TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 15
Number 2
June 2021

DOI: 10.12716/1001.15.02.07

Determination of the Loading of the Carrying Structure of a Tank Wagon During Transportation by a Railway Ferry

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ABSTRACT: A study of the dynamic loading of the carrying structure of a tank wagon during transportation on a railway ferry was carried out. The studies were carried out with the angular displacements of the railway ferry around the longitudinal axis (lurch), as the case of the highest load on the carrying structure of the tank wagon. It was found that the acceleration total value that acts on the outermost tank wagon from the bulwark is 0.31g. The resulting value of acceleration, as a component of the dynamic load, was taken into account when calculating the strength of the carrying structure of the tank wagon, taking into account the typical scheme of interaction with chain ties. The research carried out will contribute to the creation of recommendations for the safe operation of tank wagons in international rail and water traffic and increasing the efficiency of rail transport functioning.

1 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 in the longitudinal direction, 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.

a)
b)

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 shunting operations is presented in [1]. When compiling a mathematical model, the compliance of the liquid cargo in the boiler of the tank wagon was taken into account. The critical speeds of the tank wagon movement are determined.

The study of the tank wagon dynamics taking into account the liquid cargo movements in the boiler under operating conditions is given in [26]. A mathematical model has been formed that allows one to determine the effect of tank ullage with a liquid cargo on its dynamic loading.

It is important to say that no attention was paid to the study of the dynamic loading of the carrying structure of the tank car during transportation by a railway ferry.

The development of a calculation and experimental methodology for predicting the reliable operation of freight rolling stock is covered in [33]. The studies were carried out concerning the tank wagon, taking into account the residual operating time.

The work [7] is devoted to the definition of the main aspects of safety in the transportation of liquid cargo by rail. The presented results of modelling the emissions of dangerous goods from railway tank wagons.

However, these works did not take into account the issues of transportation of tank wagons on railway ferries by sea.

The study of the dynamic loading and stability of flat wagons loaded with tank wagon under operating conditions of loading is carried out in [12, 14]. Proposed measures to reduce the dynamic loading of flat wagons in operation. At the same time, no attention was paid to the issue of the dynamic loading of tank wagons in these works.

The purpose of the article is to determine the dynamic loading and strength of the carrying structure of a tank wagon during transportation on the rail ferry. To achieve this goal, the following tasks have been identified:

– to determine the dynamic loading of the carrying structure of a tank wagon during transportation on a rail ferry;
– to determine the strength of the carrying structure of a tank wagon during transportation on a rail ferry.

2 DETERMINATION OF THE DYNAMIC LOADING OF THE CARRYING STRUCTURE OF A TANK WAGON DURING TRANSPORTATION ON A RAIL 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:

$$\begin{cases}\left(\frac{D}{12\cdot g}\left(B^2+4z_g^2\right)\right)\ddot{\theta}_1+\left(\Lambda_\theta\cdot\frac{B}{2}\right)\dot{\theta}_1=p'\cdot\frac{h}{2}+\Lambda_\theta\cdot\frac{B}{2}\cdot\dot{F}(t),\\ I_{ij}\cdot\ddot{\theta}_2-m_{ij}\cdot c_{ij}\cdot l_{ij}\cdot\ddot{\theta}_1+g\cdot m_{ij}\cdot l_{ij}\cdot\theta_2=0,\end{cases} \tag{1}$$

where θ_1, θ_2 – generalized coordinates corresponding, respectively, to the angular displacement of the railway ferry and liquid cargo in the tank wagon boiler around the longitudinal axis passing through the centre of mass of the railway ferry. The coordinate system origin is located at the centre of mass of the railway ferry.

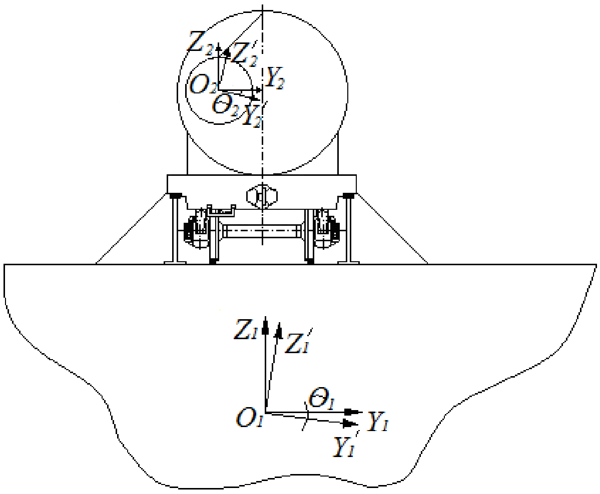

Figure 2. Design diagram of the carrying structure of the tank wagon located on the railway ferry deck

For the railway ferry: *D* - weight of displaced water; *B* - width; *h* - board height; Λ_θ is the coefficient of resistance to vibrations; z_g - coordinate of the gravity centre; *p*′- wind load; *F(t)* - law of the force action that excites the movement of the railway ferry with the wagons placed on its decks.

For the tank wagon: I_{ij} - moment of inertia of the pendulum; m_{ij} - the pendulum mass in the tank wagon boiler; c_{ij} - the distance from the plane z_i=0 to the fixation point of the pendulum in the tank wagon boiler; l_{ij} - the pendulum length; I_θ - the reduced moment of inertia of the liquid tank wagon boiler, does not participate in the movement relative to the boiler; z_{ci} - the centre height of tank wagon gravity; mi - body weight equivalent to the tank wagon boiler of a part of the liquid cargo does not participate in the movement relative to the boiler.

It is important to say that in the previous studies of the article authors, no attention was paid to the transportation of tank wagons by sea. At the same time, the issue of transportation of open wagons, covered wagons, platform wagons and tank containers by ferry was considered. In addition, this model takes into account the rigid fastening of the tank wagon on the deck, i.e. the liquid cargo takes part in the oscillatory process, and the tank wagon is considered as an "item of cargo". This assumption also distinguishes this study from previous ones.

Since the tank wagon weight is much lower (more than 600 times) than the rail ferry weight, the system of equations (1) did not take into account the effect of the liquid cargo movements in the cistern on the rail ferry movements. At the same time, it is taken into 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].

$$\chi=k\lambda\cdot L\cdot\cos\alpha, \tag{2}$$

where $k\lambda$ - coefficient depending on the shape of the ship lines; *L* - length of the ship; α - 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].

$$\begin{aligned}x&=a+Re^{kb}\sin\left(ka+\omega t\right),\\ z&=b-Re^{kb}\cos\left(ka+\omega t\right).\end{aligned} \tag{3}$$

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; *R* - the trajectory radius along which the particle is rotated; ω - 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].

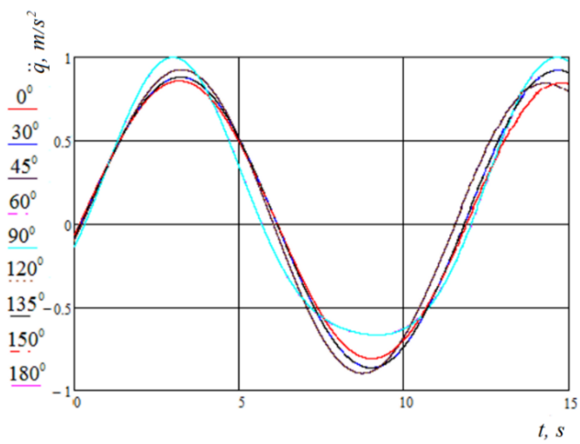

Figure 3. Acceleration acting on the outermost tank wagon from the bulwark

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).

Figure 4. Tank wagon model 15-1443

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].

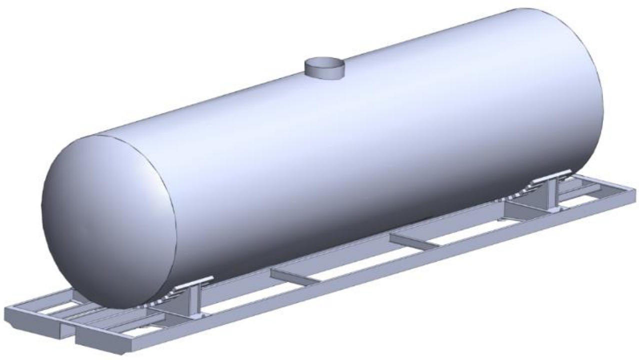

Figure 5. The carrying structure of the tank wagon

The finite element model of the carrying structure of the tank wagon is shown in Figure 6. When constructing a finite element model, isoparametric 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.

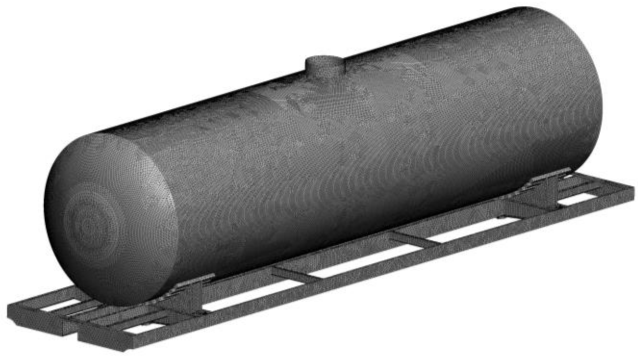

Figure 6. Finite-element model of the carrying structure of a tank wagon

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

$$p = p_s + \rho \cdot \alpha_{ekv} \cdot h,, \quad (4)$$

where p_s - saturated steam pressure; ρ - density of liquid cargo; α_{eqv} - 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_p, as well as the loading from the chain ties P_t. 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.

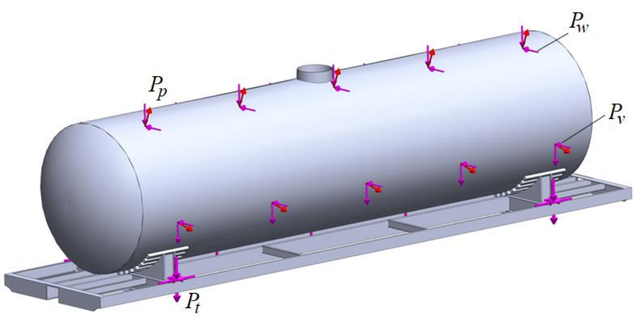

Figure 8. Calculated scheme of the carrying structure of the tank wagon with angular displacements around the longitudinal axis

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

Forces acting on the wagon body	Vertical loading, kN		p_y = 137.2 p_z = 634.7
	Side loading (wind)		74.57
	Liquid cargo pressure, kPa		190
	Loading from the chain ties, kN		54
Components of the load acting on the wagon body from chain ties	Dynamic loading, kN	XY	p_x = 17.15 p_y = 29.7
		YZ	p_y = 17.15 p_z = 19.7
		XZ	p_x =17.15 p_z = 29.7
	Wind loading, kN	XY	p_x = 9.32 p_y = 16.14
		YZ	p_y = 9.32 p_z = 16.14
		XZ	p_x =9.32 p_z = 16.14
	Forces from tension of chain ties, kN	XY	p_x = 27 p_y = 47
		YZ	p_y = 27 p_z = 47
		XZ	p_x =27 p_z = 27

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.

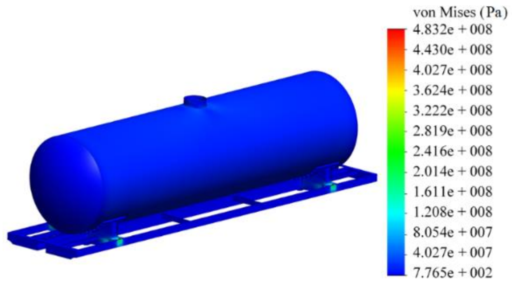

Figure 9. Stress state of the carrying structure of a tank car during angular displacements relative to the longitudinal axis

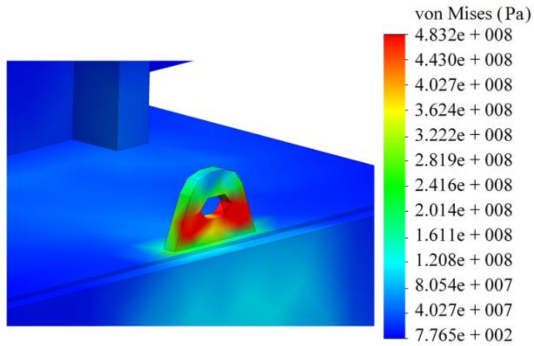

Figure 10. Maximum equivalent stresses acting in the towing bracket

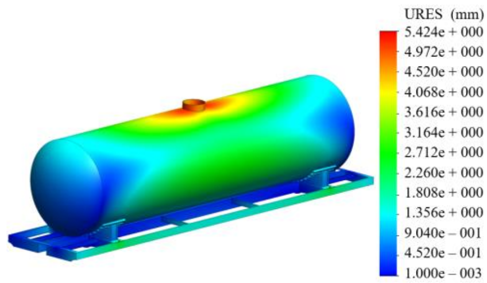

Figure 11. Displacement in the units of the carrying structure of the tank wagon during angular displacements relative to the longitudinal axis

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 $3.8 \cdot 10^{-2}$. 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.

ACKNOWLEDGEMENTS

These studies were carried out within the framework of the scientific theme of young scientists "Innovative foundations for the creation of resource-saving wagon constructions by taking into account the refined dynamic loads and functional adaptive flash concepts", which is performed at the expense of the state budget of Ukraine from 2020.

This research was supported by the Slovak Research and Development Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic in Educational Grant Agency of the Ministry of Education of the Slovak Republic in the project No. VEGA 1/0558/18: Research of the interaction of a braked railway wheelset and track in simulated operational conditions of a vehicle running in a track on the test bench.

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