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# Dynamic Load Modelling within Combined Transport Trains during Transportation on a Railway Ferry

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**Abstract:** The development of foreign economic activity of the Eurasian states led to the introduction of rail and ferry transportation. It is important to note that the current normative documentation does not fully cover the issues of transporting combined trains by sea. This can lead to a violation of the traffic safety of both the railway ferry and the transport of containers as part of combined trains by sea. In this connection, we investigated the dynamic loading of a container as part of a combined train when transported by a railway ferry. To ensure the stability of the container relative to the frame, we suggested an improvement of the load-bearing structure of a flat wagon. Additionally, we suggested the use of a viscous linkage between containers with the aim of reducing their dynamic load. To justify the suggested solutions, we carried out a mathematical modelling of the container dynamic load. The calculation was performed in MathCad. Due to the fact that the container has its own degree of freedom when transported by sea, the accelerations were separately determined for the supporting structure of the flat wagon and for the container. We found that the total amount of acceleration that acted on the container was 3.57 m/s$^2$ (0.36 g) and on the load-bearing structure of the wagon was 2.47 m/s$^2$ (0.25 g) which were, respectively, 38% and 23% less than the acceleration values in the typical scheme of their interaction. To determine the fields of acceleration distribution relative to the load-bearing structure of a flat wagon with containers, we carried out computer modelling of their dynamic load. The maximum percentage of discrepancy between the accelerations obtained by mathematical and computer modelling was 17.7%. The study will contribute to the creation of recommendations for the safe transport of combined trains by sea, as well as to increasing the efficiency of combined transport through international transport corridors.

**Keywords:** wagon; carrying structure; combined transportation; dynamics; strength

## 1. Introduction

In the context of modern development of the transport industry, it is necessary to put into operation the combination of transport systems in order to maintain the leading positions of railway transport. In fact, container transportation is one of the most successful and widespread among combined transport systems. A significant segment of this transport is carried out by sea transport. At the same time, the peculiarities of loading and transporting containers by sea are highlighted in research works [1–6]. To improve the efficiency of this type of transport, container trains are being transported by sea (see Figure 1).

According to the United Nations, the global maritime traffic is projected to grow by 3.8% in 2018–2023 [7]. Traffic is expected to increase across all sectors, with the fastest growing traffic being container and dry bulk traffic. In this connection, the issues of transporting trains of combined transport by sea are relevant.

Transportation of container trains by sea is accompanied by loads on them that are not inherent in the operating conditions for the tracks. The typical scheme of interaction between a container and a flat wagon (fittings, fitting stops) in the conditions of fluctuations of the railway ferry does not provide stability of balance. This situation may contribute to violation of combined transport traffic safety [8].

The main causes of ship sinking are technical failures, human factors, route conditions, delivery factors, as well as factors associated with the transported cargo [9]. Natural factors—wind, waves, and sea currents—also have significant impacts on the safety of sea traffic. These reasons often cause a violation of the stability of the vessel and its sinking [10].

The consequences of the sinking of sea vessels, including rail ferries, can be associated with financial losses, loss of life, as well as environmental aspects [11,12].

It is known that ship accidents cause 14% of oil pollution of the environment. The duration of the existence of an oil slick and slick on the sea surface can reach several months. In addition, oil spills tend to move over considerable distances under the influence of wind and sea currents. Bulk cargo transported by sea is no less dangerous. In case of ship accidents, heavy metals are released into the environment, as well as other materials that negatively affect the ecology of the water area [13].

The study of the causes of the sinking of sea vessels for the transport of vehicles has shown that the main reason for the loss of stability is the displacement of the cargo.

For example, in 2002, the rail ferry Mercury-2 sank in the Caspian Sea due to violation of the stability of tank wagons relative to the deck. On board of the vessel were 16 tank wagons with oil products, 1 wagon with consumer cargo, 8 passengers, and 42 crew members. The tank wagons fell off the mountings from the impact of the wave, slid in the direction of the ship's tilt, and caused the ship to sink [14]. Of the people present on board, only nine were rescued and only four bodies of victims of the disaster were found. After 5 days of almost continuous patrolling of the tragedy from the air and at sea, the search activity was stopped by a decision of a specially created government commission.

On 5 June 2009, off the coast of the island of Tonga (Indonesia), the cargo–passenger ferry Princess Ashika was lost. The reason for the overturning of the ferry was the shift of the cargo to one side or its incorrect loading while still in the port. On the deck of the ship there were 117 people and cargo (equipment, several ambulances, and trucks) [15].

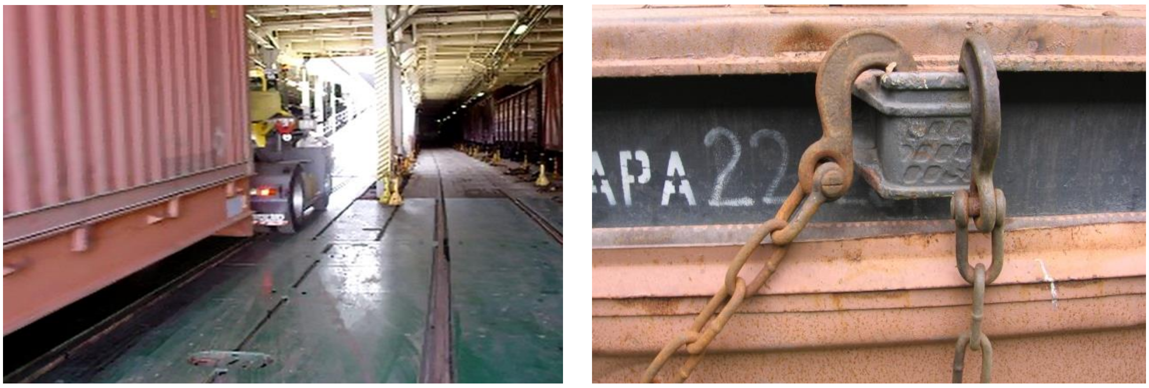
There is a known case when, as a result of an unreliable anchorage in the Mediterranean Sea during a storm on 8 December 1966, on the Greek ferry ship "Heraklion", a refrigerated trailer fell off the attachment and damaged the ferry gate through which water entered the cargo deck. As a result, the ship lost stability, threw on board, and sank [16].

Earlier, on 26 September 1954, during Typhoon Maria (Japan), five ferry ships of the Seikan N.R. company were lost, in chronological order: Hidaka Maru, Kitami Maru, No. 11 Seikan Maru, Tokachi Maru, and Toya Maru. The first four of them are railway ships, which were able to take on board 44 railway wagons [17].

The reason for the accidents of ferry ships is also the unreliable fastening of wagons on the decks. For example, on 8 September 1966, in the Skagerrak Strait (Norway), due to damage to the cargo gate, the Norwegian ferry Skagerrak lost its stability and turned over on board [18].

Therefore, the issues of transportation of railway vehicles by sea require special attention, as they concern both operational safety and environmental aspects.

A study on dynamic load of the load-bearing structure of the wagon body during transportations on a railway ferry was given in [19,20]. There was a mathematical model describing the fluctuations of a wagon during the transportation on a railway ferry, taking into account the rigid interaction relative to the deck. The mathematical modelling results were confirmed by computer modelling. However, the issue of container dynamic load within combined transport trains during transportation on a railway ferry was not addressed in these works.



(**a**) (**b**)

**Figure 1.** Combined transport trains (**a**) rolling of combined trains onto a rail ferry; (**b**) fastening a container train on the deck of a railway ferry.

Analysis of the load-bearing structure of the new-generation flat wagon was carried out in [21]. The paper presents the results of static calculations prepared in accordance with relevant standards for this type of construction. Structural features of a long base flat wagon were covered in [22]. The special feature of the wagon was the absence of a spinal beam along the length of the frame. The results of strength calculations of the flat wagon load-bearing structure were given, which were realized in an ANSYS finite element software. It is important to note that these structures of flat wagons did not provide for the stability of containers when transported on a railway ferry.

Forces acting on wagons during their transportation on a railway ferry by sea were determined in [23]. Investigations were carried out on an open top wagon loaded with bulk cargo. The defining of container load within combined transport trains during transportation on railway ferries has not been paid attention to up to now. Stress–strain state of a container body, while lifting it by a crane and dragging, was analyzed in [24]. Definition of strength indicators was carried out in the APM Machine package. Experimental research of strength was conducted with the help of electrical strain gauging method. Peculiarities of building a container for fruit and vegetable produce transportation were highlighted in [25]. The article included requirements for a container body, provided its suggested structure, as well as illustrated strength calculations on the basis of the finite element method. Significantly, the study of container dynamic load has not been conducted in the works mentioned above, but the definition of strength indicators has been carried out, taking into account normative values of loads.

Dynamic load of a container under operational load modes was determined in [26]. The obtained values of dynamic loads were taken into account during container strength calculations in an ANSYS environment. Peculiarities of floor strength calculations for a 40-feet container conducted in Abaqus/CAE v 6.1 complex were outlined in [27]. Recommendations were offered in terms of safe operation of this type of container. Measures aimed at reduction of the container dynamic load during combined transportation have not been offered in the works considered above.

The methodology for determining the forces acting on a wagon during transportation by a railway ferry is presented in [28]. A brief outline of the development of ferry services is provided. The technology of fixing wagons on the decks of railway ferries is considered. The main forces acting on the wagon during the ferry rolling are determined. In this case, the dynamic load on the wagon is determined by differentiating the law of motion of the sea wave. Moreover, the paper considers the issues of carriage stability on deck in conditions of sea waves. At the same time, the author does not propose measures to improve the wagon's supporting structure in order to adapt to safe transportation on a railway ferry.

In the study by [29], design features and the interaction of means for securing wagons on the decks of railway ferries that are operated in the Caspian Sea are considered. Moreover, special ship devices that are used on railway ferries serving the main world ferry routes are considered in the work.

The issues of carriage fastening on railway ferries are regulated [30]. Recommendations on the use of removable fasteners and wagon location on a ship as well as safety requirements for mounting wagons on decks are given. There are also other analogues of this document [31,32].

It is important to note that the removable fasteners (chain ties with lashings) have a rigid interaction with the supporting structure of the wagons and do not provide the possibility of reducing their dynamic load. Therefore, the goal of this article was to study the dynamic load of a container placed on a flat wagon, taking into account their viscous interaction during transportation on a railway ferry.

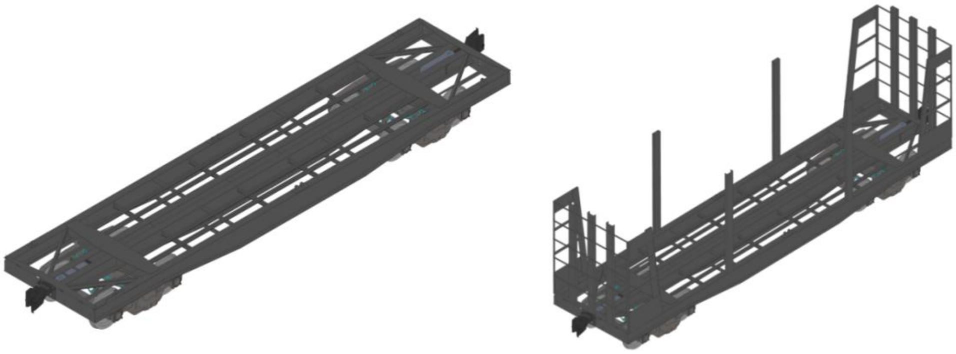
To achieve this goal, the following tasks are defined:

- To improve the load-bearing structure of the flat wagon in order to ensure the stability of containers during transportation by a railway ferry. This is done by placing removable superstructures on the wagon-supporting structure. At the same time, on the inner surface of the superstructures, there is a material with viscous energy-absorbing properties
- To conduct mathematical modelling of the dynamic load of containers, taking into account the new scheme of interaction with the flat wagon. The simulation results will make it possible to determine the more precise definition of the dynamic load, which acts on the supporting structure of the flat wagon during transportation by sea
- To conduct a computer simulation of the dynamic load of containers, taking into account the new scheme of interaction with the flat wagon. The results of computational modelling will make it possible to determine the numerical values of accelerations and their dislocation fields on the supporting structure of a flat wagon with containers, as well as to check the adequacy of the developed mathematical model.

## 2. Improvement of the Load-Bearing Structure of the Flat Wagon

The purpose of this section is to highlight the features of improving the supporting structure of a flat wagon for the safe transportation of containers on a rail ferry by sea. Research conducted by the authors of the article has established that the typical scheme of interaction between the wagon and the container does not ensure the stability of the container during sea transportation [8]. In this regard, it is advisable to use wagons of model 13-9744 (TU 3182-002-47766175-2004) with special superstructures for transporting containers as part of combined trains.

It is also possible to install such removable superstructures on the supporting structures of other models of wagons that are used for railway and ferry transport. Since the fleet of universal flat wagons has a larger number of units than a specialized one, such a solution will allow for the adaptation of universal flat wagons for the carriage of containers by sea on railway ferries. As part of this study, the model 13-401 wagon was selected as a prototype. This model of a flat wagon was chosen as a prototype because there is a project of its modernization for container transportation, developed by the Research and Development Centre "Wagons" (Russia). This modernization consists of placing fitting stops on the supporting structure for fastening and transporting containers. However, the authors of the article propose further improvement of this wagon for the possibility of safe transportation of containers by sea. The load-bearing structure of the wagons, in view of the installation of removable superstructures, is shown in Figure 2.



(**a**) (**b**)

**Figure 2.** Flat wagon of model 13-401: (**a**) typical design of a flat wagon; (**b**) improved flat wagon design.

For fastening containers on the main longitudinal beams of the frame, hinged fitting stops are installed, which makes it possible to transport containers of different standard sizes. The superstructures interact with the supporting structure by welding. The load-bearing elements of the superstructures are made of the same profiles as on the 13-9744 flat wagon. The installing of a material with viscous properties on the internal surfaces of superstructures has been proposed to reduce the dynamic load of containers. Elastomer is one option. When the supporting structure of the container interacts with such material, partial damping of natural vibrations occurs, which takes place during the roll of the ship. It is possible to use other materials with similar energy-absorbing properties.

## 3. Mathematical Modelling of the Dynamic Load of Containers

To determine the dynamic loads that act on the supporting structure of the flat wagon and container, we carried out mathematical modelling. The calculation scheme is shown in Figure 3, wherein the angular movements of the railway ferry relative to the longitudinal axis, which passes through its center of gravity, are taken into account. This type of oscillation in seafaring practice is called rolling. In the "dynamics of wagons", such vibrations are called lateral pitching. When transporting wagons by sea, the lateral rolling of a railway ferry has the greatest impact on their stability with respect to decks.

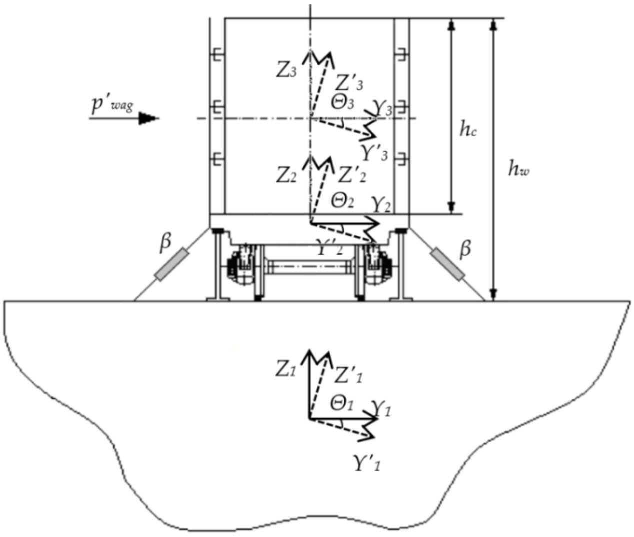



**Figure 3.** Diagram of a flat wagon with a container.

At the same time, we considered that fixing the wagon relative to the deck of the railway ferry should be carried out according to a standard scheme. In other words, to de-load the spring suspension of the flat wagon, we used four mechanical stop-jacks, which were installed under the pivot beams of the frame. Eight chain binders were also used, which were attached to the supporting structure of the wagon at one end, and to the deck eye at the other. We also installed break shoes under the end wagons in the couplings. The end wagons in the couplings also interact with dead-end stops.

A mathematical model developed by the authors that describes the movement of the supporting structure of a flat wagon with containers during oscillations of a railway ferry is given below:

$$\left.\begin{array}{c} I_S^{\theta}\cdot\ddot{q}_1+\left(\Lambda_{\theta}\cdot\frac{B}{2}\right)\dot{q}_1=p'_w\cdot\frac{h}{2}+\Lambda_{\theta}\cdot\frac{B}{2}\cdot\dot{F}(t), \\ I_{wag}^{\theta}\cdot\ddot{q}_2=p'_{wag}\cdot\frac{h_w}{2}+M_{wag}^{c}+M_{wag}^{h}, \\ I_c^{\theta}\cdot\ddot{q}_3=p'_c\cdot\frac{h_c}{2}-\beta\cdot h_c\cdot\dot{q}_3+M_c^{wag}, \end{array}\right\} \quad (1)$$

where $q_1 \approx \theta_n$—generalized coordinate that corresponds to the angular movement around the longitudinal axis of a railway ferry; $q_2 \approx \theta_w$—generalized coordinate, which corresponds to the angular movement around the longitudinal axis of the flat wagon; $q_3 \approx \theta_c$—generalized coordinate that corresponds to the angular movement around the longitudinal axis of the container; $I_S^{\theta}$—moment of inertia; $B$—width; $h$—depth; $\Lambda_{\theta}$—coefficient of resistance to vibrations; $p'_w$—wind load on the surface projection; $F(t)$—law of action of the effort that causes the movement of a railway ferry with wagons placed on its decks; $I_w^{\theta}$—moment of inertia of the flat wagon; $h_w$—height of the side surface of the flat wagon; $p'_{wag}$—wind load on the side surface of the flat wagon; $M_{wag}^{c}$—moment of forces that occurs between the flat wagon and the deck of a railway ferry during angular movements relative to the longitudinal axis; $M_{wag}^{h}$—moment of forces that occurs between the flat wagon and containers during angular movements relative to the longitudinal axis; $I_c^{\theta}$—moment of inertia of a container; $h_c$—height of the side surface of the container; $p'_c$—wind load on the side surface of the container; $M_c^{wag}$—moment of forces that occurs between the container and the flat wagon during angular movements relative to the longitudinal axis; $\beta$—coefficient of viscous resistance between the load-bearing structure of the flat wagon and the container.

It is important to note that this mathematical model has no analogues, since the proposed technical solutions were developed by the authors of the article. Previously, the issues of transporting combined trains by sea, as well as the improvement of the supporting structures of flat wagons for safe transportation by sea, were not considered.

The moment of inertia of a vessel was determined according to the classical formula [33]

$$I_s^{\theta}=\frac{D}{12g}\left(B^2+4z_g^2\right), \quad (2)$$

where $D$ is ship displacement, and $z_g$ is coordinate of the center of gravity.

The coordinate of the center of gravity of a vessel with cargo on board is determined by [33]

$$z_g=\frac{1}{D+m_1+m_2+\cdots+m_n}\sum D\cdot z_c+m_1z_1+m_2z_2+\cdots+m_nz_n, \quad (3)$$

where $m_1, m_2, \ldots, m_n$ are cargo masses, and $z_1, z_2, \ldots, z_n$ are distances of the center of gravity of the cargo from the main plane (keel).

The distance of the center of gravity of the vessel above-water surface from the current waterline is given by

$$z_c=\frac{S_1z_c+m_1z'_1+m_2z'_2+\cdots+m_nz'_n}{S_1+S_2+\cdots+S_n}, \quad (4)$$

where $S_1, S_2, \ldots, S_n$ are areas of figures into which the side projection of the surface of the ship is divided, and $z'_1, z'_2, \ldots, z'_n$ are distances of the center of gravity of areas $S_1, S_2, \ldots, S_n$ from the current waterline.

Determination of the coefficient of resistance to vibrations of a railway ferry was carried out according to the method given in [33,34].

When determining the accelerations that act on the flat wagon with containers, the course angles of the wave in relation to the body of the railway ferry are taken into account

$$\chi = k\lambda \cdot L \cdot \cos(\alpha), \quad (5)$$

where $k\lambda$ is a coefficient that depends on the shape of the vessel contours, $L$ is length of the vessel, and $\alpha$ is the angle of the wave relative to the body.

During the model building process, the impact action of sea waves was not taken into account. The motion of the wave was described as a trochoidal law.

When determining the moments of forces arising between the flat wagon and the deck, as well as between the flat wagon and the container, we took into account the horizontal components of the gross weight of the flat wagon and the container, respectively.

Since container trains are placed on the decks of a railway ferry and repeat its trajectory during oscillations, we took into account the technical characteristics of the vessel when creating and solving the mathematical model (1). Accelerations that act directly on the railway ferry and on container trains placed on decks depend on these characteristics.

Calculations were made for the railway ferry "Heroes of Shipka", running in the Black Sea waters. The main technical characteristics of the railway ferry are given in Table 1 [35].

**Table 1.** Main technical characteristics of the ship ferry "Heroes of Shipka".

| Parameter Name | Value |
|---|---|
| Length, m: | |
| Maximum | 184.25 |
| Between perpendiculars | 170 |
| Width | 26 |
| Height, m: | |
| To the upper deck | 15.2 |
| To the main deck | 9 |
| Draft, m | 6.5 |
| Deadweight, t | 12,889 |
| Displacement, t | 23,744 |
| Speed, knots | 18.6 |
| Wagon capacity, pcs. | 108 |

The parameters of the disturbing effect (sea waves) were determined on the basis of the reference literature (Table 2) [36].

**Table 2.** Parameters of sea waves used in mathematical modelling.

| Parameter Name | Numerical Value |
|---|---|
| Sea wave height, m | 8 |
| Sea wave period, s | 9 |
| Heading angle of a wave, degree | 0–180 |
| Wind pressure on the surface projection of the vessel, kPa | 1.47 |

The solution of the system of differential Equation (1) was performed using the Runge–Kutta method in the MathCad environment [37–43]. For this purpose, the transition was made from systems of second-order differential equations to systems of first-order differential equations, followed by the use of standard algorithms for solving systems using the rkfixed function of Mathcad.

That is, when $y_1 = \theta_1,\ y_2 = \dot{\theta}_1,\ y_3 = \theta_2, y_4 = \dot{\theta}_2,\ y_5 = \theta_3, y_6 = \dot{\theta}_3$, it follows that

$$Q(t,\ y) = \left| \begin{array}{c} y_2 \\ y_4 \\ y_6 \\ \frac{p'_w \cdot \frac{h}{2} + \Lambda_\theta \cdot \frac{B}{2} \cdot \dot{F}(t) - \left(\Lambda_\theta \cdot \frac{B}{2}\right) y_2}{I_S^\theta} \\ \frac{p'_{wag} \cdot \frac{h_w}{2} + M^c_{wag} + M^h_{wag}}{I^\theta_{wag}} \\ \frac{p'_c \cdot \frac{h_c}{2} - \beta \cdot h_c \cdot \dot{q}_3 + M_c^{wag}}{I_c^\theta} \end{array} \right|, \tag{6}$$

$$Z = rkfixed(Y_0,\ tn,\ tk,\ n',\ Q),$$

where $Y_0$ is a vector containing the initial conditions, *tn* and *tk* are values that define the initial and final integration variable, n′ is fixed number of steps, and $Q$ is character vector.

The initial displacements and velocities were assumed to be zero. The coefficient of viscous resistance should be in this case in the range 0.5–1.2 kN·s/m. On the basis of the calculations, we found that the greatest acceleration values occurred when the course angles of the wave in relation to the body of the railway ferry were $\chi$ = 60° and $\chi$ = 120°. At the same time, the maximum acceleration of the container was about 1.5 m/s$^2$ (see Figure 4) of the flat wagon 0.4 m/s$^2$ (see Figure 5). The numerical values of accelerations were given without taking into account the component of gravitational acceleration.

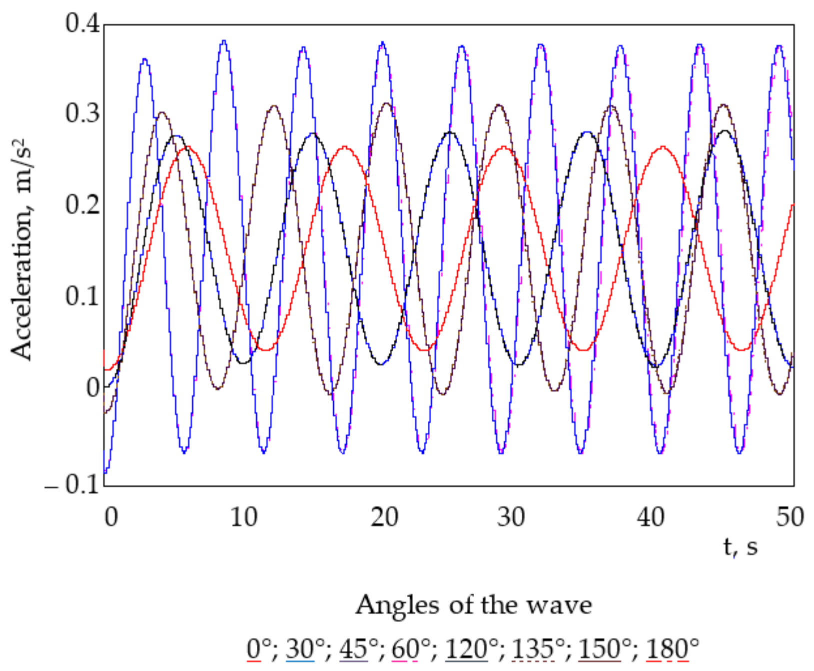



**Figure 4.** Accelerations acting on the load-bearing structure of the flat wagon when transported on a railway ferry.

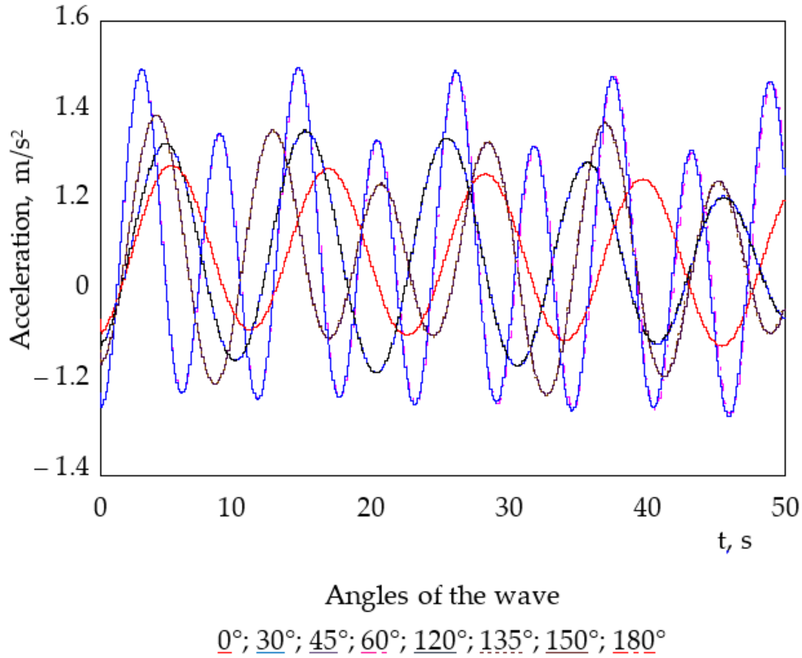



**Figure 5.** Accelerations applied to the container during transportation on a railway ferry.

The total amount of acceleration can be determined:

$$\ddot{\theta}_t = \ddot{\theta}_{prt} + g \cdot \sin\theta, \tag{7}$$

where $\ddot{\theta}_{prt}$ is acceleration, which applies to the regular position of the flat wagon with containers on the deck; g is gravitational acceleration; and $\theta$ is roll angle of the railway ferry.

Considering the hydrometeorological characteristics of the Black Sea area and the surface projection of a railway ferry of the "Heroes of Shipka" type, we obtained a value of $\theta$ = 12.2° for the roll angle of a railway ferry. The roll value was calculated for the case of static wind action on the surface projection of a railway ferry [33]. Then, the total amount of acceleration that acts on the container was 3.57 m/s$^2$ (0.36 g), and on the load-bearing structure of the flat wagon was 2.47 m/s$^2$ (0.25 g).

Therefore, the introduction of a viscous connection between the load-bearing structure of the flat wagon and the containers made it possible to reduce the dynamic load by 38% and 23%, respectively, compared to the typical interaction scheme. Dynamic load is the main factor that affects the stability of a flat wagon with containers when transported on a rail ferry. Consequently, due to the decrease in the dynamic load that acts on the container placed on the flat wagon, its stability is also improved during oscillations of the railway ferry.

## 4. Results

To check the adequacy of the mathematical model (1), we carried out a computer simulation of the dynamic load of a container placed on a flat wagon. For computer simulation of the dynamic load of a flat wagon with containers based on the suggested solution, we used the CosmosWorks package [44–47]. The calculation was done using the finite element method. Spatial isoparametric tetrahedra were used to build the finite element model. The optimal number of finite elements was determined by the graphical and analytical method [48–51]. The number of nodes was 302,512 and the number of elements was 883,801. The maximum element size was 100 mm, the minimum size was 20 mm. The design scheme considered that the carrying structure was affected by the vertical load of the container gross weight $P_{gw}$, the tension of chain binders $P_f$, the wind load $P_w$, as well as the horizontal load of the container on superstructure $P_h$, due to fluctuations of the flat wagon (see

Figure 6). Since the chain coupler has certain angles of inclination relative to the wagon when securing, when creating the computational scheme, the load that is transmitted to the supporting structure of the flat wagon through the chain coupler is laid out in three components. At the same time, the angle of inclination of the chain coupler was taken into account: in the plane YZ, the angle of inclination was 30°, for XY and XZ it was 60°.

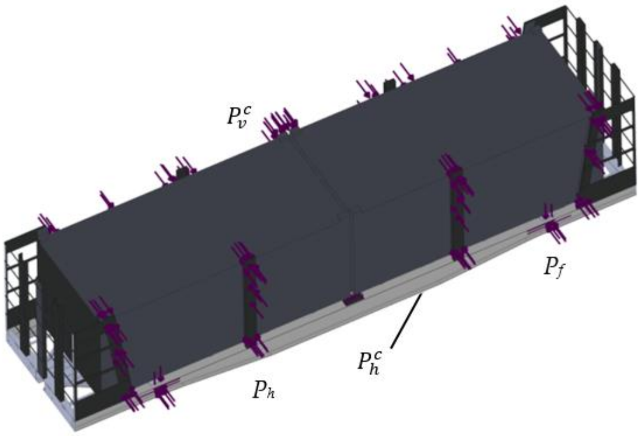



**Figure 6.** Design scheme of the load-bearing structure of the flat wagon with a container.

The container was subjected to the vertical static load $P_v^c$, the horizontal load in the areas of interaction with superstructures $P_h^c$, as well as the wind load on the side surface $P_w^c$.

Fixing the model was carried out in the areas where it rests on the bogies as well as the working surfaces of mechanical stop-jacks. To do this, the model was fitted with pads, the area of which was equal to the area of the working surfaces of the stop-jacks. The carrying structure material was 09G2S [52–54]. Between the interaction zones of the container and the superstructures of the flat wagon, we established a viscous linkage with a coefficient of viscous resistance 1.2 kN·s/m. The results of calculating the acceleration of a container placed on a flat wagon, taking into account different roll angles of a railway ferry, are shown in Figure 7. The maximum acceleration in this case affected the upper part of the containers along the central axis of the symmetry of the load-bearing structure of the flat wagon and was about 2.6 m/s$^2$.

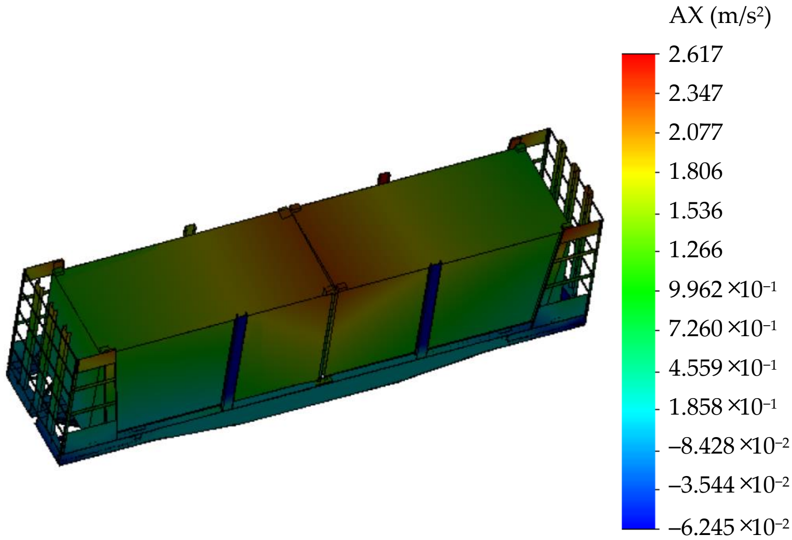



**Figure 7.** Distribution of acceleration fields relative to the load-bearing structure of a flat wagon with containers.

The accelerations acting on the container obtained by theoretical and computer modelling are shown in Figure 8, which shows that the maximum percentage of discrepancy between accelerations was 17.7% at the roll angle 10°.

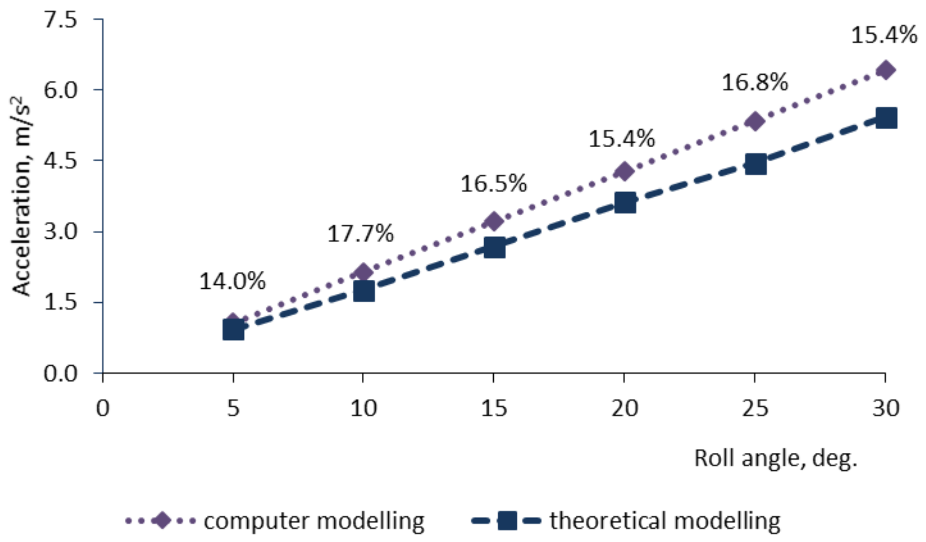



**Figure 8.** Dependence of container accelerations on the roll angle of a railway ferry and differences in the results of the theoretical and computer solution in percent.

Thus, given the viscous connection between the flat wagon and the container during transportation on a railway ferry, it becomes possible to reduce the dynamic load of the container supporting structure and improve the safety of sea transport.

The F-criterion was used to check the adequacy of the mathematical and computer models developed by the authors. The roll angle of the railway ferry was taken into account as a variation parameter (5°–30°). If the value of the dispersion adequacy $S_a = 6.0$ and the dispersion reproducibility $S_y = 4.21$, the calculated value of the criterion was $F_p = 1.41$, which was less than tabular $F_t = 4.53$. Hence the hypothesis of adequacy was not rejected.

In the future, it is planned to conduct a physical experiment aimed at studying the dynamic load of a container placed on a flat wagon during transportation by sea.

## 5. The Discussion of the Results

To ensure the safe transportation of containers as part of combined trains on railway ferries, we proposed the improvement of the supporting structure of the flat wagon. A feature of the flat wagon is the presence of superstructures, the inner surface of which is equipped with a viscous material with energy-absorbing properties. To substantiate the proposed technical solution, the authors have created a mathematical model that describes the process of moving the supporting structure of a flat wagon with containers during the rolling of a railway ferry. The limitation of the model is that it does not take into account the shock effect of sea waves on the hull of the rail ferry. In addition, the model cannot be used to study the dynamic loading of a tank container. The results of solving the mathematical model made it possible to determine the accelerations as the components of the dynamic loads that act on the supporting structure of the flat wagon with containers. In this case, the acceleration to the supporting structure of the flat wagon was 0.25 g (Figure 4), and on the container was 0.35g (Figure 5).

To determine the fields of acceleration distribution, as well as to check the results obtained by mathematical modelling, we carried out computer modelling of the dynamic load of the load-bearing structure of a flat wagon with containers (Figure 7).

We used the F-criterion in order to check the adequacy of the mathematical and computer models developed by the authors. It was found that the hypothesis of adequacy was not rejected. In subsequent studies in this area, it is important to consider the issues of the stability of the railway ferry when transporting trains of combined transport [55], as well as issues related to the energy efficiency of loading and unloading operations [56].

In further studies of the issues of dynamic loading of containers in combined trains, we plan to conduct a physical experiment. This experiment will be carried out using the electrical tensometry method. The research is planned to be carried out on the railway ferry "Heroes of Shipki" while sailing in the Black Sea. The conducted studies are a useful technical basis in the creation of load-bearing structures of flat wagons and containers of a new generation. Moreover, the results obtained will contribute to the expansion of regulatory documents that cover the issues of rail transport by sea.

## 6. Conclusions

The load-bearing structure of the flat wagon was improved in order to ensure the stability of containers during transportation by a railway ferry. We proposed the installation of removable superstructures on the supporting structure of the flat wagon. To reduce the dynamic load of containers, we proposed the installation of a material with viscous properties on the internal surfaces of the flat wagon superstructures.

Mathematical modelling of the dynamic load of containers was carried out, considering the new scheme of interaction with the flat wagon. On the basis of the conducted calculations, we found that the greatest acceleration values occurred at the course angles of the wave relative to the body of the railway ferry $\chi = 60°$ and $\chi = 120°$. The total amount of acceleration that acted on the container was 3.57 m/s$^2$ (0.36 g) and on the load-bearing structure of the flat wagon was 2.47 m/s$^2$ (0.25 g).

The viscous connection between the load-bearing structure of the flat wagon and the containers made it possible to reduce the dynamic load by 38% and 23%, respectively, compared to the typical interaction scheme.

Computer simulation of the dynamic load of containers was performed, taking into account the new scheme of interaction with the flat wagon. The maximum acceleration applied to the container was about 2.6 m/s$^2$. The maximum percentage of discrepancy between the accelerations obtained by theoretical and computer modelling was 17.7%.

The conducted studies will contribute to improving the efficiency of combined transport and may also be useful developments in the creation of new designs of flat wagons.

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