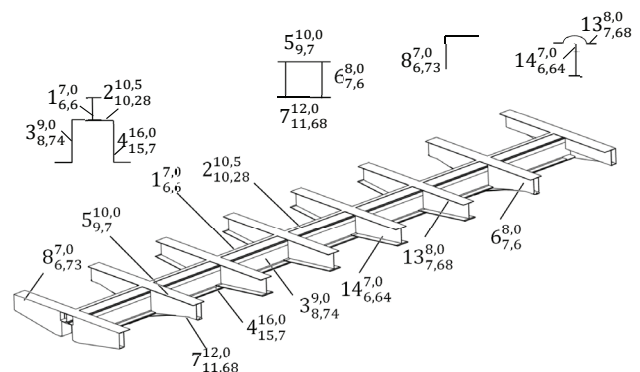| Wagon type	Mass, t	Moment of inertia, t·m²	Percentage of mass reduction compared to the prototype wagon
Gondola wagon	13.1	260.1	16.3
Covered wagon	12.7	265.6	17.0
Flat wagon	11.1	102	3.5
Tank wagon	15.05	223.9	8.2
Hopper wagon	14.1	105.5	9.3

Fig. 6. Spatial model of the gondola wagon frame with indication of the nominal and certain minimum actual average thicknesses of the bearing components
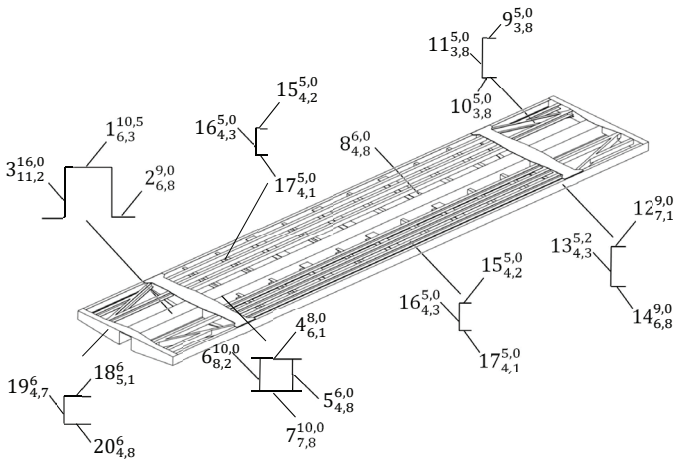
Fig. 7. Spatial model of the covered wagon frame with indication of the nominal and determined minimum actual average thicknesses of the elements of the bearing components
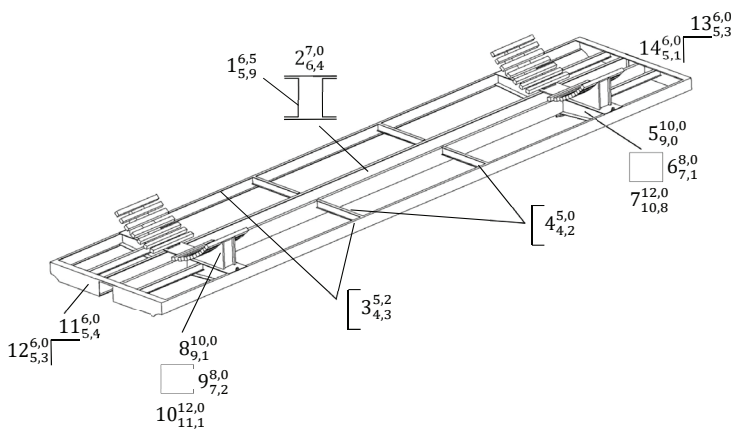

Fig. 8. Spatial model of the tank wagon frame with indication of the nominal and certain minimum actual average thicknesses of the elements of the bearing components
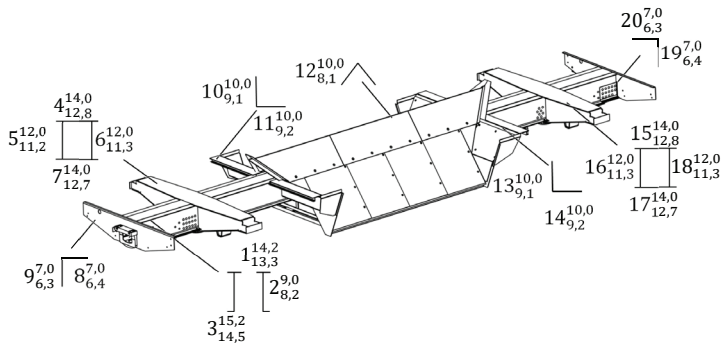

Fig. 9. Spatial model of the frame of the hopper wagon with indication of the nominal and certain minimum actual average thicknesses of the elements of the bearing components
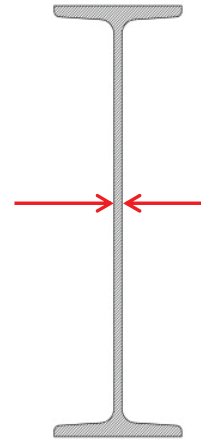
Table 2

Inertial coefficients of bearing structures of wagons for determining dynamic loading in the horizontal plane

Wagon type	Wagon gross mass, t	Bearing structure mass, t	Moment of inertia, t·m²
Gondola wagon	91.5	82.1	1228.5
Covered wagon	90.1	80.7	1207.4
Flat wagon	90.5	81.1	1111.6
Tank wagon	90.45	81.05	1084.3
Hopper wagon	92.5	83.1	1232.4

Fig. 10. Area for measuring the I-beam thickness

5. Determination of dynamic loading of bearing structures of freight wagons with actual dimensions in the vertical plane

To determine the updated dynamic loads acting on the bearing structures of freight wagons with the actual parameters, mathematical modeling was carried out. In this case, the mathematical model given in [12] is used. It is taken into account that the wagon moves in an empty state with butt inequality. The track is considered as elastic-viscous. Path reactions are proportional to both its deformation and the rate of this deformation. The design scheme is shown in Fig. 11.
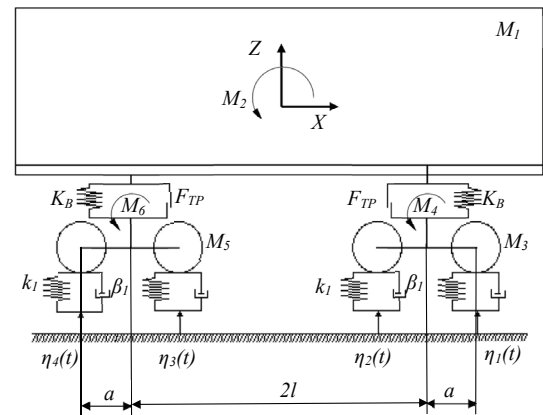

Fig. 11. Design scheme of a freight wagon

The equations of motion of the computational model are as follows:

$$M_1 \cdot \frac{d^2}{dt^2} q_1 + C_{1,1} \cdot q_1 + C_{1,3} \cdot q_3 + C_{1,5} \cdot q_5 =$$
$$= -F_{FR} \cdot \left(\text{sign}\left(\frac{d}{dt} \delta_1 \right) + \text{sign}\left(\frac{d}{dt} \delta_2 \right) \right), \quad (1)$$

$$M_2 \cdot \frac{d^2}{dt^2} q_2 + C_{2,2} \cdot q_2 + C_{2,3} \cdot q_3 + C_{2,5} \cdot q_5 =$$
$$= F_{FR} \cdot l \cdot \left(\text{sign}\left(\frac{d}{dt} \delta_1 \right) + \text{sign}\left(\frac{d}{dt} \delta_2 \right) \right), \quad (2)$$

$$M_3 \cdot \frac{d^2}{dt^2} q_3 + C_{3,1} \cdot q_1 + C_{3,2} \cdot q_2 + C_{3,3} \cdot q_3 + B_{3,3} \cdot \frac{d}{dt} q_3 =$$
$$= F_{FR} \cdot \text{sign}\left(\frac{d}{dt}\delta_1\right) + k_1(\eta_1 + \eta_2) + \beta_1\left(\frac{d}{dt}\eta_1 + \frac{d}{dt}\eta_2\right), \quad (3)$$

$$M_4 \cdot \frac{d^2}{dt^2} q_4 + C_{4,4} \cdot q_4 + B_{4,4} \cdot \frac{d}{dt} q_4 =$$
$$= -k_1(\eta_1 - \eta_2) - \beta_1 \cdot a \cdot \left(\frac{d}{dt}\eta_1 - \frac{d}{dt}\eta_2\right), \quad (4)$$

$$M_5 \cdot \frac{d^2}{dt^2} q_5 + C_{5,1} \cdot q_1 + C_{5,2} \cdot q_2 + C_{5,5} \cdot q_5 + B_{5,5} \cdot \frac{d}{dt} q_5 =$$
$$= F_{FR} \cdot \text{sign}\left(\frac{d}{dt}\delta_2\right) + k_1(\eta_3 + \eta_4) + \beta_1\left(\frac{d}{dt}\eta_3 + \frac{d}{dt}\eta_4\right), \quad (5)$$

$$M_6 \cdot \frac{d^2}{dt^2} q_6 + C_{6,6} \cdot q_6 + B_{6,6} \cdot \frac{d}{dt} q_6 =$$
$$= -k_1 \cdot a \cdot (\eta_3 - \eta_4) - \beta_1 \cdot a \cdot \left(\frac{d}{dt}\eta_3 - \frac{d}{dt}\eta_4\right), \quad (6)$$

where M_1, M_2 – respectively the mass and moment of inertia of the wagon bearing structure during vibrations of bouncing and galloping; M_3, M_4 – respectively, the mass and moment of inertia of the first bogie in the direction of movement during vibrations of jumping and galloping; M_5, M_6 – respectively, the mass and moment of inertia of the second bogie in the direction of movement during vibrations of jumping and galloping; C_{ij} – characteristic of the elasticity of the vibrating system elements; B_i – scattering function; a – half of the bogie base; q_i – generalized coordinates corresponding to translational displacement about the vertical axis and angular displacement around the vertical axis; k_i – rigidity of the spring suspension; β_i – damping factor; F_{FR} – force of absolute friction in the spring set.

The butt inequality was described by a periodic function:

$$\eta(t) = \frac{h}{2}(1 - \cos\omega t), \quad (7)$$

where h – inequality depth; ω – vibration frequency, which is determined by the formula $\omega = 2\pi V/L$ (V – speed of the wagon, L – inequality length).

Initial displacement and speed are taken equal to zero. The input parameters of the model are the technical characteristics of the bearing structure of the wagon with nominal parameters, spring suspension of bogies, as well as the disturbing action (Table 3).

The calculations took into account the parameters of the spring suspension of the model 18-100 bogie. To solve differential equations (1)–(9), they were reduced to the Cauchy normal form. After that, they are integrated by the Runge-Kutta method [13–17], which is implemented in the MathCad software package [18, 19]. On the basis of the calculations performed, the acceleration acting on the inves-

tigated wagon structures was determined. The calculation results are shown in Fig. 12–16.

According to the mathematical model (1)–(6), the main indicators of the dynamics of wagons when moving in an empty state are determined (Table 4). The calculation was carried out at a wagon speed of 80 km/h.

Table 3

Input parameters to the mathematical model

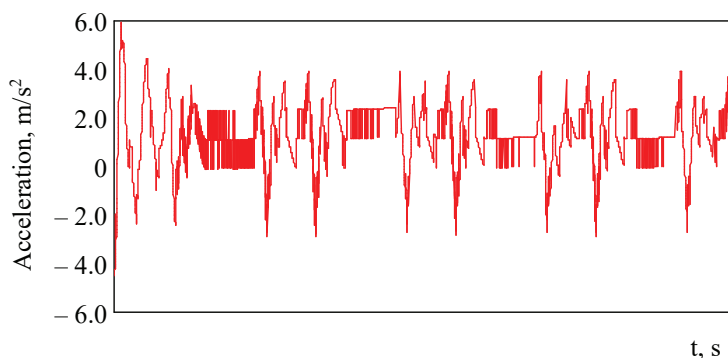| Parameter name	Value
Bogies	
mass, t	4.3
half base, m	0.925
spring suspension rigidity, kN/m	8,000
coefficient of relative friction	0.1
Way	
damping coefficient, kN·s/m	200
stiffness, kN/m	100,000
inequality amplitude, g.	0.01
inequality length, g.	25

Fig. 12. Acceleration of the bearing structure of the gondola wagon in the center of mass
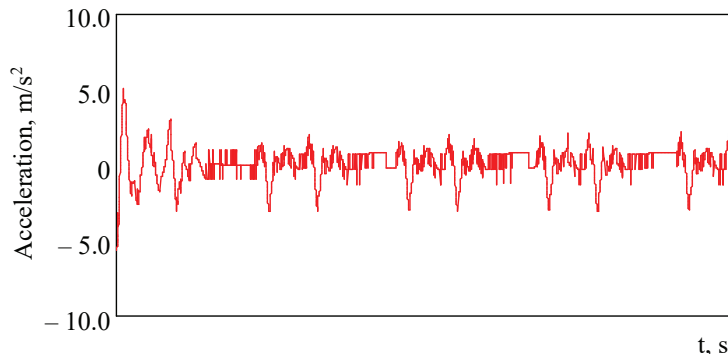

Fig. 13. Acceleration of the bearing structure of the covered wagon in the center of mass

The results obtained allow to conclude that the indicators of the dynamics of wagons are within the permissible limits [20–22].

Acceleration that act on the bearing structures of wagons with actual dimensions exceeding those obtained at the nominal: for a gondola wagon by 16 %, for a covered wagon – 25 %, for a flat wagon – 4 %, for a tank wagon – 9 %, for a hopper wagon – 2 %.
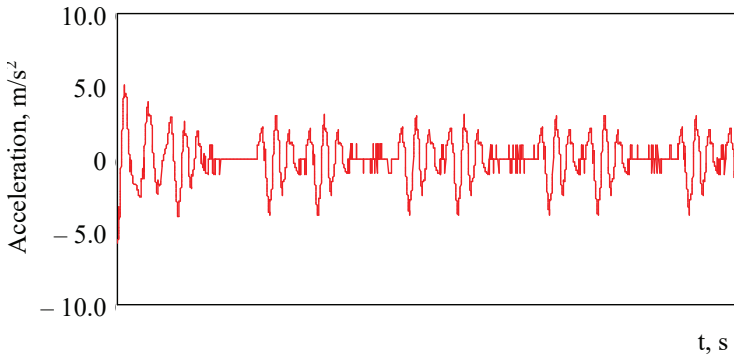
Fig. 14. Acceleration of the bearing structure of the platform wagon in the center of mass
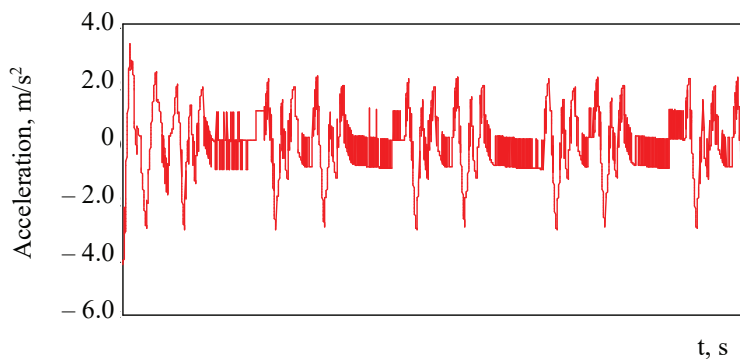

Fig. 15. Acceleration of the bearing structure of the tank wagon in the center of mass
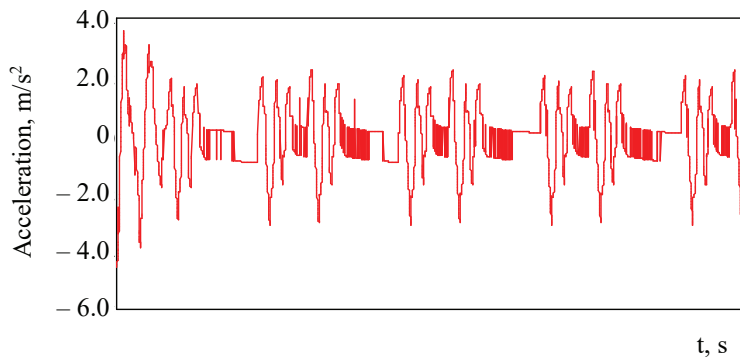

Fig. 16. Acceleration of the bearing structure of the hopper wagon in the center of mass

Table 4

Dynamic indicators of the investigated wagons when moving in an empty state

Indicator	Value				
	GW	CW	FW	TW	HW
Body acceleration, m/s^2	4.87	5.6	5.8	4.25	4.5
Body acceleration in the support zone on the first bogie in the direction of travel, m/s^2	6.4	8.7	10.1	9.98	10.3
Body acceleration in the support zone on the second bogie in the direction of travel, m/s^2	6.4	8.7	10.1	9.98	10.3
Force in the spring suspension of the first bogie, kN	42.7	41.2	42.5	44.3	44.6
Force in the spring suspension of the second bogie, kN	42.7	41.2	42.5	44.3	44.6
First bogie dynamic coefficient	0.65	0.73	0.77	0.59	0.63
Coefficient of dynamics of the second bogie	0.65	0.73	0.77	0.59	0.63
GW – gondola wagon; CW – covered wagon; FW – flat wagon; TW – tank wagon; HW – hopper wagon					

6. Determination of dynamic loading of bearing structures of freight wagons with actual dimensions in the longitudinal plane

To determine the dynamic loads acting on the bearing structures of wagons with actual dimensions under the action of a longitudinal force (shunting collision), a mathematical model is used, given in [23, 24]. The design diagram of the wagon is shown in Fig. 17.

$$M'_W \cdot \ddot{x}_W + M' \cdot \ddot{\phi}_W = S_a, \qquad (8)$$

$$I_W \cdot \ddot{\phi}_W + M' \cdot \ddot{x}_W - g \cdot \phi_W \cdot M' =$$
$$= l \cdot F_{FR}\left(\text{sign}\dot{\Delta}_1 - \text{sign}\dot{\Delta}_2\right) + l(C_1 - C_2), \qquad (9)$$

$$M_W \cdot \ddot{z}_W = C_1 + C_2 - F_{FR}\left(\text{sign}\dot{\Delta}_1 - \text{sign}\dot{\Delta}_2\right), \qquad (10)$$

where

$$M'_W = M_W + 2 \cdot m_B + \frac{n \cdot I_{WS}}{r^2}; \quad M' = M_W \cdot h;$$

$$C_1 = k_1 \cdot \Delta_1; \; C_2 = k_2 \cdot \Delta_2;$$

$$\Delta_1 = z_W - l \cdot \phi_W; \; \Delta_2 = z_W + l \cdot \phi_W,$$

M_W – mass of the bearing structure of the wagon; I_W – moment of inertia of the wagon relative to the longitudinal axis; S_a – value of the longitudinal force of impact into the automatic coupler; m_B – bogie mass; I_{WS} – moment of inertia of the wheelset; r – the radius of the mid-worn wheel; n –number of bogie axles; l – half of the wagon base F_{FR} – absolute value of the dry friction force in the spring set; k_1, k_2 – the stiffness of the spring suspension of the wagon bogies x_W, ϕ_W, z_W – coordinates corresponding, respectively, to the longitudinal, angular around the transverse axis and vertical movement of the wagon.

Differential equations are solved in the Math-Cad software package. Initial displacements and speeds caused by being equal to zero. The input parameters of the mathematical model are the technical characteristics of the bearing structures of the wagons, the parameters of the spring suspension, as well as the value of the force of the longitudinal impact into the automatic coupling. The longitudinal impact force acting on the vertical surface of the rear stop of the automatic coupler is taken equal to 3.5 MN [20, 21]. For a tank wagon, the value of the longitudinal force in the calculations was taken to be 2.5 MN.

Based on the calculations, the main indicators of the dynamics of the considered types of wagons were obtained. The calculation results are shown in Table 5 and illustrated in Fig. 18–22.

So, the accelerations acting on the bearing structures of wagons with actual dimensions exceeding those obtained at the nominal: for a gondola wagon by 2.4 %, for a covered wagon – 1.7 %, for a flat wagon – 1 %, for a tank wagon – 2.7 %, for a hopper wagon – 2.7 %.

Table 5

Acceleration that act on the bearing structures of the wagons

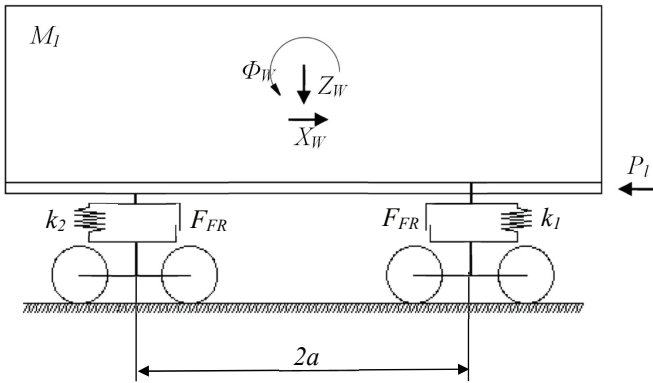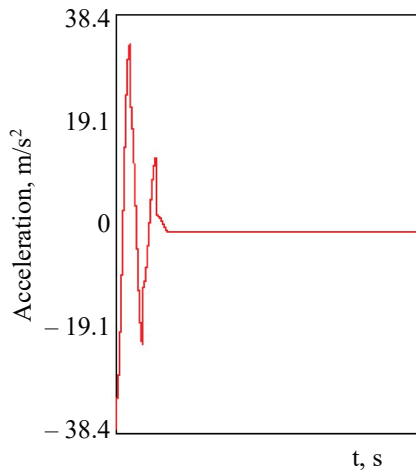| Wagon type	Acceleration, m/s²
Gondola wagon	38.35
Flat wagon	38.6
Platform wagon	38.9
Tank wagon	27.4
Hopper wagon	38.5

Fig. 17. Design scheme of a freight wagon

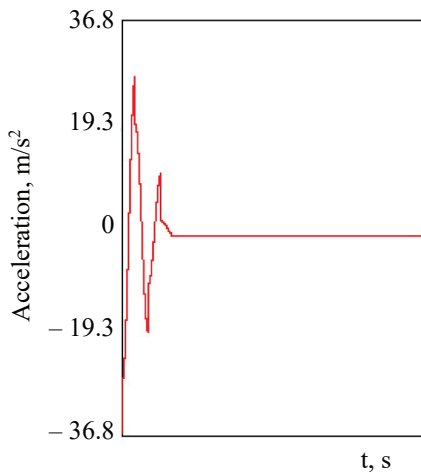Fig. 18. Acceleration acting on the bearing structure of the gondola wagon

Fig. 19. Acceleration acting on the bearing structure of the covered wagon
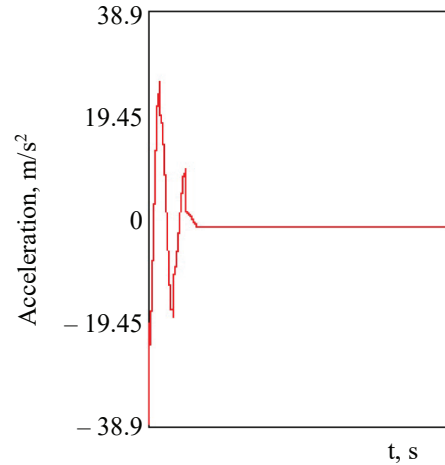

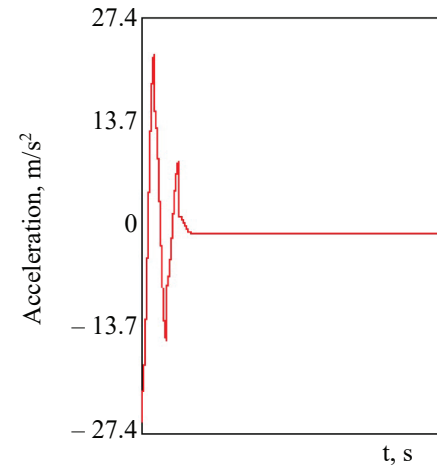Fig. 20. Acceleration acting on the bearing structure of the platform wagon

Fig. 21. Acceleration acting on the bearing structure of the tank wagon

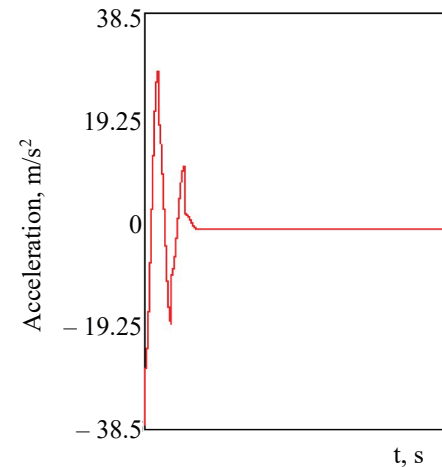Fig. 22. Acceleration acting on the bearing structure of the hopper wagon

To check the adequacy of the proposed mathematical model, a computer simulation of the dynamic loading of the bearing structures of freight wagons was carried out. As an example, below are the results of computer simulation of the dynamic loading of a flat wagon. The calculation was carried out in the SolidWorks (Simulation) software package using

the finite element method. When compiling the finite element model, isoparametric tetrahedrons were used. The optimal number of tetrahedra was determined by the graphical analytical method. When drawing up the design scheme, it was taken into account that a vertical static load acts on the bearing structure of the flat wagon, taking into account the use of the full carrying capacity of the wagon, as well as the longitudinal load on the rear stop of the automatic coupler, which is 3.5 MN [20, 21]. The simulation results are shown in Fig. 23. In this case, the force of impact into the rear stop of the coupler was chosen as a variation parameter, which varied in the range of 1.1–3.5 MN.

The F-criterion was used to test the adequacy of the proposed model. It was found that the calculated value of the criterion is $F_p=1.02$, which is less than the table value $F_t=3.29$. So the hypothesis of adequacy is not rejected.
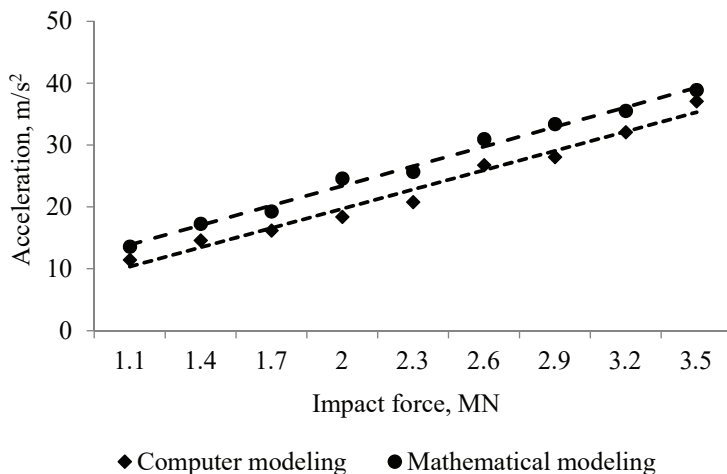

Fig. 23. Acceleration of the bearing structure of a flat wagon with longitudinal loading

7. Discussion of the research results of the dynamic loading of the load-carrying structures of freight wagons with the actual dimensions

The dynamic loading of bearing structures of freight wagons with actual dimensions is investigated. It has been established that the indicators of the dynamics of the bearing structures of the wagons are within the permissible limits. At the same time, for a gondola wagon, the vertical accelerations of the bearing structure amounted to 4.87 m/s², for a covered wagon – 5.5 m/s², for a flat wagon – 5.8 m/s², for a tank wagon – 4.25 m/s²for a hopper wagon – 4.5 m/s² (Fig. 6). Longitudinal accelerations acting on the bearing structure of the gondola wagon are 38.25 m/s², for a covered wagon – 38.6 m/s², for a flat wagon – 38.9 m/s², for a tank wagon – 27.4 m/s², for a hopper wagon – 38.5 m/s² (Fig. 8). This is due to the fact that the actual dimensions of the main bearing elements of freight wagons during the standard service life are slightly reduced in comparison with the nominal ones (Fig. 2, 3, Tables 1, 2). The obtained results will contribute to the refinement of the existing methods for extending the service life of wagons that have exhausted their standard resource.

It is known that at present, when extending the service life of wagons, the standard values of the loads acting on the bearing structures of wagons in operation are used [1–3]. This circumstance contributes to the appearance of an error

in determining the additional service life of wagons, since the dynamic load is decisive in the analysis of the loading of their bearing structures. Therefore, in order to obtain its true value in this study, the dynamic loading of individual wagons was determined with the actual values of the demolition of the bearing elements, which were recorded during field studies.

However, the limitations of this study are that they do not take into account the cyclicity of the action of dynamic loads on the bearing structures of the wagons under study in operation. In addition, in further studies, it is important to determine the strength of the welded seams of the bearing structures of the wagons, in respect of which the service life is extended.

In further research in this direction, it is important to determine the dynamic loading of wagons and for other modes of vibration. The experimental determination of the dynamics of the considered types of wagons also requires attention.

8. Conclusions

1. Spatial models of the bearing structures of the main types of freight wagons with the actual dimensions of the constituent elements have been created. The following types of wagons are taken into account: gondola wagon, covered wagon, platform wagon, tank wagon, hopper wagon. It was found that, taking into account the demolition of structural elements of the bearing structures of the wagons, the actual mass decreases in comparison with prototype wagons: gondola wagon – 16.3 %, covered wagon – 17.0, flat wagon – 3.5 %, tank wagon – 8.2 % and the hopper wagon – 9.3 %.

2. The dynamic loading of the load-carrying structures of freight wagons with actual dimensions in the vertical plane has been determined. The calculation was carried out when the wagons were moving in an empty state. It was found that the acceleration acting on the bearing structures of the wagons with the actual dimensions of the elements are within the permissible limits. At the same time, the acceleration acting on the bearing structures of wagons with actual dimensions exceeding those obtained at nominal: for a gondola wagon by 16 %, for a covered wagon – 25 %, for a flat wagon – 4 %, for a tank wagon – 9 % for a hopper wagon – 2 %.

3. The dynamic loading of the load-carrying structures of freight wagons with the actual dimensions in the longitudinal plane has been determined. The calculation was carried out for the case of a shunting collision of wagons or "jerk" (tank wagon). At the same time, the full use of the carrying capacity of the wagons is taken into account. It was found that the acceleration acting on the bearing structures of wagons with actual dimensions exceeding those obtained with the nominal ones: for a gondola wagon by 2.4 %, for a covered wagon – 1.7 %, for a flat wagon – 1 %, for a tank wagon – 2.7 %, for a hopper wagon – 2.7 %.

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