Determination of the strength of the flat wagon fitting stops by elastic viscous interaction with fittings of the tank container

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Abstract. The article highlights the peculiarities of determining the strength of the flat wagon fitting stops, taking into account the viscous and elastic-viscous interaction with the fittings of the tank container. Mathematical modelling was performed to determine the dynamic load of the flat wagon with tank containers in the case of shunting collision taking into account elastic, viscous and elastic-viscous interaction between fittings and fitting stops. It is established that the elastic interaction does not compensate for the dynamic loads acting on the flat wagon in the case of shunting collision. Accelerations acting on the flat wagon with the tank containers do not exceed the normative values taking into account movement of the fittings relative to the fitting stops by viscous and elastic-viscous interaction. It was established that the strength of the bearing structure of the flat wagon and fitting stops is provided by viscous or elastic-viscous connections between fittings and fitting stops, taking into account the possible movements of tank containers in relation to the frame. The conducted researches will provide efficiency increase of combined transportations and develop recommendations for designing modern constructions of railway rolling stock.

1. Introduction
The geographical location of Ukraine at the junction of transport corridors between Europe and Asia ensures its participation in international transportation. In accordance with the National Transport Strategy of Ukraine until 2030 (from May 30, 2018 No. 430-p), it is necessary to put into operation highly efficient interoperable rolling stock with improved technical, economic, operational and environmental characteristics in order to increase the efficiency of the transport process in international traffic.

The most common type of rolling stock for interoperable transportation is flat wagons. It is important to note that their versatility causes different load of bearing structure in operation depending on the type of cargo [1-3].
The regulatory framework, according to which the flat wagons are constructed, does not fully reflect the load characteristics of bearing structures during interoperable transportation. This necessitates its refinement and addition for designing highly efficient rolling stock.

The issue of designing a railway rolling stock for transportation of heavy loads is considered in [4]. The study of dynamics and strength was conducted using modern software environments such as ProMechanica and CosmosWorks. During designing the bearing structure of a carrier, the study was conducted on the possibility of its constructing from various types of materials.

Peculiarities of the development of high-speed articulated flat wagon for the transportation of containers are given in [5]. The technical solutions adopted in the design of the flat wagon allow simultaneous transportation of two 40- or 45-foot or four 20-foot containers.

Measures to reduce the dynamic load of railway rolling stock under the most adverse operating conditions are not highlighted in these works.

Study of dynamics of a flat wagon using multibody methods is given in [6]. The calculation was made in the MSC Adams software environment for the flat wagon with rotating middle section. The equations of the movement of the flat wagon were formulated in absolute coordinates using the Lagrange method of the first kind.

The study of the strength of a flat wagon with static and dynamic load of its construction is given in [7]. In this case the experimental methods were used, namely electrical strain gauge measurement.

In this case, attention to the study of the dynamic load of flat wagons by shunting collision was not paid in these works.

Peculiarities and results of the cataloguing of bearing systems of freight wagons and the requirements that they must meet at the present stage of development of the railroad industry are given in [8]. However, the requirements for the dynamic load of wagons by shunting collision are not highlighted in this paper.

Strength of the frame of the flat wagon, taking into account a road semi-trailer placed on it, is modelled in [9]. The paper proposes an analytical model that allows obtaining the specified values of stress in the bearing structure of the flat wagon.

Attention to the research of the dynamics of the flat wagon at operating load conditions is not paid in this paper.

Dynamic load of the bearing structure of a wagon during combined transportation is determined in [10, 11]. The mathematical models which allow obtaining accelerations acting on the bearing structure of a wagon during movements of the railroad ferry were presented. The results of mathematical modelling were verified by computer modelling.

The results of computer modelling of the bearing structure dynamics of the wagon body during transportation by railroad ferry in conditions of sea disturbance are given in [12]. The research was conducted in the CosmosWorks software environment using the finite element method.

The issue of determining the strength of bearing structures of wagons in is not considered in these works.

Obtaining samples of high density and analysis of mechanical strength characteristics of ZrO$_2$-WC nanopowders composite is considered in [13]. However, the peculiarities of the application of this material in bearing structures of the railway rolling stock are not highlighted in this paper.

Spatial movements of the “subframe – track” system is modelled in [14]. The calculation is based on the finite element method implemented in the Ansys software environment.

Peculiarities of the mathematical modelling of the flat wagon dynamics are not considered in the work.

The purpose of the article is to determine the strength of the fitting stops of the flat wagon with elastic-viscous interaction with the fittings of the tank container. In order to achieve this aim the following tasks are defined:

1. To determine the dynamic load of the flat wagon with elastic-viscous interaction with the tank container fittings;
2. To develop a model of the strength of a flat wagon with elastic, viscous and elastic-viscous connections between fitting stops and fittings of tank containers by shunting collision;
3 Determine the strengths of the flat wagon with elastic, viscous and elastic-viscous connections between the fitting stops and fittings of tank containers by shunting collision.

2. Determination of dynamic load of the flat wagon by elastic-viscous interaction with the fittings of the tank container

It was proposed to install elastic, viscous and also elastic-viscous elements into the fitting of the tank container to reduce the dynamic load of the flat wagon in the most unfavourable operating mode – shunting collision.

Mathematical simulation of the dynamic load was performed in order to determine the accelerations acting on the flat wagon taking into account the proposed scheme of interaction of fitting stops and fittings.

The case of elastic interaction between the fitting stops of the flat wagon and the fittings of the tank container was considered at the initial stage of the study.

It is established that the elastic interaction between fittings and fitting stops in this calculation scheme does not fully compensate for the dynamic load of the flat wagon, as it exceeds the normative value of acceleration in accordance with [15-18] by 20%.

The second stage of the study considered the presence of viscous interaction between fittings and fitting stops. The mathematical model of dynamic load of the flat wagon thus has the form:

\[
\begin{align*}
M'_{\text{wag}} \cdot \ddot{q}_i &= P_i - \sum_{i=1}^{n} (F_{r\text{g}} \cdot \text{sign}(\dot{q}_i - \dot{q}_j) + \beta_i (\ddot{q}_i - \ddot{q}_j)), \\
M'_{c} \cdot \ddot{q}_2 &= \sum_{i=1}^{n} (F_{r\text{g}} \cdot \text{sign}(\dot{q}_i - \dot{q}_j) + \beta_i (\ddot{q}_i - \ddot{q}_j) + M_w \cdot I \cdot q_j), \\
I_w \cdot \ddot{q}_3 &= M_w \cdot I \cdot \ddot{q}_3 - g \cdot M_w \cdot I \cdot q_3,
\end{align*}
\]

where \(M'_{\text{wag}}\) – gross weight of the flat wagon; \(P_i\) – magnitude of the longitudinal force acting on the automatic coupler; \(F_{r\text{g}}\) – friction force between fitting stops and fittings; \(M_c\) – weight of the tank container; \(\beta_i\) – coefficient of viscous resistance in the fittings of the tank container; \(M_w\) – weight of the pendulum that simulates the movement of liquid bulk cargo in the tank container; \(I_w\) – moment of inertia of the pendulum; \(q_1, q_2, q_3\) – coordinates determining the movement, respectively, of the flat wagon, tank container and liquid bulk cargo relative to the longitudinal axis.

Accelerations acting on the flat wagon are 40 m/s² (≈ 4g) by viscous resistance to movement of the tank container and do not exceed the normative values [15-18].

The next stage of the study examined the existence of a elastic-viscous interaction between fittings and fitting stops. Then the mathematical model of dynamic load of the flat wagon has the form:

\[
\begin{align*}
M'_{\text{wag}} \cdot \ddot{q}_i &= P_i - \sum_{i=1}^{n} (F_{r\text{g}} \cdot \text{sign}(\dot{q}_i - \dot{q}_j) + c_i (q_i - q_j) + \beta_i (\ddot{q}_i - \ddot{q}_j)), \\
M'_{c} \cdot \ddot{q}_2 &= \sum_{i=1}^{n} (F_{r\text{g}} \cdot \text{sign}(\dot{q}_i - \dot{q}_j) + c_i (q_i - q_j) + \beta_i (\ddot{q}_i - \ddot{q}_j) + M_w \cdot I \cdot q_j), \\
I_w \cdot \ddot{q}_3 &= M_w \cdot I \cdot \ddot{q}_3 - g \cdot M_w \cdot I \cdot q_3,
\end{align*}
\]

where \(c_i\) – rigidity of the elastic elements in the fittings of the tank container.

The accelerations acting on the flat wagon thus amounted to 38 m/s² (≈ 4g), therefore, do not exceed the permissible values [15-18].

The obtained values of accelerations were taken into account in the study of the strength of the fitting stops of the flat wagon.
3. Determination of strength indexes of the flat wagon fitting stops with elastic-viscous interaction with the fittings of the container

Finite element calculation was performed in the CosmosWorks software environment for the study of the strength of the flat wagon with viscous and elastic-viscous connections between fitting stops and fittings of tank containers by shunting collision [19, 20].

The analytical model of the bearing structure of the flat wagon is shown in figure 1. It was taken into account that $P_l$ impact load acts on the bearing structure of the flat wagon, and $P_v$ vertical load from tank containers acts on the fitting stops, as well as $P_g$ horizontal load, that is due to the movement of the fittings relative to the fitting stops.

![Analytical model of the bearing structure of the flat wagon](image)

**Figure 1.** Analytical model of the bearing structure of the flat wagon.

Spatial isoparametric tetrahedra were used as finite elements. Optimal number of elements of the continuum model is determined by semigraphical method. The number of units of the lath was 311601, elements – 932166. Maximum dimension of the element was 80 mm, the minimum – 16 mm. The minimum number of elements in the circle was 9, the ratio of increase in the size of elements in the lath – 1.7. The maximum ratio of the sides was 470.8, the percentage of elements with side ratios of less than 3 – 41.5, more than 10 – 8.17. Material of the construction – steel of grade 09G2C. The fastening of the model was in the areas of supporting of the bearing structure on the running gear. The calculation results are shown in figure 2.

![Stressed state of the bearing structure of the flat wagon](image)

**Figure 2.** The stressed state of the bearing structure of the flat wagon by the viscous interaction of fittings with fitting stops (side view).
It was established that maximum equivalent stresses are about 270 MPa by viscous interaction of fittings with fitting stops by shunting collision of the flat wagon and they are concentrated in the area of interaction of the longitudinal tie rod with the draw bar.

That is, the maximum equivalent stresses in the bearing structure of the flat wagon are within acceptable limits [15-18].

Distribution of equivalent stresses along the longitudinal tie rod of the flat wagon is shown in figure 3. In this case, the maximum stresses arise in the console part of the frame from the side of the impact load. Minimal stresses can be observed in the middle part of the frame.

The distribution of movements in the units along the main sole bar of the frame is shown in figure 4.

![Figure 3](image1.png)  
Figure 3. Distribution of equivalent stresses along the longitudinal tie rod of the flat wagon.

![Figure 4](image2.png)  
Figure 4. Distribution of movements in the units along the main sole bar of the frame.

The minimum values of movement are observed in the console parts and the maximum values – in the middle part of the main sole bar of the frame. Maximum movements arise in the middle parts of the main sole bars of the frame of the flat wagon and reach 12.1 mm (figure 5).

![Figure 5](image3.png)  
Figure 5. Movements in the units of the bearing structure of the flat wagon by viscous interaction of fittings with fitting stops.
The calculation was made to determine the strength of the welding joint in the area of interaction of fitting stops with the frame of the flat wagon. In this case, the condition of strength has the form [21, 22]:

\[
\sigma_c = \frac{3 \cdot M}{(\beta \cdot h_c) \cdot l_s} + \frac{N}{F} \leq R_s^{pr},
\]

where \(M\) – bending moment acting at the intersection of the joint; \(\beta \cdot h_c\) – calculated seam thickness; \(\beta\) – coefficient of joint depth; \(l_s\) – calculated joint length; \(N\) – the calculated force acting on the connection; \(F\) – connection area; \(R_s^{pr}\) – calculated joint strength.

It was established that the strength of the welding joint was ensured taking into account the calculations. The proposed solutions for improving the scheme of interaction of the flat wagon with tank containers allow reducing the maximum equivalent stresses that act in the fittings stops to almost a third (figure 6), and in the tank container fittings – to almost a seventh.

![Figure 6](image)

**Figure 6.** The stressed state of the fitting stops of the flat wagon: a - a typical scheme of interaction; b - an improved scheme of interaction.

In addition, the maximum equivalent stresses are reduced in the main bearing elements of the frame of the flat wagon in the new scheme of interaction of fitting stops with fittings (figure 7).

![Figure 7](image)

**Figure 7.** Percentage of stress reduction in the main bearing elements of the frame of the flat wagon.

Consequently, the load of the main bearing elements of the flat wagon frame can be reduced by 20% taking into account the proposed technical solutions.
4. Conclusions
1 The dynamic load of the flat wagon by elastic-viscous interaction with the fittings of the tank container was determined. It is established that the elastic interaction between the fitting stops and the fittings does not fully compensate for dynamic load of the tank container during the operational modes. Accelerations acting on the tank container do not exceed the permissible values by viscous and elastic-viscous interaction;
2 The model of the strength of the flat wagon with viscous and elastic-viscous connections between the fitting stops and tank containers fittings has been developed. The model takes into account the effect of the longitudinal loading on the vertical surface of the rear stop by shunting collision;
3 Strength of the flat wagon with viscous and elastic-viscous connections between fitting stops and fittings of tank containers by shunting collision has been determined. It was established that the maximum equivalent stresses are about 270 MPa and are concentrated in the bearing structure of the flat wagon. That is, the maximum equivalent stresses in the bearing structure of the flat wagon are within the permissible limits. Maximum movements arise in the middle parts of the main sole bar of the frame of the flat wagon and are 12.1 mm.

The maximum equivalent stresses in the bearing structure of the flat wagon by elastic-viscous interaction of fittings with fitting stops are about 260 MPa. Maximum movements are 11.8 mm.

The conducted research will promote increase of operation efficiency of combined transportations and developing recommendations for modern constructions of rolling stock.

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