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Features of Determining the Expansion Forces of Bulk Cargo Acting on the Wagon Body Walls When Transported by a Railway Ferry

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ABSTRACT: The results of the study are aimed at improving the safety of wagons transportation by the sea and the efficiency of rail ferry transportation. The article highlights the features of calculating the expansion forces of bulk cargo acting on the wagon body during its transportation by the sea. When determining the expansion forces of bulk cargo, it is proposed to consider the dynamic load, which also affects its value in conditions of side sway. As an example, an application of this method to an open wagon loaded by coal during its transportation through the Black Sea is given.
An algorithm for considering the forces of bulk cargo pushing against the walls of an open wagon body during sea transportation is proposed.

1 INTRODUCTION

Railway transport represents one of the most effective and reliable kind of transport of passengers and goods [1, 2]. Regarding land transport, railway transport has known advantages, such as low resistance to movement, high axle load, possibilities of transport of large volumes of goods, ecology and high standard of transport safety [3-5]. In comparison with road transport, long trainsets provide lower air drag [6] which together with low rolling resistance of a couple of a railway wheel and a rail [7-9] contribute to high efficiency and lower energy losses of railway transport [10-12]. Modern designs of freight wagons allow to transport many types of goods [13]. The significant advantages of rail transport are even more pronounced when it comes to long-distance transport between countries. Here, the combination with shipping is also advantageous [14-16], where it is possible to transport many wagons by a railway ferry across the water without the laborious unloading and reloading of wagons on the other side of the coast [17].

The integration of Ukraine into the system of international transport corridors necessitates the creation of combined transport systems. In this regard, railway ferry transportation has developed. Ukraine is one of the countries of the Black Sea basin that uses this type of transportation [18, 19].

The development of railway ferry connections in Ukraine began in 1954. Later, railway ferry routes connected Ukraine with Bulgaria, Georgia and Turkey. Given the relevance of this type of transportation, an increase of the number of railway ferry routes is predicted not only in the Black Sea area, but also in other world water areas.

Bulk and bulk cargoes are of the most frequently transported cargoes in wagons by the sea. These cargoes cause pressure on the walls of an open wagon. In a case of sea transportation, this pressure exceeds the magnitude of that which occurs during operation on main tracks. This can cause not only damage of wagon bodies, but also threaten the safety of their transportation by sea.

Therefore, it is important to study the loading of wagon bodies during railway ferry transportation. This will contribute not only to the adaptation of their structures to the given operating conditions, but also to the increase of railway ferry transportation.

In the work by I. M. Zemlezyn [20], the case of wagon loading wagon with the efforts of bulk cargo expansion during transportation by railway ferry is considered. It is shown that the pressure of bulk cargo on the wagon body walls is a function of the roll angles during side swaying and the accelerations that arise in this case. It is assumed that the total acceleration value is the same for all cargo particles, when the inertial effects of the bulk cargo on the wagon walls are taken into account. It was established from these studies that the difference between the horizontal accelerations of the cargo during fluctuations of the load centre at the level of the wagon centre of gravity and at the floor level does not exceed 2 to 2.5%, and vertical accelerations do not depend on the height of the centre of gravity above the level of a rail head. The disadvantages of the above method of determining the inertial load on the side wall of the wagon body are the inability to consider the course angle of the wave in relation to the body of the railway ferry, as well as the wind load acting on the surface projection of the railway ferry with wagon bodies placed on its upper deck.

In work [21], the features of determining the impact of bulk cargo on the wagon body walls are highlighted. At the same time, the body load was studied using the mathematical and computer modelling methods. However, the author did not determine the pressure of bulk cargo on the wagon body walls during transportation by railway ferry.

The determination of the strength of an open wagon body of a lightweight design is highlighted in publication [22]. The authors performed a topological optimization to lighten the wagon container. The calculation results proved the feasibility of the proposed solutions. At the same time, the authors did not consider the loads acting on it during transportation by railway ferry when calculating the wagon body. A similar drawback can be said about the work [23], where a new design of a wagon made of steel with improved properties is also proposed.

Solutions of improvement the technical and economic indicators of a freight wagon are highlighted in publications [24, 25]. The authors proposed the use of materials with improved physical and mechanical properties to create a body shell. However, when calculating the strength of the wagon, the authors did not consider the loads acting on it during transportation by railway ferry.

The use of laminated composite panels was proposed to improve the strength of the side wall shell in the work [26]. The feasibility of such an improvement was proven using the example of a freight wagon. However, the strength of the wagon body with such a shell during transportation by railway ferry was not studied.

Hence, in can be concluded by analysing the works [20-26], that the issue of determining the forces of expansion of bulk cargo on an open wagon body during its transportation by railway ferry requires the research.

Therefore, the purpose of the study is to highlight the features of determining the forces of expansion from bulk cargo on an open wagon body walls during transportation by railway ferry.

2 METHODOLOGY FOR DETERMINING THE EXPANSION FORCES OF BULK CARGO ON WAGON THE WALLS WHEN TRANSPORTED BY A RAILWAY FERRY

It is proposed to use the Coulomb method to determine the forces of the strut on the open wagon walls during transportation by a railway ferry, according to which it is equal to the equation [20]:

$$p = G\frac{\sin(\vartheta-\rho)}{\sin(\vartheta+\psi-\rho)}, \left[\mathrm{Pa}\right] \tag{1}$$

where

G – pressure of the prism of the load displacement [Pa];

ϑ – angle of a plane slope of the horizontal line declination [°];

$\psi = 90^0 - \alpha - \delta$;

ρ – angle of internal friction (it is equal to the angle of natural slope for a perfectly free-flowing medium [°] [20]);

δ – angle of friction between the load and the wall [°].

It is important to note that the maximum pressure will correspond to the direction of the sliding plane. To determine the value of the maximum pressure, the method proposed by V. V. Sinelnikov [20] can be applied, according to which it is necessary to replace the variable ϑ in the condition of maximum pressure $\left(\frac{dp}{d\vartheta}=0\right)$, i. e. the angle of inclination of the sliding plane. In a general case, it cannot be determined analytically, for some variable x (in our case the angle α = θ). The point A was chosen as the origin of the coordinate system (Fig. 1). The x axis is directed at an angle ρ to the horizontal plane, and the y axis is aligned with the line AB, i.e. along the side wall of the wagon body. The segment AD = x determines the position of the slope plane.

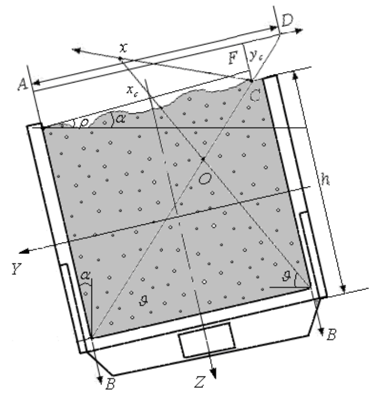

Figure 1. A scheme of action of the bulk cargo forces on the open wagon side walls

It is proposed to use the formula (2) to determine the pressure of bulk cargo on the open wagon side walls [20]:

$$p=\gamma h\frac{\cos^2(\rho-\alpha)}{\left[1+\sqrt{\frac{\sin\rho\sin(\rho-\alpha)}{\cos\alpha}}\right]^2\cos\alpha},\left[\mathrm{Pa}\right] \tag{2}$$

where
γ – volumetric mass of cargo [kg/m^3];
h – a height of the open wagon body [m].

The formula for determining the pressure for the opposite wall of the open wagon body has the following form:

$$p=\gamma h\frac{\cos^2(\rho+\alpha)}{\left[1+\sqrt{\frac{\sin\rho\sin(\rho+\alpha)}{\cos\alpha}}\right]^2\cos\alpha},\left[\mathrm{Pa}\right] \tag{3}$$

When transporting an open wagon by the sea, it is also necessary to consider the magnitude of the accelerations acting on it. The diagram of the action of forces on the open wagon body during the rolling movement of the railway ferry is shown in Fig. 2.

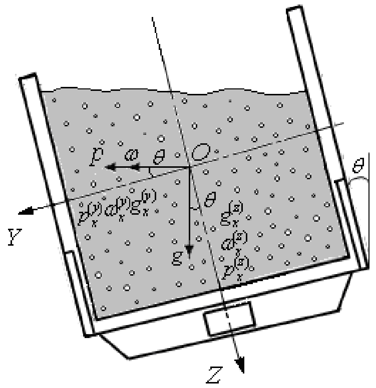

Figure 2. A scheme of the forces acting on the open wagon body during roll movement of a railway ferry: $\omega_x^{(y)}$, $\omega_x^{(z)}$ – components of the acceleration of the wagon body; $g_x^{(y)}$, $g_x^{(z)}$ – components of the acceleration of a free fall; p – inertial force acting on the wagon body; $p_x^{(y)}$, $p_x^{(z)}$ – components of the inertial force.

3 CONSIDERING THE DYNAMIC LOAD WHEN DETERMINING THE EXPANSION FORCES OF BULK CARGO ON THE OPEN WAGON BODY WALLS

The features of determining the dynamic loading on the wagon body during roll movement are given in [18]. In this case, a mathematical model is used as follows:

$$I\cdot\ddot{q}+\left(\Lambda_\theta\cdot\left(\frac{B}{2}\right)^2\right)\dot{q}=\left(\left(p'+F(t)\right)\cdot\left(\frac{B}{2}\right)^2\right), \tag{4}$$

where
I is the moment of inertia of the railway ferry [kg·m^2],
B is the width of the hull [m],
Λ_θ is the coefficient characterizing the resistance to oscillations of the railway ferry [N·s/m],
$F(t)$ is the law of action of the disturbing force [N],
p' is the wind force of the surface projection [N]
q is a generalized coordinate that characterizes the movement of a railway ferry with wagons when tilted [m].

When assigning a disturbing action, the heading angles of the sea wave to the hull of the railway ferry were considered [18]:

$$\lambda=\kappa_\lambda\cdot L|\cos\chi|,\left[\mathrm{m}\right] \tag{5}$$

where
κ_λ is a coefficient that varies in the range from 0.5 to 0.8 depending on the shape of the vessel's hull contours;
L is the wave length [m];
χ is the wave heading angle [°] (0° to 180°).

The solution of this model using the example of the Black Sea and the railway ferry "Geroi Shipki" established that the acceleration acting on the wagon body, which is located on the far side of the track from the bulwark, is about 0.2g.

Since the load is distributed relative to the wagon body wall, then the additional expansion force will be:

$$F_B=\frac{F_F}{L_K\cdot h_K},\left[\mathrm{Pa}\right] \tag{6}$$

where
F_F – the inertia force acting on bulk cargo [N];
L_K – the length of the side wall of the wagon body [m];
h_K – the height of the side wall of the wagon body [m].

Then, the following formula can be used to determine the force of the bulk cargo spreading on the open wagon body walls when the railway ferry rolls:

$$p=\gamma h\frac{\cos^2(\rho+\alpha)}{\left[1+\sqrt{\frac{\sin\rho\sin(\rho+\alpha)}{\cos\alpha}}\right]^2\cos\alpha}\pm F_B,\left[\mathrm{Pa}\right] \tag{7}$$

When determining the forces of bulk cargo expansion on the side walls of the open wagon body during railway ferry rolling, it is proposed to use the law of a triangle with a maximum at the base (Fig. 3), in accordance with [20].

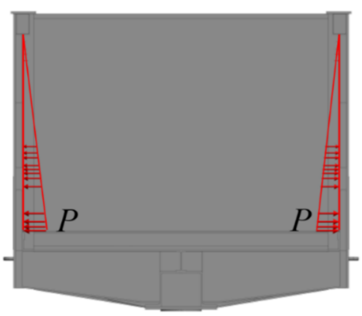

Figure 3. A distribution of the force of the bulk cargo spread on the open wagon body side walls

The approach of determining the pressure of bulk cargo on the open wagon body walls when transported by a railway ferry in the rough sea conditions differs from [20] in the method of determining the inertial component, as well as the law of distribution of the expansion force on the open wagon body wall.

The expansion force on the end walls when the railway ferry is trim can be determined by the method described above. This approach can also be used to determine the expansion pressure of bulk cargo on the walls of a container. However, in the case of its placement on an open wagon [27-31] transported by a railway ferry, this method must be modified considering the additional dynamic loads caused by the gaps between the fittings and fitting stops.

Coal (as one of the most common export cargoes) with a bulk mass of kN/m^3 was chosen as the bulk cargo to determine the numerical value of the bulk cargo expansion force on the walls of the open wagon body when transported by railway ferry across the Black Sea. Based on the calculations performed for a roll angle of the railway ferry of 12.2°, the value of the bulk cargo pressure on the side wall of the open wagon body was obtained and it was equal to the value about 15 kPa. This value exceeds the bulk cargo pressure during the operation of wagons on main tracks by more than 50%.

4 CONCLUSIONS FROM THE STUDY AND PROSPECTS, FURTHER DEVELOPMENT IN THIS DIRECTION

The results of the research allowed to obtain a refined value of the pressure of bulk cargo on the open wagon body side walls during transportation by a railway ferry. This can be considered when designing and calculating new generation wagon bodies with improved technical and economic indicators at wagons' building plants. In turn, this will help to ensure the strength of the load-bearing structures of wagon bodies during transportation on railway ferries in international traffic.

The future direction of this research will be an experimental study of the loading of an open wagon loaded by coal during sea transportation.

It is important to note that the authors have already conducted similar tests. Some of their points are reflected in the publication [18]. However, the task was then to study the stresses in the areas of fastening of wagon on the deck using chain ties. Therefore, considering the existing basis, the authors plan to use it in their subsequent studies in this direction.

Moreover, a further development of this research is the influence of uneven loading of the body with bulk cargo on the expansion force transmitted to the walls of the open wagon body during its transportation by the sea.

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