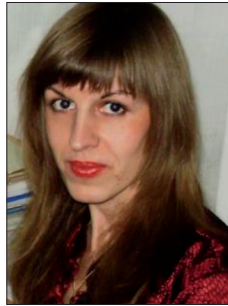# Research of dynamic loads acting on the supporting structures of car bodies in train ferries

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Abstract

The results of researches of dynamics of supporting structures of bodies of freight cars during transportation on railway trains are given. The mathematical model for definition of accelerations occurring at car bodies placed towards the decks of railway trains in the conditions of sea disturbance is developed.

For the purpose of approbation of the results obtained, computer modeling of dynamics of cars during transportation on railway trains in the conditions of main types of oscillatory processes is carried out.

Results of the conducted researches will promote creation of cars of new generation for operation in the international railway-water communication.

Keywords: CAR, CAR DYNAMICS, CONSTRUCTION LOADING, RAILWAY-WATER TRANSPORT, RAILWAY AND FERRY TRANSPORTATIONS

Formulation of the problem

The agreement on free trade zone of Ukraine with the EU countries determines the development prospects of its participation in maritime transportation of European countries. In order to increase the volume of cargo transportation through the international transport corridors that pass across the Black Sea area the development of rail and ferry transportation is forecasted.

The cars movement by train ferries (TF) in the sea in conditions of its commotion is accompanied by the appearance and acting on the body supporting structure of different types of forces determining of which are dynamic forces. Therefore, to ensure the safety of TF cars motion it is necessary to research the dynamic forces acting on the supporting structure of bodies during transportation by sea.

Analysis of the latest researches

Investigation of dynamic forces acting on the bodies of cars during TF transportation in sea commotion conditions are given in [1]. Disadvantages of the above method are the inability of accounting angle of wave approach relative to the TF body and the wind force which acting on the abovewater TF projection with cars bodies placed on its upper deck. In addition, this technique can only be considered for plane waves.

Assessment of external forces acting on the cars during TF transportation is given in [2]. In this case the acceleration acting on the cars bodies in the conditions of commotion are determined based on the calculation of TF rocking that happens with six degrees of freedom in a three-dimensional irregular commotion at a speed of 6.5 knots.

This technique can be used for single-deck TF of a limited navigation area.

Researches of the car body dynamics during TF transportation are given in [3]. A mathematical model of TF bodies movement was developed in order to determine the accelerations acting on the cars bodies during their transportation by sea. The disadvantages of this model are the absence of wind load action on the abovewater TF projection with the cars bodies placed on the upper deck.

The purpose of the article

To research the dynamic loads acting on the supporting structure of car bodies during transportation by train ferries.

Statement of the main article material

Dynamic of sea waves has a significant influence on the magnitude of the forces acting on the cars bodies during TF transportation. When assessing the seaworthiness of the vessel for describing the regular commotion formulas of the theory of progressive waves of relatively low amplitude are most commonly used.

Profile of trochoidal wave is described by equations in parametric form [4]:

$$x = a + \text{Re}^{kb} \sin(ka + \omega t)$$
$$z = b - \text{Re}^{kb} \cos(ka + \omega t) \tag{1}$$

where a and b – horizontal and vertical coordinates of the center trajectory at which particle is rotating has current coordinates x and z; R – trajectory radius at which particle rotates, m; ω – frequency of the sea wave, s^{-1}; k – frequency of disturbing force trajectory .

TF oscillations with cars on its board in conditions of sea commotion can be considered as the oscillations of a rigid body with weights attached to it. The forces proportional to the magnitude of TF movement in respect to the first starting position occur during these oscillations. These forces are presented in the form of additional buoyancy forces of TF body [5]. Therefore, TF is considered as a rigid body with three degrees of freedom (Fig 1.):
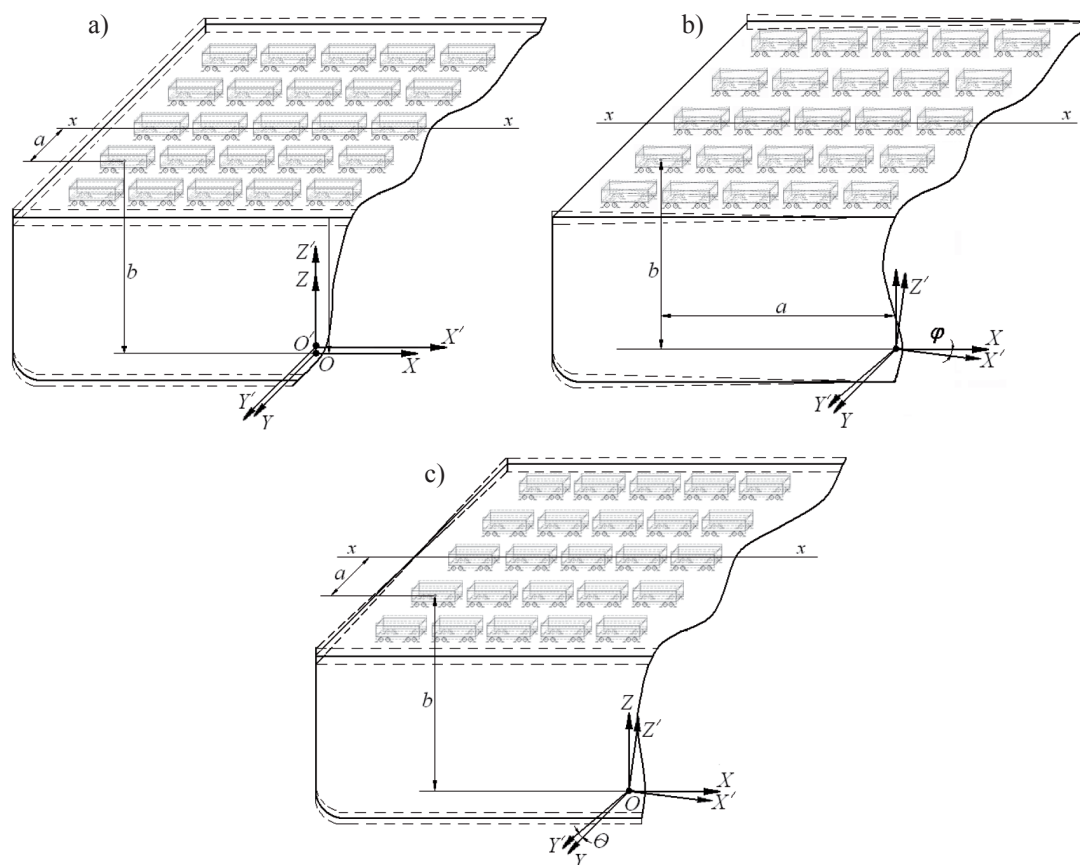
Figure 1. Moving the car body in sea commotion conditions
a) in the vertical direction; b) about the transverse axis; c) about the longitudinal axis

– progressive movement in the vertical direction of the axis Z (Fig. 1a));

– angular movements about the cross axis Y on the angle φ (Fig. 1, b));

– angular movements about the longitudinal axis X on the angle θ (Fig. 1, c)).

The other three possible movements (translational movement longitudinally relative to the X axis, the angular movement about the Z axis by the angle ψ, translational movement transversely to the axis Y) cannot be in the nature of oscillatory motion because they are not accompanied by changes in the size or shape of the underwater volume of TF body [5, 6].

In the case of TF oscillations with cars on board in commotion conditions in addition to the rotational movements about the longitudinal and transverse axes passing through its center of gravity, it also receives a movement in which these axes move along some trajectories close to a circle. This movement occurs with a period which is equal to the period of the wave. The radius of this movement trajectory of TF with the cars on board can be accepted in the calculation equals half of the sea wave height.

Significant impact on the value of the forces acting on the cars bodies in the conditions of the sea commotion has their placing relatively TF decks. So, the cars that are located at the extreme platforms from the bulwark with angular TF movements about the longitudinal axis will have bigger loads, than cars, which are closer to the diametrical plane of TF. The same situation is also observed at angular TF movements about the transverse axis, i.e. the extreme from sternpost cars will have greater forces than the cars, which are located closer to the plane of the midship frame.

A mathematical model of the TF car body movement has been developed in the cars department of Ukrainian State University of Railway Transport in order to determine the inertial component of the load acting on the supporting structure of cars bodies during TF transportation in the sea commotion conditions, which has the form:

$$D' \cdot \ddot{q}_1 + \Lambda_z \cdot \dot{q}_1 = \Lambda_z \cdot \dot{F}(t); \qquad (1)$$

$$\left(0.07\frac{0.8}{g}D \cdot L^2\right)\ddot{q}_2 + \left(\Lambda_\varphi \cdot \frac{L}{2}\right)\dot{q}_2 = p' \cdot \frac{h}{2} + \Lambda_\varphi \cdot \frac{L}{2} \cdot \dot{F}(t); \qquad (2)$$

$$\left(\frac{D}{12 \cdot g}(B^2 + 4z_g{}^2)\right)\ddot{q}_3 + \left(\Lambda_\theta \cdot \frac{B}{2}\right)\dot{q}_3 = p' \cdot \frac{h}{2} + \Lambda_\theta \cdot \frac{B}{2} \cdot \dot{F}(t), \qquad (3)$$

where $q_1 = z, q_2 = \varphi, q_3 = \theta$ – generalized coordinates corresponding: z – movement of the body relative to the vertical axis that passes through its center of mass, φ – angular movement about the transverse axis, θ – angular movement about the longitudinal axis. The beginning of the coordinate system is located in the center of mass of TF.

D' – mass water repellency, t; D – weight water repellency, kN; L, B –length and the width of TF, respectively, m; h – moulded depth of TF, m; Λ_i – oscillations resistance coefficient, kN·s·m^{-1}; z_g – TF center of gravity coordinate, m; p' – wind load, kN; $F(t)$ – law of force action, which disturbs the movement of TF with the cars bodies placed on its decks.

The drag coefficient by moving TF is defined by the following formula:

$$\Lambda_i = \int\limits_{-L/2}^{L/2} \rho\omega T^2 \overline{\Lambda}_i dL, \qquad (5)$$

where $\overline{\Lambda}_i$ – dimensionless damping coefficient determined by graphical dependencies from the reference books, in accordance with the technical specifications of TF [7].

When compiling a mathematical model taken into account that the car body is rigidly fixed relative to the supporting plane and performs the movement with it. The impact action of the sea waves on the TF body with cars placed on its board has not been taken into account. [8]

The input parameters of the mathematical model are geometric characteristics of TF [9, 10], hydrometeorological characteristics of the Black Sea [11], coordinates of the cars bodies placement relative to the oscillations center of TF [12].

Differential equations of motion of the car body (2-4) were carried out by the method of variation constants.

In order to solve the differential equations of the car body motion the program of calculation in Mathcad package was made up [13, 14], for which they were reduced to the normal Cauchy form and then integrated by the Runge - Kutta method. The results obtained are shown in Fig. 2.

In the study of the cars bodies dynamics under condition of following the sea area by TF each type of oscillation process was considered separately, the duration of which was assumed to be equal to the period of wave, the disturbance nature was trochoidal, the amplitude equaled a maximum wave height for the specified sea area and the frequency was determined by course angle of the wave with respect to the TF body.

Fig. 2a) shows the acceleration of the car body in conditions of translational movements of TF in the vertical direction taking into account different wave course angles relative to the body ($0^0, 30^0, 45^0, 60^0, 90^0, 120^0, 135^0, 150^0, 180^0$).

The maximum acceleration is observed at course angle of the wave with respect to the plane of the TF
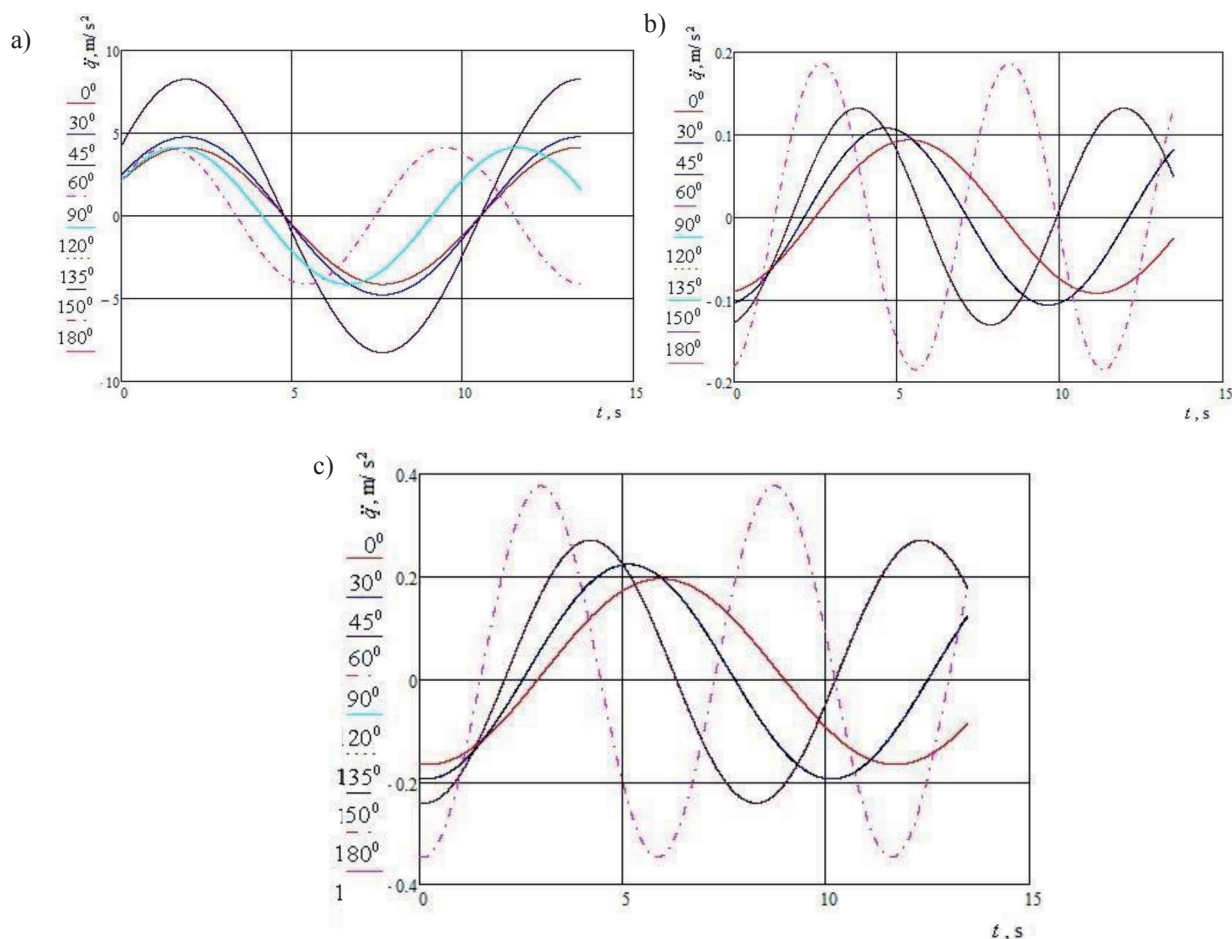
Figure 2. Acceleration of the car body when TF oscillation
a) when translation movements of TF in the vertical direction; b) when the angular movements about the transverse axis; c) when the angular movements about the longitudinal axis

body $\chi = 60^0$, the lowest frequency of the acceleration is observed at $\chi = 135^0$.

Fig. 2b) shows the acceleration of the extreme TF from the sternpost (aft body) for the car of the main deck in sea commotion conditions taking into account the different course angles of the wave with respect to TF body. The greatest value of the acceleration reaches at course angle of the wave with respect to the TF body $\chi = 120^0$.

Fig. 2, c) reflects the acceleration of cars placed on the extreme platform from the bulwarks of TF upper deck at the angular movements about the longitudinal axis. The greatest value of the cars acceleration occurs when $\chi = 120^0$. In other cases, the value of acceleration is of less importance. The greatest frequency of acceleration changing is observed when $\chi = 120^0$.

Thus, the value of cars accelerations when translation movements of TF in the vertical direction does not depend on their location behind the deck relative to the diametrical and midship planes of TF, but depends on the placement of cars on TF height, i.e. the value of acceleration acting on the cars placed behind

the decks increases with distance from the oscillations center.

The value of cars accelerations when angular movements of TF about the transverse axis depends on the placement of cars relative to the plane of the midship frame.

The acceleration value of car bodies depends on their placement relative to the diametrical plane when angular movements of TF about the longitudinal axis.

For approbation of the results obtained computer modeling of the dynamics of cars placed on TF in conditions of sea rocking was carried out on CosmosWorks software [15]. The spatial model of a fragment TF " Geroi Shipki" type with the car bodies placed relative to its deck are shown in Fig. 3. When compiling the modal the basic structural elements of TF body were taken into account. Model length is 39.6 m and width is 26 m. The car of model 12-757 by PJSC "KRCBW" construction was chosen as a type of the test car.

The Spatial Model of TF fragment with taking into account low-sided cars placed relative to its decks is shown in Fig. 3.
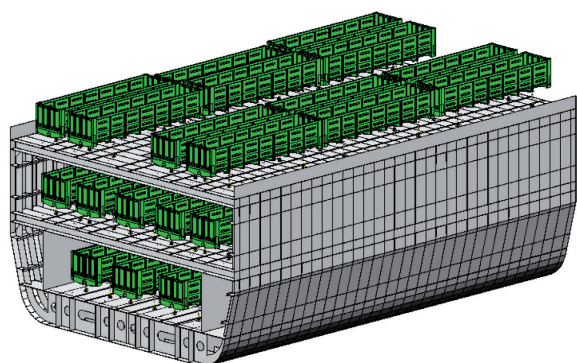
Figure 3. The Spatial Model of TF fragment with low-sided cars placed relative to its decks

Figure 4. Modeling of the interaction of low-sided car body with the mechanical stop-jack
a) mechanical stop-jack in the free state;
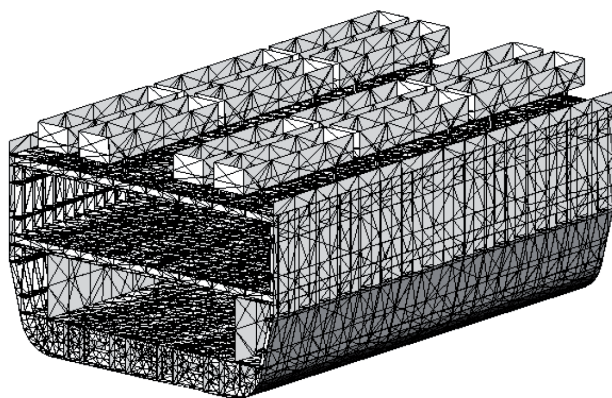b) when interacting with the car body

In order to ensure bearing of the car bodies supporting structures on the deck the Spatial Model of mechanical stop-jack was built on the album of drawings of multiturn fixing means (Fig. 4a, b).

On the basis of prepared spatial model, a model for determining the low-sided cars accelerations placed on TF in conditions of rolling motion was built.
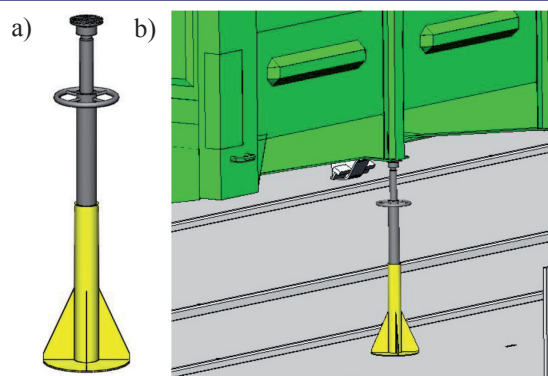
The calculation was performed using the finite element method in CosmosWorks software, version 2015.

FEM of TF with low-sided cars bodies are shown in Fig. 5. When preparing FEM the space isoparametric tetrahedrons were used. The number of grid nodes was 149 223, of elements – 500354. The maximum size of the element was equal to 1000 mm, the minimum – 200 mm. The minimum number of elements in the circle was 15, the ratio of elements sizes increasing in the grid was 1.8. Maximum aspect ratio was $9.5 \cdot 10^5$, the elements percentage with the aspect ratio of less than 3 – 6.96, more than 10 – 81.5.

When preparing the strength model it was taken into account that the following loads acting TF: vertical-static P_v^{st} determined by TF gross weight, wind P_w, hydrostatic pressure $P_{h.s..}$ on the immersed part of TF body, buoyancy force P_a, forces acting on TF deck by cars in the vertical $P_{v.car}^{st}$ and horizontal $P_{h.car}^{st}$ direction, as well as the forces acting on the deck by multiturn cars fixing means , i. e. the chain ties $P_{c.t.}^i$ and mechanical stop-jacks $P_{s.j..}$

Fig. 6 shows the model of TF strength with the cars bodies placed relative to its decks in terms of angular movements about the longitudinal axis, as in case of the highest loading of the supporting structure of cars bodies in conditions of the sea rocking.

In connection to the fact that TF fragment had been considered in the calculations, then in order to account its discarded part the forces (vertical, longitudinal and transverse) were applied in relative cross sections. The forces numerical values were defined by the sectioning method.

When determining the forces acting on the deck of TF by cars placed on it the heeling angle of TF is taken into account while a horizontal load applied from the wheel flanges to the rails from the inside of

Figure 5. FEM of TF fragment of "Geroi Shipki" type with the car bodies
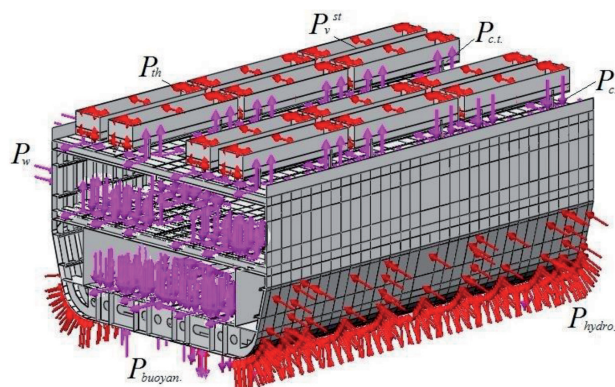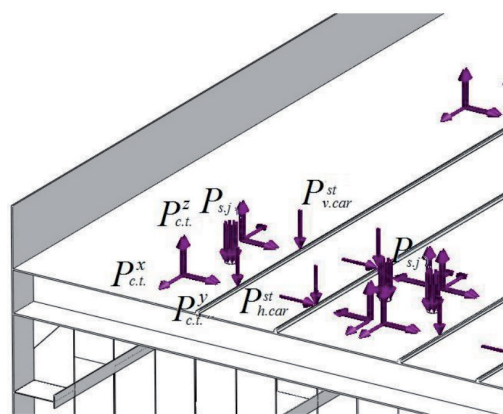

Figure 6. The strength model of TF fragment with cars bodies

the disturbing force includes component of free fall acceleration, wind and inertial loads.

When determining the wind load acting on the abovewater TF projection with the car bodies placed on the upper deck the wind pressure is taken into account which is peculiar to the Black Sea area and is equal to 1.47 kN / m².

The plate configuration of which was identical to the geometry of the zone of frame fixing to the deck was used for modeling of the force acting on the TF deck via chain ties. As a result of spatial distribution of chain ties the force acting on the deck through them was decomposed into components with taking into account ties placement angles in space (Fig. 7). In the areas of the mechanical stop-jacks supporting on TF deck the plates were also installed, which geometry followed the geometry of the stop-jack supporting part on the deck. Force to the plates was determined taking into account TF heeling angle, i.e. it

was unloaded from the outer side of the disturbing force action and from the inside it was loaded.

As the material of TF model the steel of D grade has been applied, which characteristic value of tensile strength is $\sigma_B = 440 - 590$ MPa and yield strength is $\sigma_T = 315$ MPa , the steel 09G2S is used for the supporting structure of the car body with such values $\sigma_B = 490$ MPa and $\sigma_T = 345$ MPa.

The studies take into account that the low-sided car supporting structure is under the influence of the following loads (Table. 1): vertical-static load P_v^{st} determined by car gross weight, wind P_w on the extreme from bulwark cars placed from the side of wind load action, thrust force of bulk cargo P_{th} (coal) and forces acting on the low-sided car body via chain ties $P_{c.t.}^i$.

The fixation of low-sided car body was simulated in the corners formed by the vertical stand of the body with draw-bar in accordance with the «Securing Manual....». Due to the fact that the chain tie has a spatial arrangement, the force that is acting from it on the body has been decomposed into three components.

Results of the research of acceleration acting on the cars bodies placed on TF are shown in Fig. 7. At the same time in order to reduce the calculation time studies were carried out in three stages. In the first stage low-sided cars were placed on the upper deck, second time - on the main, third time – in the bilge.

In order to test the adequacy of the developed model the check by the Fisher test was carried out.

We assume that the considered model is linear, i. e. it is one-factor and represents the change in accelerations of the low-sided car body taking into account

Figure 7. The scheme of forces acting on the TF deck from cars placed on it and from multiturn fixing means

Table 1. The forces acting on the low-sided car body in conditions of rocking in the case of symmetrical fixing relative to the deck

| Car body movement | Forces acting on the low-sided car body | | | | The components of the load acting on the low-sided car body from of chain ties | | | | | |
| | | | | | Wind load, kN | | | The forces from tension of chain ties, kN | | |
	Vertical-static load , kN	Wind load, kN	Thrust force, MPa	Force from chain ties tension, kN	XY	YZ	XZ	XY	YZ	XZ
Translational relative to the vertical axis	829.93	–	$7 \cdot 10^{-3}$	54	–	–	–	$p_x=27$ $p_y=47$	$p_y=27$ $p_z=47$	$p_x=27$ $p_z=47$
Angular relative to the transverse axis (trim different)	$p_x=36,2$ $p_z=829$	0.5	$13.4 \cdot 10^{-3}$ $0.53 \cdot 10^{-3}$	54	$p_x=0.09$ $p_y=0.09$	$p_y=0.06$ $p_z=0.1$	$p_x=0.06$ $p_z=0.1$	$p_x=27$ $p_y=47$	$p_y=27$ $p_z=47$	$p_x=27$ $p_z=47$
Angular relative to the longitudinal axis (heel)	$p_y=175$ $p_z=811$	9.4	$15.5 \cdot 10^{-3}$ $-1.02 \cdot 10^{-3}$	54	$p_x=1.7$ $p_y=1.7$	$p_y=1.2$ $p_z=2.04$	$p_x=2.04$ $p_z=1.2$	$p_x=27$ $p_y=47$	$p_y=27$ $p_z=47$	$p_x=27$ $p_z=47$

their location relative to TF decks. The number of degrees of freedom when $N = 5$ will be $f_1 = 3$.

When determining the adequacy of model in the conditions of TF offensive movements with the car bodies relative to the vertical axis it was established that when dispersion of reproducibility of $S_y^2 = 0.1$ and the adequacy dispersion of $S_{ad}^2 = 0.0375$ the actual value of Fisher test was $F_P = 2.67$, that was less than tabular value $F_t = 5.41$. So the hypothesis of the adequacy model wass not disputed. Approximation error was about 3%.

In conditions of the angular movements of TF with cars bodies relative to the transverse axis the values of dispersion reproducibility $S_y^2 = 0.002$ and the adequacy dispersion $S_{a\partial}^2 = 0.0007$ were obtained. At the same time the actual value of Fisher test $F_P = 2.86$ was less than tabular value $F_t = 5.41$. The hypothesis of the adequacy model was not disputed. Approximation error was about 10%.
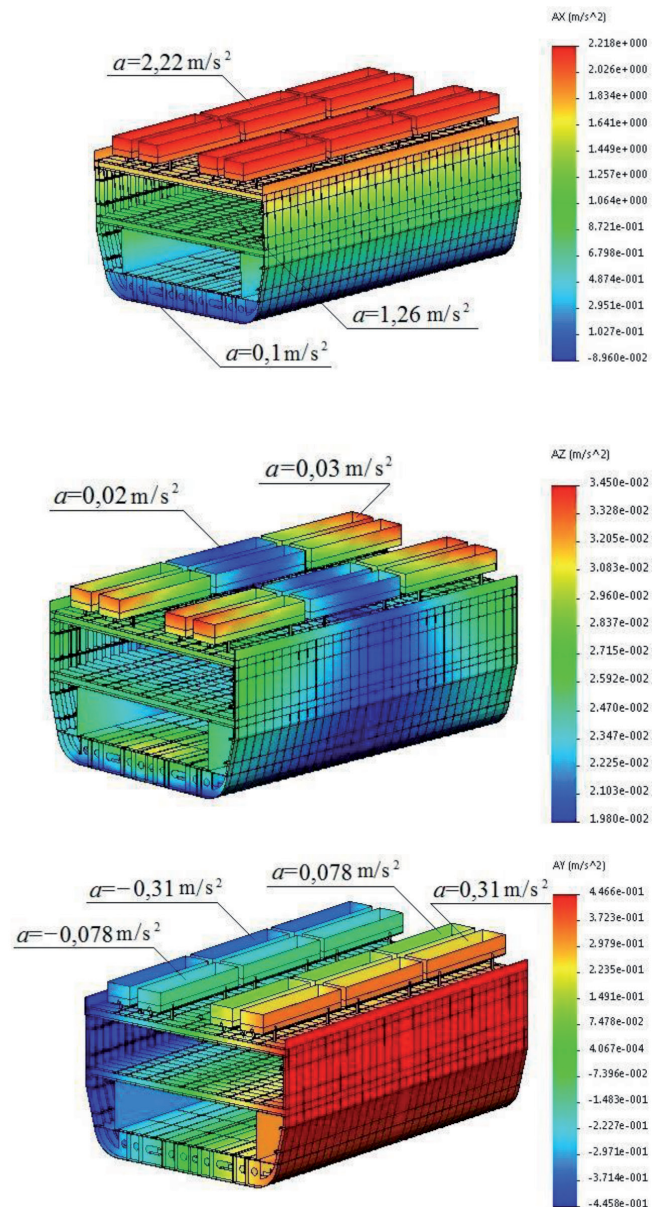
When TF angular movements with the cars bodies relative to the longitudinal axis the values of dispersion reproducibility $S_y^2 = 0.07$, the adequacy dispersion $S_{ad}^2 = 0,017$ were obtained at $f_2 = 5$ it was established that the actual value of Fisher test $F_P = 5.24$ was less than tabular value $F_t = 5.41$. So hypothesis of the adequacy of developed model was not disputed. Approximation error was about 6%.

Conclusions

Based on researches performed we can draw the following conclusions:

1. The mathematical model developed for determining the nature and characteristics of car bodies movements during transportation on the TF by sea offers the possibility of determining the accelerations of cars bodies placed on multi-decker TF with taking into account the wave course angles relative to the body and wind load acting on abovewater TF projection with the cars bodies placed on the decks;

2. For actual commotion conditions of the Black Sea area we obtained the values of maximum acceleration acting on the car bodies placed relative to TF decks, which were as follows: when moving body in a vertical direction for the car located on the upper deck – 8.2 m/s², at angular relative to the transverse axis for the extreme car body from the stern frame– 0.6 m/s², at angular abound the longitudinal axis of the extreme car body from the bulwarks – 2.4 m/s². The computer modeling of the dynamics of car bodies placed with respect to TF decks was carried out for approbation of the obtained results. These results led to the conclusion that the adequacy hypothesis of the developed model was not denied;

Figure 8. The accelerations acting on the car bodies placed relative to the upper deck of TF in sea rocking conditions *a*) when TF translational movements in the vertical direction; *b*) when TF angular movements relative to transverse axis; *c*) when TF angular movements relative to the longitudinal axis

3. The researches will contribute to improving the safety of cars movement on TF by sea, as well as the expansion of n. 2.18 " Standards..." [16], taking into account adjustments of accelerations values acting on the cars bodies during transportation by different types of TF and appropriate characteristics of their floating areas;

4. When designing the cars of a new generation in the conditions of cars factories planning and design office it is necessary to take into account the revised values of the forces acting on their supporting structures in conditions of sea commotion.

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