INTRODUCTION

The development of foreign economic relations between European countries necessitates reforming the transport sector. One of the most promising solutions in this direction is the creation of combined transport systems. In countries that have access to international traffic through sea areas, rail-ferry transportation has been developed. A feature of such transportation is the ability to move wagons by sea on ships specially equipped for this - railway ferries [17].

At the same time, there is a trend towards an increase in the transportation volume of liquid cargo by rail ferries. Transportation of such goods is carried out mainly in tank wagons (Figure 1). The stochastic process of container loading is described in [24] with special emphasis to ship motion when she is lying at a quay.

To ensure the stability of tank wagons relative to the decks, they are fastened using a complex of multi-turn means: chain ties with lanyards, stop-jacks and brake pads. To keep the tank wagons from moving by sea, the wagons that are extreme in the connections are connected to dead-end stops.

It is important to note that the carrying structures of tank wagons do not provide for special elements that are designed to be fixed relative to the decks of railway ferries. Therefore, when transporting tank wagons by sea, their interaction with the fixing means is carried out for any component of the structure. This situation leads to damage to the carrying structures of tank wagons during their transportation by sea and the need for unscheduled repairs. Besides, the disruption of the tank wagon's stability on decks can contribute to the disruption of the railway ferry stability and its overturning.

In this regard, it is important to conduct research on the dynamic loading and strength of the carrying structures of tank wagons during transportation on...
rail ferries and to create measures to ensure the safety of their transportation.

At the present stage of development of the railway industry it is necessary at the stage of designing cars to implement new innovative solutions for their design [5, 6, 28]. The results of determining the maximum equivalent stresses and deformations in the tank wagon boiler taking into account different levels of its workload are given in [29]. Recommendations for improving the boiler strength characteristics were formed.

Figure 1. Transportation of tank wagons on railway ferries
a) the approach of a rail ferry loaded with tank wagons to the ramp;
b) securing tank wagons on the deck

Improvement of the carrying device design of the tank car for the transportation of liquid cargo is given in [30]. The strength calculation was conducted by the finite element method, implemented in LIRA software.

However, the strength calculations did not take into account the loads that can act on the carrying structure of the tank wagon during transportation on a railway ferry.

Determination of the dynamic loading of the carrying structure of a tank wagon during transportation on a railway ferry.

To determine the dynamic loading of a tank wagon during transportation by railway ferry, a mathematical model was created (1). At the same time, the absence of the tank wagon movements relative to the deck during ferry oscillations is taken into account, that is, the case when only liquid cargo is involved in the oscillation process, the movement of which is limited by the walls of the boiler. The angular displacements of the railway ferry relative to the longitudinal axis (lurch) are taken into account. The design diagram of the carrying structure of the tank wagon located on the railway ferry deck is shown in Figure 2.

In this case, the mathematical model of the dynamic loading of the tank wagon has the form:
account that tank wagons located on the deck have the same loading with liquid cargo. In view of this, the accelerations that act on tank wagons located on the same ferry rail track will have the same values. In this connection, the research is carried out to determine the acceleration of one tank wagon during transportation on a rail ferry.

The determination of the resistance coefficient to vibrations of a railway ferry was conducted according to the methodology given in [2].

When determining the accelerations acting on the tank wagon, the heading angles of the wave concerning the railway ferry body were taken into account [4].

\[ \chi = k \lambda \cdot L \cdot \cos \alpha, \]

where \( k \lambda \) - coefficient depending on the shape of the ship lines; \( L \) - length of the ship; \( \alpha \) - the angle of the wave to the ship body.

When compiling the model, the shock effect of sea waves was not taken into account. The wave motion was described in the form of a trochoidal law [20].

\[ x = a + Re^{ib} \sin (ka + \omega t), \]
\[ z = b - Re^{ib} \cos (ka + \omega t). \]

where \( a \) and \( b \) - the horizontal and vertical coordinates of the trajectory centre on which the particle currently has the coordinates \( x \) and \( z \) rotates; \( K \) - the trajectory radius along which the particle is rotated; \( \omega \) - sea wave frequency; \( k \) - the trajectory frequency of exciting force.

The movement of the liquid cargo in the boiler is described in accordance with [3]. The determination of the hydrodynamic characteristics of the liquid cargo was conducted according to the method described in [18]. Gasoline is accepted as liquid cargo. The calculations take into account the case of the maximum allowable load of the tank wagon boiler with liquid cargo per [25].

The solution of the mathematical model was conducted in the MathCad software package by the Runge-Kutta method [10, 11, 15, 19].

The input parameters of the mathematical model are the technical characteristics of the railway ferry, liquid cargo, as well as hydrometeorological characteristics of the cruising areas. The initial displacement and velocity are taken equal to zero.

The results of the calculations are shown in Figure 3.

The total amount of acceleration acting on the carrying structure of the tank wagon also takes into account the horizontal component of the gravitational acceleration. Taking this into account, the total acceleration that acts on the tank wagon, which is outermost from the bulwark, was 0.31g. The resulting value of acceleration does not exceed the normative one acting on the carrying structure of the wagon when moving on the main track with "satisfactory running" [8, 16].
3 DETERMINATION OF THE STRENGTH OF CARRYING STRUCTURE OF THE TANK WAGON DURING TRANSPORTATION BY RAILWAY FERRY

To determine the strength indicators of the carrying structure of a tank wagon during transportation on the railway ferry, model 15-1443 was chosen as the base (Figure 4).

The spatial model of the carrying structure of the tank wagon was created in the SolidWorks software package (Figure 5). Strength analysis was conducted using the finite element method in the SolidWorks Simulation software package [13, 31, 32]. Tetrahedrons were used. The optimal number of grid elements was determined using the graphical-analytical method [20-23]. The number of grid elements was 778286, nodes - 253823. The maximum size of a grid element is 40.0 mm, the minimum is 8.0 mm, the maximum side ratio of elements is 105.21, the percentage of elements with a side ratio of less than three is 18.4, and more than ten is 0.371. The minimum number of elements in the circle - 9, the ratio of increasing the element size - 1.7.

The finite element model of the carrying structure of a tank wagon

The value of pressure on the inner surface of the boiler was determined based on the hydrostatic dependence [27]:

\[
p = p_s + \rho \cdot \alpha_{eq} \cdot h,
\]

where \( p_s \) - saturated steam pressure; \( \rho \) - density of liquid cargo; \( \alpha_{eq} \) - equivalent acceleration of liquid cargo; \( h \) - the distance from the point located on the inner surface of the tank wagon boiler to the free surface plane.

One of the most unfavourable cases of fixing the tank wagon relative to the deck, recorded during field research, is taken into account (Figure 7). In this case, two chain ties were attached to the towing bracket.

Figure 7. The scheme of fixing the tank wagon relative to the railway ferry deck

Figure 8 shows a diagram of the application of loads to the carrying structure of the tank wagon during transportation on a railway ferry. It is taken into account that the carrying structure is affected by the vertical loading \( P_v \), the side loading \( P_w \) (wind), the
liquid cargo pressure on the boiler $P_W$, as well as the loading from the chain ties $P$. Due to the spatial arrangement of chain ties, the load that will be transmitted through them to the carrying structure was decomposed into components taking into account the placement of the ties in space [4]. The calculated values of the loads acting on the carrying structure of the tank wagon during transportation on the railway ferry are given in Table 1.

Table 1. Loads acting on the carrying structure of the tank wagon during transportation by railway ferry

<table>
<thead>
<tr>
<th>Forces acting on the wagon body</th>
<th>Vertical loading, kN</th>
<th>Side loading (wind)</th>
<th>Liquid cargo pressure, kPa</th>
<th>Loading from the chain ties, kN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p_v = 137.2$</td>
<td>$p_s = 634.7$</td>
<td>$190$</td>
<td>$54$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Components of the load acting on the wagon body from chain ties</th>
<th>Dynamic loading, kN</th>
<th>Wind loading, kN</th>
<th>Forces from tension of chain ties, kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>$p_x = 17.15$</td>
<td>$p_x = 9.32$</td>
<td>$p_x = 16.14$</td>
</tr>
<tr>
<td>$P$</td>
<td>$p_y = 29.7$</td>
<td>$p_y = 16.14$</td>
<td>$p_y = 19.7$</td>
</tr>
<tr>
<td>$P$</td>
<td>$p_z = 29.7$</td>
<td>$p_z = 16.14$</td>
<td>$p_z = 19.7$</td>
</tr>
</tbody>
</table>

The calculation results showed that the maximum equivalent stresses in the carrying structure of the tank wagon are about 480 MPa (Figures 9, 10). The maximum displacements occur in the area of the loading hatch and are 5.4 mm (Figure 11). The maximum deformations were $3.8 \cdot 10^{-2}$.

The obtained values of the maximum equivalent stresses exceed the allowable for a given grade of steel metal structures of the tank car [8, 9, 16]. That is, a typical fixing scheme for a tank wagon does not contribute to ensuring the strength of the carrying structure during transportation on a railway ferry and endanger the safety of its movement by sea.

This necessitates the creation of measures to adapt the carrying structures of tank wagons to reliable interaction with the means of fixing rail ferries to ensure the safety of their transportation by sea.

Figure 9. Stress state of the carrying structure of a tank car during angular displacements relative to the longitudinal axis

Figure 10. Maximum equivalent stresses acting in the towing bracket

Figure 11. Displacement in the units of the carrying structure of the tank wagon during angular displacements relative to the longitudinal axis

4 CONCLUSIONS

1. The dynamic loading of the carrying structure of a tank wagon during transportation on a railway ferry has been determined. In this case, the angular displacements of the railway ferry relative to the longitudinal axis are taken into account, as in the case of the highest loading of the carrying structure of the tank car. It was found that the total value of acceleration that acts on the outermost tank wagon from the bulwark is 0.31g. The obtained value of acceleration does not exceed the normative one acting on the carrying structure of the wagon when moving on the main track with "satisfactory running".

2. The strength of the carrying structure of a tank wagon during transportation on a railway ferry has been determined. The calculation is implemented using the finite element method in
the SolidWorks Simulation software package. The maximum equivalent stresses in the carrying structure of the tank wagon are about 480 MPa and are fixed in the towing bracket. The maximum displacements occur in the area of the loading hatch and are 5.4 mm. The maximum deformation was $3.8 \times 10^2$. The obtained stresses exceed the permissible values for the caused steel grade of the metal structure of the tank wagon. This makes it necessary to improve the carrying structure of the tank wagon for reliable interaction with the means of fixing railway ferries.

The conducted research will contribute to the creation of recommendations for the safe operation of tank wagons in the international rail-water service and increase the efficiency of railway transport.

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