Peculiarities of determining the bearing structure load of the body of articulated open wagon made of round pipes

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Abstract. The article highlights the peculiarities of creating a wagon of articulated type, the supporting elements of which are made of round pipes. To determine the dynamic load of an open wagon, a mathematical model has been developed, which includes the movement of the open wagon body during the action of longitudinal force on the automatic coupler. The mathematical model solution has been implemented using the Runge-Kutta method in the MathCad software. Accelerations obtained as a component of dynamic load have been taken into account when calculating the strength of the bearing structure of the wagon body. The strength analysis has been carried out using the finite element method implemented in the CosmosWorks software. The results of the calculations showed that the maximum equivalent stresses are within the permissible ones. The strength margin of main elements of the wagon bearing structure and the critical oscillation frequencies are determined. The conducted research will help to develop recommendations on the design of articulated open wagons and increase their operation efficiency.

1. Introduction
The prospects for the development of the transport industry at the present stage challenge rail transport as its foremost component. In this regard, there is a need to provide the transport industry with modern rolling stock. Careful attention should be paid to bearing structures when designing such rolling stock, since their payload capacity (load capacity), as one of the most important technical and economic indicators of rolling stock, depends on their peculiarities. One of the ways to solve the problem of increasing the load capacity of rolling stock is to create wagons of articulated type. This is due to their significant advantages over other types of wagons: reducing the cost for manufacturing, reducing the vertical load of frames, reducing the required fleet of wagons, as well as the cost of their lifecycle, etc.

It is known that the most popular type of freight rolling stock is multi-purpose wagons. Therefore, the creation of articulated open wagons will significantly increase the efficiency of rolling stock operation, as well as ensure the maintenance of the leading position of railway transportations in the market of transport services.
Determination of the strength of the bearing structure of the open wagon under operational load conditions is carried out in [1]. The calculation was made using the finite element method. Normative values of loads have been taken into account when developing the strength model.

Structural and elemental analysis of the freight wagon is carried out in [2]. The calculation was made using finite element method. As a prototype wagon was used a “BOXN25” type wagon.

However, the study of the dynamic load of the wagon was not carried out in the work.

The peculiarities of determining the load of an articulated wagon on mathematical models are highlighted in [3]. The estimation of own forms of oscillations and stability of undisturbed motion of the wagon has been made.

Improvements in the technical characteristics of the sectional flat wagon by developing its design are given in [4]. The paper presents mathematical models that allow determining the dynamic and strength characteristics of the articulated flat wagon. The obtained theoretical calculations were confirmed by experimental studies of the strength of the flat wagon.

However, no attention is paid to determining the dynamic load of other types of articulated wagons in these works.

Determination of the dynamics and strength of the wagon body, the bearing elements of which are made of round pipes in the most unfavourable operating modes is carried out in [5]. However, the study of the load of the articulated wagon was not considered in the work.

Measures to increase the strength of the elements of the bearing structure of the wagon were considered in [6]. In particular, to eliminate deformation of the elements of wagons bearing structures, it is proposed to use the method of thermal lining.

These studies have been conducted in relation to four axle wagons. That is, it is not paid attention to the study of the strength of articulated open wagons in these works.

Fatigue strength of the body bearing structure of the C80V model wagon constructed in the PRC was calculated in [7, 8]. This method is used to predict the fatigue strength of the body based on hybrid dynamics modelling and finite element analysis.

However, the aim of research the fatigue strength of the articulated open wagon is not set in these works.

Strength of the Zans body wagon is calculated in [9]. Theoretical calculations were performed using the finite element method. Complex three-dimensional analytical models have been developed that accurately describe body geometry.

Peculiarities of determining the strength of the wagon are covered in [10]. The causes of cracks in the construction elements of the wagon were revealed. Measures to improve the construction elements of the wagon are proposed.

However, these works do not pay attention to the issues of determining the strength of the articulated open wagons.

The analysis of the results of scientific publications and research suggests that due attention is not paid to the dynamic load and strength of the articulated open wagons.

The aim of the article is to highlight the peculiarities of determining the load on the bearing structure of the body of articulated open wagon made of round pipes. In order to achieve this aim, the following objectives have been defined:
- to create a bearing structure of articulated open wagon made of round pipes;
- determine the dynamic load of the articulated open wagon body made of round pipes;
- determine the strength of the body of the articulated open wagon made of round pipes.

2. The create a bearing structure of articulated open wagon made of round pipes
The construction of the articulated open wagon 12-6877 (12-6877-02) type constructed in Research and production corporation “United wagon company” is well-known (figure 1) [11].

The peculiarity of the wagon is that it has an increased load capacity – 117 t, that is, 47 t higher than the prototype wagon. The formation of trains using this type of rolling stock allows increasing tonnage rating to 8900 tons, i.e. 32% higher than that of the prototype wagon.
The disadvantage of this articulated wagon is that the main bearing elements of the body are made of typical for rail car manufacturing structural iron of the corresponding sections, which leads to an increased cost of production and operation of the railway wagon due to the increased dead load, and consequently reduced load capacity.

It is suggested to create resource efficient construction of an open wagon in order to increase the efficiency of the transportation process. A feature of the design is that the supporting elements of the body are made of pipes of circular cross-section. The optimal parameters of the pipes are selected based on the strength reserve of the elements of the typical bearing structure of the open wagon body selected as a prototype (the wagon of 12-757 model constructed by public joint-stock company Kriukiv Railway Car Manufacturing Plant). The developed construction of the articulated open wagon is shown in figure 2.

The proposed solution made it possible to reduce the dead load of each section by almost 10% compared to the prototype wagon.

At the same time, the draw bar was replaced with a beam of round section from the side of sections support of the wagon on the middle bogie (figure 3).
3. Determine the dynamic load of the articulated open wagon body made of round pipes

Mathematical modelling was performed to determine the dynamic load on the bearing structure of the body of the articulated open wagon. One of the most unfavourable modes of loading – “surge-stretching” – has been taken into account. Dynamic loading was determined in the plane coordinates. It is assumed that each section of the open wagon body has three degrees of freedom by action of longitudinal force on its bearing structure: oscillations of jerking, jumping and pitching [12-14]. The calculation scheme is shown in figure 4.

\[
M_{c1} \cdot \ddot{x}_{c1} + M_{c1} \cdot h \cdot \ddot{\phi}_{c1} + k'(x_{c1} - x_{c2}) = P_x, \\
I_{c1} \cdot \ddot{\phi}_{c1} + M_{c1} \cdot h \cdot \ddot{x}_{c1} - g \cdot \phi_{c1} \cdot M_{c1} \cdot h = l \cdot F_{jr} \left( \text{sign} \Delta^c - \text{sign} \Delta^c \right) + l \left( k_i \cdot \Delta^c - k_i \cdot \Delta^c \right), \\
M_{c1} \cdot \ddot{\Delta}_{c1} = k_i \cdot \Delta^c + k_i \cdot \Delta^c - F_{jr} \left( \text{sign} \Delta^c - \text{sign} \Delta^c \right), \\
M_{c2} \cdot \ddot{x}_{c2} + M_{c2} \cdot h \cdot \ddot{\phi}_{c2} - k'(x_{c1} - x_{c2}) = 0, \\
I_{c2} \cdot \ddot{\phi}_{c2} + M_{c2} \cdot h \cdot \ddot{x}_{c2} - g \cdot \phi_{c2} \cdot M_{c2} \cdot h = l \cdot F_{jr} \left( \text{sign} \Delta^c - \text{sign} \Delta^c \right) + l \left( k_i \cdot \Delta^c - k_i \cdot \Delta^c \right), \\
M_{c2} \cdot \ddot{\Delta}_{c2} = k_i \cdot \Delta^c + k_i \cdot \Delta^c - F_{jr} \left( \text{sign} \Delta^c - \text{sign} \Delta^c \right),
\]

here \( \Delta_i = z_{ci} - l \cdot \phi_{ci} \); \( \Delta_i' = z_{ci} + l \cdot \phi_{ci} \),

where \( M_{c1}' \) – gross weight of the i-th section; \( M_{c1} \) – weight of the bearing structure of the i-th section; \( I_{c1} \) – moment of inertia of the i-th section; \( P_x \) – magnitude of the longitudinal force acting on the
automatic coupler; $F_{nx}$ – absolute value of dry friction force of in the coil spring group; $k'$ – rigidity of connection between sections; $k_1, k_2$ – rigidity of springs of coil spring groups of bogies; $x, \varphi, z$ – coordinates determining the movement of sections relative to the corresponding axes.

In this case, the articulation was modelled by rigid connection. The magnitude of the longitudinal force acting on the bearing structure of the wagon is assumed to be 2.5 MN [15-18]. It is considered that the 18-100 model bogies are used as trucks. Gross weight of the wagon should not exceed 1383.21 kN as the wheel pairs have an axial load of 23.5 t/axle (230.535 kN/axle). Or it is possible to use trucks with increased axial loads. The solution of differential equations (1-6) was carried out in the software environment MathCad [19-21].

The calculation was performed using the Runge-Kutta method. The initial velocities and movements are assumed to be zero.

It has been established based on the calculations, that the maximum value of acceleration acting on the first side of the load section is about $31 \text{ m/s}^2$, and the second – $32 \text{ m/s}^2$.

4. Determine the strength of the body of the articulated open wagon made of round pipes

Obtained accelerations were taken into account in determining the strength indexes of the bearing structure of the articulated open wagon. The calculation was performed using the finite element method implemented in the CosmosWorks software environment [22, 23].

It has been taken into account when developing the calculation model that the longitudinal load $P_n$ applied to the front stops of the section acts on the bearing structure of the open wagon body. Also, the body is subjected to a vertical-static load $R_v$ due to the gross weight of the wagon. Dry bulk cargo side thrust acting on the side and end walls, were determined according to the procedure given in [24]. Coal was accepted as dry bulk cargo. The analytical model of the bearing structure of the articulated open wagon is shown in figure 5.

![Figure 5. Analytical model of the bearing structure of the articulated open wagon.](image)

Isoparametric tetrahedra were used to construct the continuous model. The optimal number of model elements was determined by the semigraphical method. The number of model units was 437921, the elements – 1368810. The maximum element size was 85 mm and the minimum element size was 17 mm. The percentage of elements with aspect ratio less than three is 30.6, more than ten is 11.4. The minimum number of elements in a circle was 15, the ratio of increasing the size of the elements – 1.9.

The fixing of the model was in the areas of support of the body bearing structure on the trucks. The articulation unit was modelled by a body with equivalent rigidity to the typical structure.

The results of the calculation are shown in figures 6, 7. In this case, the maximum equivalent stresses occur in the area of interaction between the draw bar and the back frame and are about 300 MPa, i.e. do not exceed the allowable [15-18]. The maximum movements in the units of the structure occur in the middle part of the back frame of sections – 3.6 mm. The maximum deformations were $1,6 \cdot 10^3$. 

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The developed wagon construction is designed for fatigue in the CosmosWorks software environment. The test base was $10^7$ cycles. The results of the calculation are shown in figure 8. At the same time, the minimum strength margin is fixed in the area of interaction of the back frame with the draw bar, as well as in the side walls of the body from the support of sections on the middle bogie. The numerical value of the strength margin $n = 1.4$.

Modal analysis was performed using the finite element method implemented in the CosmosWorks software environment in order to determine the critical oscillation frequencies of the bearing structure of the articulated open wagon.

Figure 6. The stressed state of the bearing structure of the articulated open wagon.

Figure 7. Movements in the units of the bearing structure of the articulated open wagon.

Figure 8. Calculation results of the bearing structure fatigue of the articulated open wagon.
These results allow us to conclude that the values of the critical oscillation frequencies are within acceptable [15-18].

5. Conclusions

1. The bearing structure of the articulated open wagon body made of round pipes was created. The optimal parameters of the pipes are selected by the elements strength reserve of a typical bearing structure of the body of the open wagon chosen as a prototype. It is important to note that the proposed solution reduced the container dead load of each section by almost 10% compared to the prototype wagon.

2. The dynamic load of the articulated open wagon body made of round pipes has been determined. It was established based on the calculations that the maximum value of acceleration acting on the first from the load side section is about 31 m/s² and the second – 32 m/s²;

3. Indexes of strength of the articulated open wagon body made of round pipes have been determined. The maximum equivalent stresses in this case occur in the area of interaction between the draw bar and the back frame and are about 300 MPa, so they do not exceed the allowable. The maximum movements in the units of the structure occur in the middle part of the back frames of sections were 3.6 mm. The maximum deformation was .

The developed construction of the open wagon is designed for fatigue. The minimum strength margin was recorded in the area of interaction of the back frame with the draw bar, as well as in the lateral walls of the body from the support of the sections on the middle bogie and was about 1.4.

The calculation of the critical oscillation frequencies was performed. The results of the calculation showed that the values of the critical oscillation frequencies are within acceptable limits.

The calculations made will provide development of recommendations for designing of articulated open wagon and increase their operational efficiency.

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