*Проведено моделювання динамічної навантаженості контейнера-цистерни при перевезенні у складі комбінованого поїзда на залізничному поромі. Розроблено математичні моделі, які враховують можливі варіанти взаємодії контейнерів-цистерн з рамою вагонів-платформ. Розрахунки проведені стосовно контейнера-цистерни типорозміру 1СС, розміщеного на вагоні-платформі моделі 13-4012М. Враховано, що перевезення контейнера-цистерни здійснюється на залізничному поромі "Герои Шипки" акваторією Чорного моря. Встановлено, що найбільша величина прискорень діє на контейнер-цистерну в випадку наявності переміщень вагона-платформи відносно палуби та контейнера-цистерни відносно рами. Загальна величина прискорення при цьому склала близько 0,9g.*

*Досліджено стійкість контейнера-цистерни при перевезенні на залізничному поромі. Розраховано допустимі кути крену залізничного порому, при яких забезпечується стійкість контейнера-цистерни відносно рами вагона-платформи.*

*Проведено комп'ютерне моделювання динамічної навантаженості контейнера-цистерни при перевезенні на залізничному поромі. Розрахунок проведений в середовищі програмного забезпечення CosmosWorks. Визначено поля та чисельні значення прискорень, які діють на контейнер-цистерну. Здійснено перевірку адекватності розроблених моделей за F-критерієм.*

*Проведені дослідження сприятимуть забезпеченню безпеки та створенню рекомендацій щодо перевезень комбінованих поїздів на залізничних поромах морем, а також проектуванню контейнерів-цистерн з покращеними техніко-економічними, міцністними та екологічними характеристиками*

*Ключові слова: контейнер-цистерна, динамічна навантаженість, моделювання навантаженості, коефіцієнт стійкості, залізнично-поромні перевезення*

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# DETERMINATION OF DYNAMIC LOAD FEATURES OF TANK CONTAINERS WHEN TRANSPORTED BY RAIL FERRY

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## 1. Introduction

The development of foreign economic relations between Eurasian states contributes to the creation of combined transport systems. One of the most common vehicles for combined transportation are containers and tank containers.

To reduce the time of goods delivery from the consignor to the consignee, transportation of combined trains on rail ferries has become widely used (Fig. 1).

In order to ensure the stability of flat cars with containers (tank containers) on decks, they are attached with multi-turn means (chain ties, mechanical jacks, buffer stops and brake shoes).

Attachment of containers (tank containers) relative to flat car frames is carried out according to a typical scheme, i. e. by fitting on fitting stops.

It is important to note that the dynamic processes accompanying railway rolling stock, including containers (tank containers) during carriage by sea differ significantly from operating conditions on main tracks. This may cause the tipping of containers (tank containers) relative to the placement on the flat car and threaten the rail ferry safety. In additio n, the presence of free bulk cargo surface in the tank container contributes to an additional dynamic load on it and deterioration of stability during transportation by sea.

*a*

*b*

Fig. 1. Loading of combined trains on rail ferry: *a* – dry cargo containers; *b* – tank containers

Therefore, it is necessary to study the dynamic load of tank containers and to make recommendations for the safety of transportation by rail ferries. These studies will also help to create tank containers with improved technical-economic, strength and environmental characteristics.

## 2. Literature review and problem statement

The results of optimization of the bearing structure of the tank container are given in [1]. The paper proves the expediency of designing and commissioning tank containers as vehicles. An advanced design of a tank container for the transport of light petroleum products is developed. It is important to note that the loads that may affect the tank container when transported by rail ferry are not taken into account.

Requirements for bearing structures of modern vehicles are covered in [2]. These requirements are proposed to be applied in manufacturing new vehicle designs as well as those undergoing modernization. However, no attention is paid to the study of the dynamic load of tank containers when transported by rail ferries.

Measures to improve the stability of rolling stock under operating load conditions are discussed in [3]. The results of mathematical modeling are confirmed by experimental studies.

Determination of the impact load of vehicles is carried out in [4]. Accelerations are considered as components of dynamic load. Calculations are made by mathematical modeling. At the same time, the stability of tank containers under operating load conditions is not determined in these works.

Determination of the dynamic load of containers under operating conditions is carried out in [5]. Mathematical models are justified by computer simulation and verification.

At the same time, the study of the dynamic load of tank containers when transported by rail ferry is not carried out in the work.

The study of the dynamic load of vehicles during transportation by rail ferry is carried out in [6, 7]. The results of mathematical modeling are computer-verified. However, the case of the dynamic load of the tank container when transported as part of a combined train by rail ferry is not taken into account.

Determination of strength indices of the T11 tank container, placed on the flat car, in maneuvering collision is carried out in [8]. The results of theoretical studies are confirmed by experimental ones, carried out by the method of electrical strain gaging. Modeling of the dynamic load of vehicles during operation on main tracks is carried out in [9]. To improve the dynamics of vehicles, it is proposed to use promising designs of LEILA and SUSTRAIL trucks.

Determination of the dynamic load of tank containers as part of combined trains during transportation by rail ferries is not investigated in these works.

Modeling of the longitudinal load of the tank container, placed on the long-wheelbase structure of the flat car, is carried out in [10]. Numerical values of the accelerations acting on the tank container are given, taking into account possible displacements of fittings relative to fitting stops. The issue of studying the dynamic load of the tank container when transported by rail ferry is not given attention in this work.

Determination of the dynamic load of vehicles in maneuvering collision is performed in [11]. The mathematical model that allows obtaining accelerations acting on the vehicle is given. The results obtained are confirmed by computer simulation. However, the dynamic load of tank containers as part of combined trains is not determined.

The analysis of literature [1–11] suggests that due attention has not been given to determining the dynamic load of tank containers when transported by rail ferry. This makes it necessary to carry out appropriate research and to formulate recommendations that will help to improve the efficiency of tank containers and traffic safety at the present stage of development of the transport industry.

## 3. The aim and objectives of the study

The aim of this study is to determine the dynamic load characteristics of tank containers when transported by rail ferry. This will increase the safety of transport of tank containers by rail ferries, as well as facilitate the development of tank containers with improved technical-economic, operational and environmental performance.

To achieve this aim, the following objectives are defined:

– to carry out mathematical modeling of the dynamic load of tank containers when transported by rail ferry;

– to examine the stability of tank containers relative to flat car frames when transported by rail ferry;

– to carry out computer simulation of the dynamic load of tank containers when transported by rail ferry;

– to verify the developed models of the dynamic load of tank containers when transported by rail ferry.

## 4. Mathematical modeling of dynamic load of tank containers when transported by rail ferry

Mathematical models (1)–(3) have been compiled to determine the dynamic load of tank containers when transported by rail ferry. Three schemes of interaction of tank containers with the flat car frame have been taken into account:

– no displacement of the flat car with tank containers relative to the deck. That is, when the rail ferry oscillates, the flat car and tank containers placed on it completely follow the vessel oscillation trajectory (Fig. 2, *a*);

– displacement of the flat car relative to the deck and no displacement of tank containers relative to the flat car frame (Fig. 2, *b*);

– displacement of the flat car relative to the deck and tank containers relative to the flat car frame (Fig. 2, *c*).

At the same time, the angular displacements of the rail ferry relative to the longitudinal axis (roll) are taken into account as a case of the highest load of flat cars with tank containers during sea transportation [12, 13].

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

$$\begin{cases} \left(\frac{D}{12\cdot g}\left(B^2+4z_g^2\right)\right)\ddot{\theta}_1+\left(\Lambda_\theta\cdot\frac{B}{2}\right)\dot{\theta}_1=p'\cdot\frac{h}{2}+\Lambda_\theta\cdot\frac{B}{2}\cdot\dot{F}(t),\\ \left(I_{\theta i}+\sum_{j=1}^{k}m_{ij}\cdot c_{ij}^2\right)\cdot\ddot{\theta}_2+\sum_{j=1}^{k}m_{ij}\cdot c_{ij}\cdot l_{ij}\cdot\ddot{\theta}_3-g\cdot\left(m_i\cdot z_{ci}+\sum_{j=1}^{k}m_{ij}\cdot c_{ij}\right)\cdot\theta_2=M_T^{FC},\\ I_{ij}\cdot\ddot{\theta}_3-m_{ij}\cdot c_{ij}\cdot l_{ij}\cdot\ddot{\theta}_2+g\cdot m_{ij}\cdot l_{ij}\cdot\theta_3=0, \end{cases} \tag{2}$$

$$\begin{cases} \left(\frac{D}{12\cdot g}\left(B^2+4z_g^2\right)\right)\ddot{\theta}_1+\left(\Lambda_\theta\cdot\frac{B}{2}\right)\dot{\theta}_1=p'\cdot\frac{h}{2}+\Lambda_\theta\cdot\frac{B}{2}\cdot\dot{F}(t),\\ I_{FC}\cdot\ddot{\theta}_2=p'_{FC}\cdot\frac{h_{FC}}{2}+M_{FC}^{D}+M_{FC}^{T},\\ \left(I_{\theta i}+\sum_{j=1}^{k}m_{ij}\cdot c_{ij}^2\right)\cdot\ddot{\theta}_3+\sum_{j=1}^{k}m_{ij}\cdot c_{ij}\cdot l_{ij}\cdot\ddot{\theta}_4-g\cdot\left(m_i\cdot z_{ci}+\sum_{j=1}^{k}m_{ij}\cdot c_{ij}\right)\cdot\theta_3=M_T^{FC},\\ I_{ij}\cdot\ddot{\theta}_4-m_{ij}\cdot c_{ij}\cdot l_{ij}\cdot\ddot{\theta}_3+g\cdot m_{ij}\cdot l_{ij}\cdot\theta_4=0. \end{cases} \tag{3}$$

The origin of the coordinate system is in the center of mass of the rail ferry.

*For the railway ferry*: $D$ – weight water displacement; $B$ – width of the rail ferry; $h$ – height of the rail ferry side; $\Lambda_\theta$ – coefficient of oscillation resistance; $z_g$ – coordinate of the center of gravity of the rail ferry; $p'$ – wind load; $F(t)$ – law of action of the force that excites the displacement of the rail ferry with cars placed on its decks.

*For the flat car*: $I_{FC}$ – moment of inertia of the flat car relative to the longitudinal axis; $p'_{FC}$ – wind load on the side projection of the flat car; $h_{FC}$ – height of the lateral projection of the flat car; $M_{FC}^{D}$ – moment of forces arising between the flat car and ferry deck; $M_{FC}^{T}$ – moment of force arising between the flat car and tank container.

*For the tank container and bulk cargo:* $I_{ij}$ – pendulum moment of inertia; $m_{ij}$ – mass of the *j*-th pendulum in the *i*-th tank container; $c_{ij}$ – distance from the plane $z_i=0$ to the point of attachment of the *j*-th pendulum in the *i*-th tank container; $l_{ij}$ – length of the *j*-th pendulum; $I_\theta$ – reduced moment of inertia of the *i*-th tank container and bulk cargo, which does not participate in the displacement relative to the tank; $z_{ci}$ – height of the center of gravity of the tank container; $m_i$ – mass of the body equivalent to the *i*-th tank container with part of the bulk cargo, which does not participate in the displacement relative to the tank; $M_T^{FC}$ – moment of forces arising between the tank container and flat car.

As a prototype, the 13-4012M flat car was chosen. The studies were carried out regarding the tank container of 1CC type size, loaded with gasoline up to 95 % of the tank capacity [14]. It is taken into account that the transportation of tank containers is carried out on the "Geroi Shipki" type rail ferry through the Black Sea.

Bulk cargo movement was described by a set of mathematical pendulums [10].

Differential equations (1)–(3) are solved using the Runge-Kutta method implemented in the MathCad software environment [15, 16].

The transition from second-order differential equation systems (1)–(3) to first-order differential equation systems (4)–(6) was conducted to apply standard algorithms for solving the systems using the rkfixed function of Mathcad.

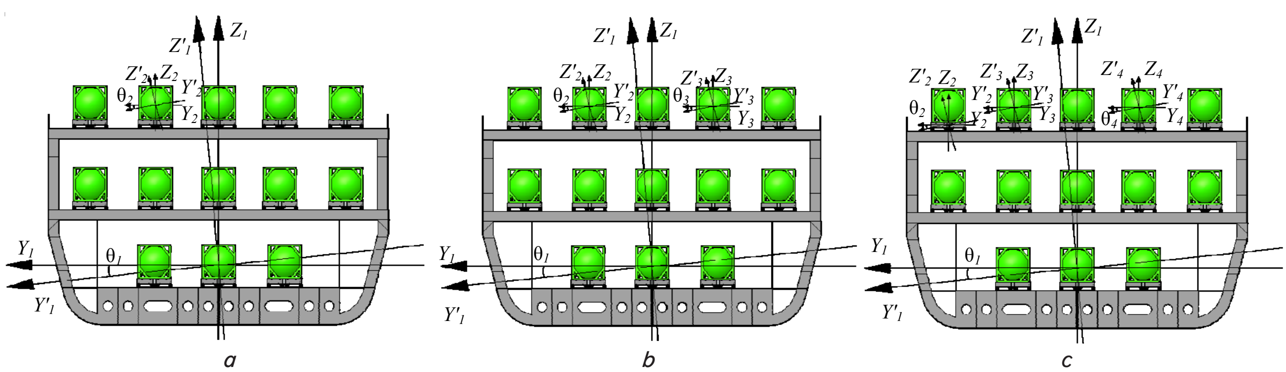


Fig. 2. Schemes of displacements of tank containers as part of combined trains when transported by rail ferry: *a* – no displacement of the flat car with tank containers relative to the decks; *b* – displacement of the flat car relative to the deck and no displacement of tank containers relative to the flat car frame; *c* – displacement of the flat car relative to the deck and tank containers relative to the flat car frame

That is, for the first scheme, for

$$y_1=\theta_1,\quad y_2=\dot{\theta}_1,$$

$$y_3=\theta_2, y_4=\dot{\theta}_2,$$

we have

$$Q1(t,y)=\left|\begin{array}{c} y_2 \\ y_4 \\ \dfrac{p'\cdot\dfrac{h}{2}+\Lambda_\theta\cdot\dfrac{B}{2}\cdot\dot{F}(t)-\left(\Lambda_\theta\cdot\dfrac{B}{2}\right)y_2}{\left(\dfrac{D}{12\cdot g}\left(B^2+4z_g^2\right)\right)} \\ \dfrac{m_{ij}\cdot c_{ij}\cdot l_{ij}\cdot\dot{y}_2-g\cdot m_{ij}\cdot l_{ij}\cdot y_3}{I_{ij}} \end{array}\right|. \qquad (4)$$

$$Z1=rkfixed\,(Y0,\ tn,\ tk,\ n',\ Q1),$$

where $Y0$ is the vector containing initial conditions, $tn$, $tk$ are the values determining the initial and final integration variables, $n'$ is the fixed number of steps, $Q1$ is the symbol vector.

For the second scheme, for

$$y_1=\theta_1,\quad y_2=\dot{\theta}_1,\quad y_3=\theta_2,$$

$$y_4=\dot{\theta}_2,\quad y_5=\theta_3,\quad y_6=\dot{\theta}_3,$$

we have

$$Z2(t,y)=\left[\begin{array}{c} y_2 \\ y_4 \\ y_6 \\ \dfrac{p'\cdot\dfrac{h}{2}+\Lambda_\theta\cdot\dfrac{B}{2}\cdot\dot{F}(t)}{I}-\dfrac{\Lambda_\theta\cdot\dfrac{B}{2}}{I}\cdot y_2 \\ \dfrac{-\left(\sum\limits_{j=1}^{k}m_{ij}\cdot c_{ij}\cdot l_{ij}\right)\dfrac{\mathrm{d}}{\mathrm{d}t}y_6+g\cdot\left(m_i\cdot z_{ci}+\sum\limits_{j=1}^{k}m_{ij}\cdot c_{ij}\right)\cdot y_3}{\left(I_{\theta i}+\sum\limits_{j=1}^{k}m_{ij}\cdot c_{ij}^2\right)}+\dfrac{M_T^{FC}}{\left(I_{\theta i}+\sum\limits_{j=1}^{k}m_{ij}\cdot c_{ij}^2\right)} \\ \dfrac{\left(m_{ij}\cdot c_{ij}\cdot l_{ij}\right)\cdot\dfrac{\mathrm{d}}{\mathrm{d}t}y_4-\left(g\cdot m_{ij}\cdot l_{ij}\right)\cdot y_5}{I_{ij}} \end{array}\right]. \qquad (5)$$

$$Z2=rkfixed\,(Y0,\ tn,\ tk,\ n,\ Q2).$$

For the third scheme, for

$$y_1=\theta_1,\quad y_2=\dot{\theta}_1,$$

$$y_3=\theta_2,\quad y_4=\dot{\theta}_2,$$

$$y_5=\theta_3,\quad y_6=\dot{\theta}_3,$$

$$y_7=\theta_4,\quad y_8=\dot{\theta}_4,$$

we have

$$Q3(t,y)=\left|\begin{array}{c} y_2 \\ y_4 \\ y_6 \\ y_8 \\ \dfrac{p'\cdot\dfrac{h}{2}+\Lambda_\theta\cdot\dfrac{B}{2}\cdot\dot{F}(t)-\left(\Lambda_\theta\cdot\dfrac{B}{2}\right)y_2}{\left(\dfrac{D}{12\cdot g}(B^2+4z_g^2)\right)} \\ \dfrac{p'_{FC}\cdot\dfrac{h_{FC}}{2}+M_{FC}^{D}+M_{FC}^{T}}{I_{FC}} \\ \dfrac{M_T^{FC}-\sum\limits_{j=1}^{k}m_{ij}\cdot c_{ij}\cdot l_{ij}\cdot\dot{y}_8+g\cdot\left(m_i\cdot z_{ci}+\sum\limits_{j=1}^{k}m_{ij}\cdot c_{ij}\right)\cdot y_5}{\left(I_{\theta i}+\sum\limits_{j=1}^{k}m_{ij}\cdot c_{ij}^2\right)} \\ \dfrac{m_{ij}\cdot c_{ij}\cdot l_{ij}\cdot\dot{y}_6-g\cdot m_{ij}\cdot l_{ij}\cdot y_7}{I_{ij}} \end{array}\right|. \qquad (6)$$

$$Z3=rkfixed\,(Y0,\ tn,\ tk,\ n,\ Q3).$$

Initial displacements and velocities are assumed to be zero.

The results of the calculation in the form of dependencies of the accelerations acting on the tank container on the wave-to-course angles relative to the rail ferry body are shown in Fig. 3. These dependencies are described by the equations shown in the Fig. 3.

It was found that in the absence of displacements of the flat car and tank containers relative to the starting position, the total acceleration acting on the last container car from the bulwark was about 0.3*g*.

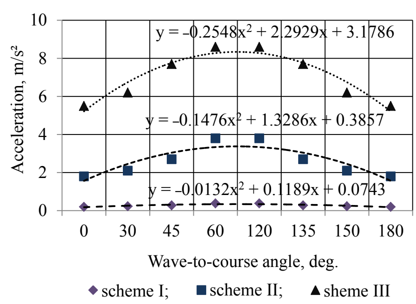


Fig. 3. Accelerations acting on the tank container when transported by rail ferry

In the presence of displacements of the flat car relative to the deck and at the stability of the tank containers relative to the frame, the total acceleration acting on the last tank container from the bulwark was about 0.6*g*. This value of acceleration exceeds that acting on the tank container when operating on main tracks by 17 % [17].

In the case of displacement of the flat car relative to the deck and tank container relative to the frame, the total acceleration acting on the last tank container from the bulwark was about 0.9*g* (Fig. 4). That is, this value of acceleration exceeds 40 % of that acting on the tank container when operating on main tracks.

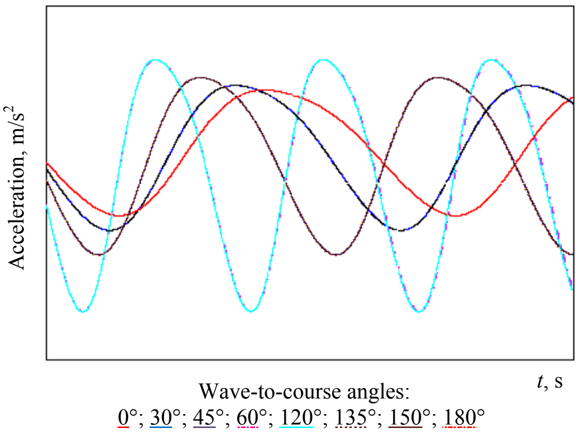


Fig. 4. Accelerations acting on the tank container placed on the flat car when transported by rail ferry

Each color of the curve in Fig. 4 corresponds to the value of acceleration obtained for a certain wave-to-course angle relative to the body of the rail ferry with the flat cars placed on it (the signatures of the angles are shown on the side of the ordinate axis).

So, the maximum accelerations acting on the tank container correspond to the wave-to-course angles with respect to the rail ferry body – 60° and 120°.

## 5. Study of the stability of tank containers relative to the flat car frames when transported by rail ferry

The obtained values of accelerations are taken into account when examining the stability of the tank container relative to the flat car frame.

To ensure the stability of the tank container relative to the flat car frame, the following conditions must be fulfilled:

$$k_c = \frac{M_{rest}}{M_{tip}} \geq 1, \qquad (7)$$

where $M_{rest}$ is the value of restoring moment; $M_{tip}$ is the value of tipping moment.

It is found that the stability of tank containers for the most unfavorable load case is ensured at a roll angle of up to 10° (Fig. 5). In the second scheme, the stability of tank containers is ensured at roll angles up to 12°, while in the third – up to 25°.

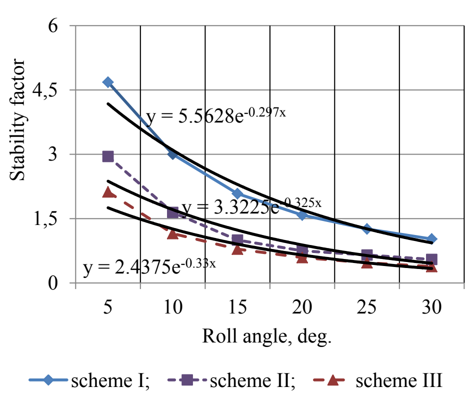


Fig. 5. Dependence of the stability factor of the tank container relative to the flat car frame on the rail ferry roll angle

Therefore, to ensure the safety of sea transportation of bulk cargo in tank containers, it is important to comply with the relevant conditions, namely to keep the roll angles of the rail ferry within 10°.

## 6. Computer simulation of dynamic load of tank containers when transported by rail ferry

To study the dynamic load of tank containers when transported by rail ferry, computer simulation was performed using the finite element method implemented in the CosmosWorks software package (France) [18, 19].

Spatial isoparametric tetrahedra are used as finite elements. The optimal number of elements is determined by the graphoanalytic method. Basic data on the finite element model of tank containers placed on the flat car during transportation on the rail ferry are given in Table 1.

Table 1

Data on the finite element model of tank containers placed on the flat car when transported by rail ferry

| Parameter | Value |
|---|---|
| Number of Jacobian points | 4 |
| Number of nodes | 396.934 |
| Number of elements | 1192935 |
| Maximum element size | 70 |
| Minimum element size | 14 |
| Minimum number of elements in the circle | 9 |
| Ratio of elements upsizing | 1.7 |
| Maximum aspect ratio | 13.317 |
| Percentage of elements with aspect ratio less than 3 | 36.7 |
| Percentage of elements with aspect ratio less than 10 | 15.4 |

The model for determining the dynamic load of the tank container placed on the flat car when transported by rail ferry is shown in Fig. 6. It is taken into account that the flat car is subjected to vertical load from the tank containers $P_v^{FC}$ (Fig. 7) placed on it, horizontal load on the fitting stops $P_h^{FC}$ from the fittings, and also the load exerted through the nodes for fastening the chain ties $P_{ct}$. Due to the spatial arrangement of the chain ties [20, 21], the load transmitted through them to the flat car frame was decomposed into three components according to the angles of spatial arrangement.

The flat car was fixed in the areas of support on the running gear, as well as working surfaces of mechanical jacks. To do this, on the main longitudinal beams of the flat car frame in the area of interaction with the bolsters, circular plates, the diameter of which is equal to the diameter of the working parts of mechanical jacks were installed.

The tank container is subjected to vertical-static load $P_v^{st}$, bulk cargo pressure $P_{bc}$ and wind load $P_w$.

Attachment of the tank container was carried out in the areas of its support on the flat car. 09G2C steel was used as structural material. The results of the calculation are shown in Fig. 8.

The maximum accelerations acting on the tank container are concentrated in the frame from the tension of the chain ties and are about 0.9*g*. At the top of the tank container, acceleration was 0.3*g*.

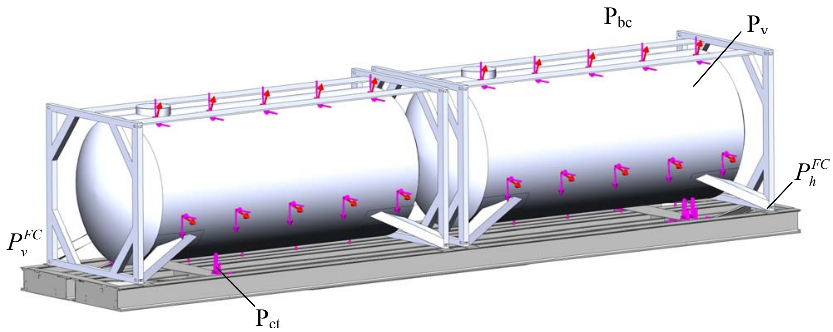


Fig. 6. Model for determining the dynamic load of the tank container when transported by rail ferry

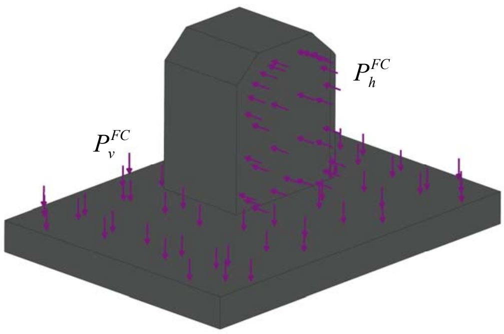


Fig. 7. Loads acting on the flat car fitting stop from the container fitting during rail ferry oscillations

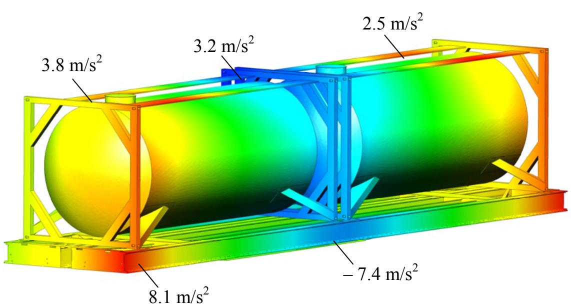


Fig. 8. Distribution of fields of acceleration acting on the tank container when transported by rail ferry

## 7. Verification of the developed models of dynamic load of tank containers when transported by rail ferry

To verify the adequacy of the developed models of the dynamic load of tank containers when transported by rail ferry, calculation was performed according to the *F*-criterion [22, 23].

$$F_p = \frac{S_{ad}^2}{S_r^2}, \tag{8}$$

where $S_{ad}^2$ is the adequacy variance; $S_r^2$ is the reproducibility variance.

As a variation parameter, the rail ferry roll angle is taken into account. The results of the calculation are given in Table 2.

Divergence between the results of mathematical modeling and computer simulation of the dynamic load of the tank container when transported by rail ferry is shown in Fig. 9.

The optimal number of measurements is determined by the Student test:

$$n = \frac{t^2 \cdot \sigma^2}{\delta^2}, \tag{9}$$

where $t$ is the table value of the Student's test; $\sigma$ is the standard deviation of a random variable; $\delta^2$ is the absolute error of measurement result.

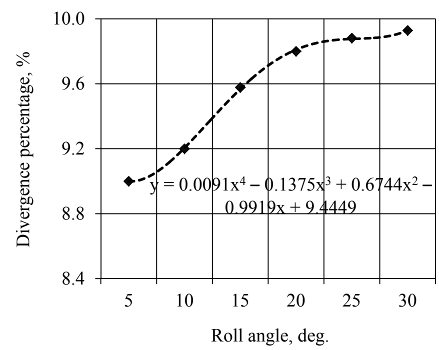


Fig. 9. Divergence between the results of mathematical modeling and computer simulation of the dynamic load of the tank container

Table 2

Results of simulation of dynamic load of the tank container when transported by rail ferry

| Roll angle, deg. | Acceleration acting on the tank container, m/s² | |
|---|---|---|
| | Mathematical modeling | Computer simulation |
| 5 | 3.8 | 3.4 |
| 10 | 7.4 | 6.7 |
| 15 | 11.3 | 10.2 |
| 20 | 15 | 13.5 |
| 25 | 18.2 | 16.4 |
| 30 | 21.5 | 19.4 |

The results of the calculations suggested that the estimated value of the *F*-criterion is $F_p$=0.81 with the table $F_t$=4.53. Therefore, the hypothesis of adequacy is not rejected.

## 8. Discussion of the results of determining the dynamic load of tank containers when transported by rail ferry

The dynamic load of the tank container when transported by rail ferry is determined. For this purpose, mathematical models describing the oscillations of the tank container at angular displacements of the rail ferry relative to the longitudinal axis are developed. The feature of the simulation is that various schemes of the tank container interaction with the flat car placed on the rail ferry deck are taken into account. It is found that the maximum acceleration occurs in the presence of displacements of the flat car relative to the deck and the tank container relative to the frame. The numerical value of acceleration was about 0.9*g*. This value exceeds the acceleration acting on the tank container when operating on main tracks.

Therefore, to ensure reliable operation of tank containers, it is necessary to take into account the loads acting on them when transported by rail ferries at the design stage.

The factor of stability of the tank container relative to the flat car frame is calculated. Permissible roll angles of the rail ferry that ensure the stability of the tank container relative to the frame are determined. For the most unfavorable load case, the stability of the tank container is ensured at roll angles of up to 10°. These calculations will help to increase the safety of transport of tank containers on rail ferries.

Computer simulation of the dynamic load of the tank container when transported by rail ferry was carried out. The strength model takes into account the loads acting on the tank container from bulk cargo, as well as from the flat car fitting stops. The simulation results made it possible to determine the fields of acceleration dislocation relative to the tank container and their numerical values. The results obtained were verified by the F-criterion.

Thus, the research made it possible to determine the dynamic load of the tank container when transported as part of a combined train on a rail ferry.

It is important to note that the above mathematical models do not take into account the stochasticity of the disturbing action, that is, sea disturbance. In this study, no attention was paid to determining the dynamic load of the tank container, taking into account different levels of tank filling with bulk cargo. It was also assumed that there was a sliding lid on the bulk cargo surface, that is, its surface perturbations were not taken into account.

At this stage, studies are limited to computer simulation of the dynamic load of the tank container when transported by rail ferry. For the further development of this issue, it is important to conduct a physical experiment.

## 9. Conclusions

1. Mathematical modeling of the dynamic load of tank containers when transported by rail ferry is carried out. It is found that the maximum acceleration acting on a tank container during sea transportation by rail ferry occurs in the case of displacement of the flat car relative to the deck and tank containers relative to the flat car frame. Taking into account the horizontal component of free-fall acceleration, the total acceleration is about 0.9*g* and corresponds to the wave-to-course angles relative to the ferry body – 60° and 120°.

2. The stability of tank containers relative to the flat car frames when transported by rail ferry is investigated. The stability of tank containers for the most unfavorable load case is ensured at a roll angle of up to 10°.

3. Computer simulation of the dynamic load of tank containers when transported by rail ferry is carried out. The maximum accelerations acting on the tank container are concentrated in the frame from the tension of the chain ties and are about 0.9*g*. At the top of the tank container, acceleration was 0.3*g*.

4. Verification of the developed models of the dynamic load of tank containers when transported by rail ferry is made. The divergence between the results of mathematical modeling and computer simulation was about 10 %. The results of the calculations made it possible to conclude that the hypothesis about the adequacy of the developed models is not rejected.

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