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DETERMINATION OF THE DYNAMIC LOAD OF THE CARRYING STRUCTURE OF THE HOPPER WAGON WITH THE ACTUAL DIMENSIONS OF STRUCTURAL ELEMENTS

The object of research is the supporting structure of the pellet wagon with the actual dimensions of the supporting elements. One of the most problematic areas is the determination of the indicators of dynamics and strength of the supporting structure of the hopper wagon with the actual dimensions of the structural elements.

A study of the dynamic loading of the supporting structure of the hopper wagon was carried out. At the same time, the actual dimensions of the structural elements were determined by means of field studies. Mathematical modeling of the dynamic loading of the load-carrying structure of a hopper wagon with the actual dimensions of structural elements was carried out by means of mathematical modeling. The studies were carried out in a flat coordinate system. The presence of three degrees of freedom of the supporting structure of the hopper wagon was taken into account: vibrations of twitching, bouncing and galloping. Differential equations were solved in the MathCad software package. In doing so, they were reduced to the Cauchy normal form, and then integrated using the Runge-Kutta method. It was found that the maximum value of the acceleration acting on the supporting structure of the hopper wagon is 38.5 m/s^2 , which is 2.7 % higher than the acceleration of the supporting structure with nominal dimensions.

Computer simulation of the dynamic loading of the supporting structure of the hopper wagon was carried out. The calculation was carried out using the finite element method in the SolidWorks Simulation (CosmosWorks) software package. It was found that the maximum accelerations are concentrated in the middle part of the supporting structure of the hopper wagon and amount to 36.2 m/s^2 . The F-criterion was used to verify the developed model. The calculations showed that the calculated value of the criterion is $F_c=1.09$ and is less than the table value $F_t=3.29$. The adequacy hypothesis is not rejected.

The natural frequencies and vibration modes of the hopper wagon supporting structure were determined. It has been established that the values of natural vibration frequencies of the hopper wagon bearing structure with the actual dimensions of the structural elements are within the permissible limits.

The research will contribute to the creation of relevant developments to extend the service life of wagons that have exhausted their standard resource, as well as to increase the efficiency of railway transport operation.

Keywords: hopper wagon, supporting structure, dynamic loading, service life, railway transport, transport mechanics.

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1. Introduction

Rail transport is the leading branch of the transport system. To maintain its leading position in the transportation services market, it is important to provide the transport industry with a serviceable rolling stock. Now the level of replenishment of the railway fleet is insignificant. Therefore, in order to ensure a timely transportation process and maintain the leadership position of the railway industry, it is relevant to study the possibility of extending the service life of wagons that have exhausted their standard service life. In this regard, it is important to create appropriate developments to determine the refined service life of wagons, taking into account its extension.

2. The object of research and its technological audit

The object of research is the supporting structure of the pellet wagon with the actual dimensions of the supporting elements. As a prototype, a hopper wagon model 20-9749 built by the Paniutyne wagon-repair plant branch of the Ukrzaliznytsia joint-stock company, Ukraine is considered (Fig. 1).

The wagon is designed for transportation of hot pellets and agglomerate with a temperature not exceeding $700 \text{ }^\circ\text{C}$, as well as bulk materials (crushed stone, sand, coal, expanded clay) that do not require protection from atmospheric precipitation. Unloading of such wagons is carried

out on both sides of the track through unloading bins. The wagon body is of an all-welded structure, consists of a frame and sheathed from smooth sheets. To exclude the accumulation of cargo on the planes of the side wall straps, a corner is installed on the upper strapping around the body perimeter, the lower side wall strapping is sheathed with an inclined sheet. To protect the cantilever parts of the frame and the equipment located on it, visors are installed on the wagon body (as on metering wagons). The end valves of the unloading system are installed symmetrically to the brake valves on the left side of the coupler. The unloading hatches are opened and closed using a special mechanism, which is driven by a pneumatic cylinder with remote control.



Fig. 1. Hopper wagon for transportation of pellets:
a – end view; b – side view

The provision of the transportation process of goods by rail requires its provision with serviceable rolling stock. The lack of rolling stock predetermines the need to study the possibility of extending the service life of the existing load-bearing structures of wagons. This is especially true for wagons that can be used for bulk and bulk cargo. Therefore, it is important to study the possibility of extending the service life of wagons that have exhausted their standard resource.

3. The aim and objectives of research

The aim of research is to determine the dynamic loading of the supporting structure of a hopper wagon with the actual dimensions of structural elements. To achieve this aim, the following objectives have been identified:

1. Determine the actual dimensions of the structural elements of the supporting structure of the hopper wagon.
2. Conduct mathematical and computer modeling of the dynamic loading of the load-carrying structure of a hopper wagon, as well as verify the developed models.
3. Determine the natural frequencies and modes of vibrations of the supporting structure of the hopper wagon.

4. Research of existing solutions of the problem

The specifics of determining the assessment of reliability indicators of load-bearing structures of freight wagons with a residual resource are highlighted in [1]. An algorithm for determining the limiting service life of a wagon is presented.

Justification of measures to extend the service life of freight wagons was carried out in [2]. A scheme for technical diagnostics of freight wagons has been developed. The conclusion is made about the possibility of extending the service life of freight wagons by performing high-quality technical diagnostics. However, these studies are not of an applied nature.

Extension of the service life of the supporting structures of gondola wagons that have exhausted their standard resource are given in [3]. Mathematical modeling of the dynamic loading of the wagon supporting structure with the actual dimensions is carried out. The simulation results are taken into account when determining the strength indicators.

The work [4], devoted to the creation of a methodology for the calculation and experimental substantiation of the extension of the service life of gondola wagons, is of interest. The proposed method takes into account statistical data on the technical condition of the supporting structures of the wagons and allows, based on the reliability indicators, to assign a new service life of the wagon. However, the issue of extending the service life of hopper wagons for transporting pellets was not investigated in the authors' works.

The need to adjust the Regulation on the extension of the service life of freight wagons plying in the message is considered in [5]. The expediency of introducing requirements for rolling stock, the service life of which is increasing, has been substantiated.

The features of extending the service life of wagons for transporting pellets that have exhausted their normative resource are highlighted in [6]. The results of the experimental determination of the strength indicators of the load-bearing structures of the wagons are presented. However, at the same time, the authors did not carry out modeling of the dynamic loading of the supporting structures of wagons, taking into account the actual values of the dimensions of the structural elements.

The prediction of the residual life of the hopper-batcher wagon after long-term operation, taking into account the actual physical and mechanical characteristics of the material of the supporting structures, is carried out in [7]. The results of virtual and experimental studies of the strength of the wagon supporting structure are presented. However, the authors limited themselves to the standard values of dynamic loads acting on the supporting structure of the wagon in operation.

The work [8] presents the results of determining the stresses in tank containers located on railway platform wagons. In this case, the authors do not describe the actual state of the investigated wagon.

In works [9, 10], the features of carrying out and the results of studies of the stress-strain states of wagons with containers during their transportation by sea ferry are given. But such studies did not include an analysis of their actual condition.

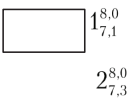
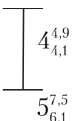






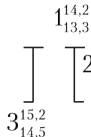
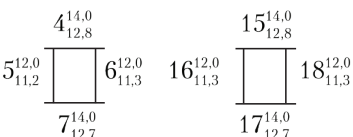
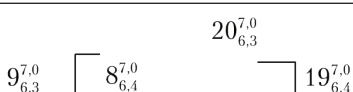
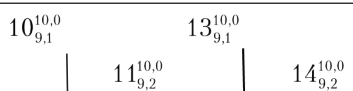

Thus, the results of the analysis allow to conclude that the issues of determining the dynamic loading of the supporting structure of a hopper wagon with the actual dimensions of structural elements are important for solving, but they have not been given sufficient attention.

5. Methods of research

To determine the dynamic loading of the bearing structure of the hopper wagon with the actual dimensions of the constituent elements, mathematical modeling is carried out.

The actual dimensions of the elements of the supporting structure of the hopper wagon are determined on the basis of field studies and are given in Table 1. 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.

Table 1
Actual dimensions of the elements of the supporting structure of the hopper wagon

Structural element name	Dimension, mm
Body	
Lower strapping	
Rack	
Side wall intermediate brace	
Side wall brace	
Top strapping	
Struts	
End wall belt (1 and 2 on top)	
End wall belt (3 and 4 on top)	
Frame	
Central beam	
Pivot beam	
End beam	
Cross beam	
Half log	

It was found that the mass of the bearing structure of the hopper wagon, taking into account the greatest value of the demolition of elements recorded during field studies, is less by 9.3 % in comparison with the bearing structure of the hopper wagon, which has nominal dimensions.

In order to determine the dynamic loads acting on the bearing structures of the wagons with the actual dimensions under the action of the longitudinal force (shunting collision), the mathematical model given in [8] was used. The design diagram of the wagon is shown in Fig. 2.

$$\left(M_W + 2 \cdot m_W + \frac{n \cdot I_{WS}}{r^2} \right) \cdot \ddot{x}_W + (M_W \cdot h) \cdot \ddot{\varphi}_W = S_a, \quad (1)$$

$$I_W \cdot \ddot{\varphi}_W + M' \cdot \ddot{x}_W - g \cdot \varphi_W \cdot M' = l \cdot F_{FR} (\text{sign } \dot{\Delta}_1 - \text{sign } \dot{\Delta}_2) + l (k_1 \cdot \Delta_1 - k_2 \cdot \Delta_2), \quad (2)$$

$$M_W \cdot \ddot{z}_W = k_1 \cdot \Delta_1 + k_2 \cdot \Delta_2 - F_{FR} (\text{sign } \dot{\Delta}_1 - \text{sign } \dot{\Delta}_2), \quad (3)$$

where

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

M_W – mass of the supporting 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} – inertia moment of the wheelset; r – radius of the mid-worn wheel; n – the 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 – 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 the vertical movement of the wagon.

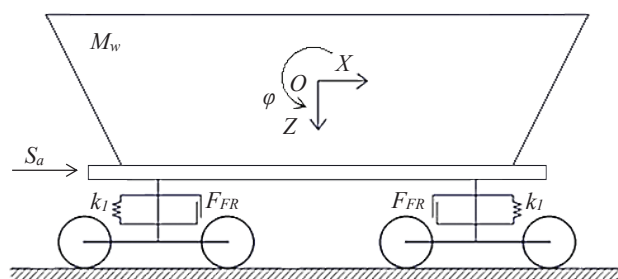


Fig. 2. Design scheme of a hopper wagon

Differential equations are solved in the MathCad software package. Moreover, they were reduced to the Cauchy normal form, and then integrated using the Runge-Kutta method [11, 12].

Initial displacements and speeds caused by being equal to zero. The input parameters of the mathematical model are the technical characteristics of the supporting 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.

6. Research results

6.1. Results of mathematical modeling. When determining the dynamic loading of the supporting structure of the hopper wagon, it was taken into account that the parameters of spring suspension are equal to those characteristic of typical freight bogies of model 18-100. The longitudinal impact force acting on the vertical surface

of the rear stop of the automatic coupler is taken equal to 3.5 MN [13, 14].

Based on the calculations performed, the acceleration acting on the supporting structure of the hopper wagon was obtained (Fig. 3). The maximum acceleration value was 38.5 m/s².

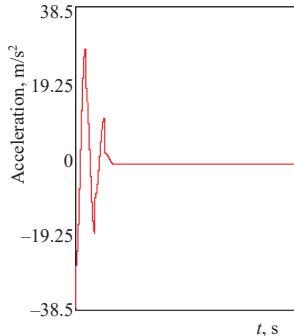


Fig. 3. Acceleration acting on the supporting structure of the hopper wagon

Consequently, the acceleration that acts on the supporting structure of the hopper wagon with actual dimensions exceeds those obtained at nominal by 2.7 %.

6.2. Computer simulation results. To determine the fields of distribution of accelerations relative to the supporting structure of the hopper wagon, a computer simulation of its dynamic loading was carried out. The calculation was carried out in the SolidWorks Simulation (CosmosWorks) software package. Graphic work was carried out in the SolidWorks software [9, 10, 15]. For this, a spatial model of the supporting structure of the hopper wagon was created with an album of drawings (Fig. 4).

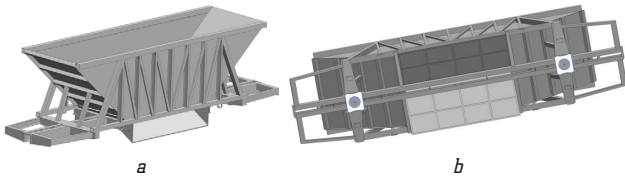


Fig. 4. Spatial model of the supporting structure of a hopper wagon: a – side view; b – bottom view

When compiling a finite element model, isoparametric tetrahedrons are used (Fig. 5). The optimal number of elements of the model is determined by the graphical-analytical method [16–18]. The number of grid elements is 374,143, nodes – 125,817, the maximum aspect ratio – 432.78, the percentage of elements with an aspect ratio of less than 3 – 7.71, more than ten – 32.9.

When drawing up the design diagram of the supporting structure of the hopper wagon, it is taken into account that the vertical static load P_w^{st} , the expansion forces of the bulk cargo P_e , as well as the shock load P_{sh} on the rear stop of the coupler act on it.

The fixing of the model is carried out in the areas of bearing of the supporting structure on the chassis. Construction material – 09G2S steel. The calculation results are shown in Fig. 6.

The maximum accelerations are concentrated in the middle part of the supporting structure of the hopper wagon and amounted to 36.2 m/s².

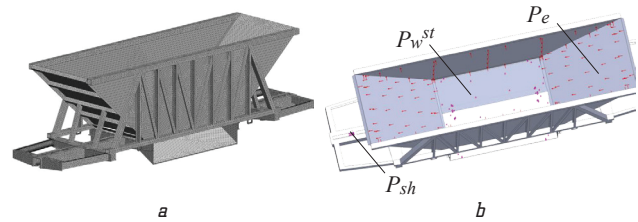


Fig. 5. Calculation of the strength of the supporting structure of the hopper wagon: a – finite element model; b – design scheme

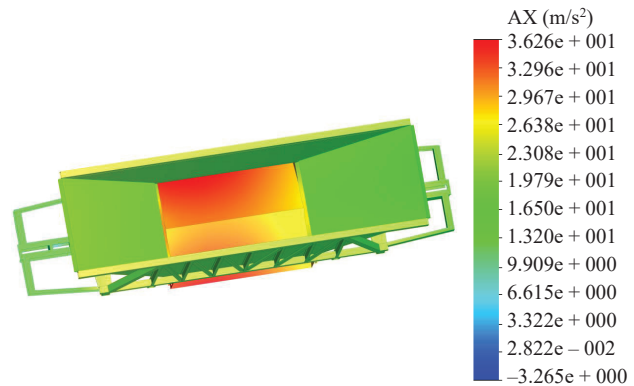


Fig. 6. Acceleration acting on the supporting structure of the hopper wagon

6.3. Verification of the developed models. The F-criterion is used to verify the developed model [19, 20]. The force of impact into the coupler is taken as a variation parameter.

The calculation results are shown in Fig. 7.

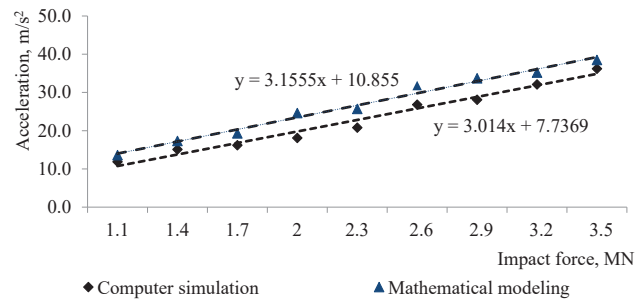


Fig. 7. Results of modeling the dynamic loading of the supporting structure of the hopper wagon

The calculations show that the calculated value of the criterion is $F_c=1.09$, which is less than the tabular value $F_t=3.29$. So, the hypothesis of adequacy is not rejected.

According to the design scheme shown in Fig. 5, b, the natural modes of vibrations of the bearing structure of the hopper wagon were also determined. Some of them are shown in Fig. 8.

The value of the natural frequencies of vibrations of the supporting structure of the hopper wagon is given in Table 2.

From the Table 2 it is seen that the values of the natural frequencies of vibrations are within the permissible limits [13, 14].

The results obtained will be taken into account when justifying the extension of the service life of the supporting structure of the hopper wagon, which has exhausted its standard resource.

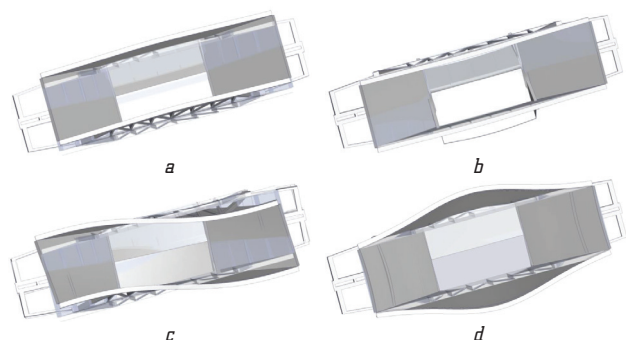


Fig. 8. Forms of vibrations of the supporting structure of the hopper wagon (deformation scale 30:1): *a* – the first form; *b* – the second form; *c* – the third form; *d* – the fourth form

Table 2

The value of the natural frequencies of vibrations of the supporting structure of the hopper wagon

Forms of vibrations	Frequency, Hz	Forms of vibrations	Frequency, Hz
1	10.8	6	35.9
2	24.5	7	42.4
3	25.5	8	43.1
4	30.5	9	50.9
5	34.2	10	54.4

7. SWOT analysis of research results

Strengths. As a result of the research, the actual dimensions of the constituent elements of the supporting structure of the hopper wagon were determined. At the same time, when determining the fields of distribution of accelerations relative to the supporting structure of the hopper wagon, a computer simulation of its dynamic loading was carried out. The calculation was carried out in the SolidWorks Simulation (CosmosWorks) software package. The use of the results will allow specialists involved in the operation, testing and research of the supporting structure of a hopper wagon to more accurately predict their actual technical condition. This, in turn, will reduce the costs of its maintenance and operation.

Weaknesses. For further research and development work in the direction indicated in the study, it is mandatory to carry out field experimental studies. And the determination of the strength of the bearing structural elements of the hopper wagon using modern methods of full-scale tests.

Opportunities. Among the additional possibilities of using the results obtained, one can single out the feasibility of their application even in design procedures. That is, the use of the results obtained will allow the designer of new wagons to see the strengths and weaknesses of the structure that will arise after long-term operation.

The freight wagon is a structure of heavy transport engineering. Therefore, the results obtained will be useful for studying by specialists in various areas of transport engineering.

Threats. This level of research does not require additional costs when implementing the results.

8. Conclusions

1. The actual dimensions of the structural elements of the supporting structure of the hopper wagon have been determined. The studies were carried out in relation to a hopper wagon model 20-9749 built by the Paniutyne wagon-repair plant branch of the Ukrzaliznytsya joint-stock company, Ukraine. It was found that the mass of the bearing structure of the hopper wagon, taking into account the greatest value of the demolition of elements recorded during field studies, is less by 9.3 % in comparison with the bearing structure of the hopper wagon, which has nominal dimensions.

2. Mathematical modeling and computer simulation of the dynamic loading of the bearing structure of the hopper wagon was carried out, as well as the verification of the developed models. The results of mathematical modeling showed that the maximum acceleration was 38.5 m/s².

To determine the fields of distribution of accelerations relative to the supporting structure of the hopper wagon, a computer simulation of its dynamic loading was carried out. The calculation was carried out in the SolidWorks Simulation (CosmosWorks) software package. In this case, the maximum accelerations are concentrated in the middle part of the supporting structure of the hopper wagon and amounted to 36.2 m/s².

The F-criterion was used to verify the developed model. The calculations showed that the calculated value of the criterion is $F_c=1.09$ and is less than the tabular value $F_t=3.29$. So, the hypothesis of adequacy is not rejected.

3. The natural frequencies and modes of vibration of the bearing structure of the hopper wagon were determined. The results of the studies have shown that the values of the natural vibration frequencies of the bearing structure of the hopper wagon with the actual dimensions of the structural elements are within acceptable limits. In this case, the value of the first natural vibration frequency is 10.8 Hz.

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