ANALYSIS OF DYNAMIC LOADING OF IMPROVED CONSTRUCTION OF A TANK CONTAINER UNDER OPERATIONAL LOAD MODES

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Abstract

An increase in the volume of bulk cargo transportation through international transport corridors necessitates the commissioning of tank containers. Intermodalization of a tank container predetermines its load in various operating conditions depending on the type of vehicle on which it is carried: aviation, sea, air or rail. The analysis of the operating conditions of tank containers, as well as the regulatory documents governing their workload, led to the conclusion that the most dynamic loads acting on the supporting structures during transportation by rail. Namely, during the maneuvering collision of a wagon-platform, on which there are tank containers. In this case, it is stipulated that for a loaded tank container, the dynamic load is assumed to be 4g, and for an empty (for the purpose of checking the reinforcement) – 5g. It is important to note that when the tank container is underfilled with bulk cargo and taking into account movements of fittings relative to fittings, the maximum value of dynamic load can reach significantly larger values. Therefore, in order to ensure the strength of tank containers, an improvement of their structures has been proposed by introducing elastic-viscous bonds into the fittings.

To determine the dynamic loading of the tank container, taking into account the improvement measures, mathematical models have been compiled, taking into account the presence of elastic, viscous and elastic-viscous bonds between the fittings, stops and fittings. It is established that the elastic bond does not fully compensate for the dynamic loads acting on the tank container. The results of mathematical modeling of dynamic loading, taking into account the presence of viscous and elastic-viscous coupling in the fittings, made it possible to conclude that the maximum accelerations per tank container do not exceed the normalized values.

The determination of the dynamic loading of the tank container is also carried out by computer simulation using the finite element method. The calculation takes place in the software package CosmosWorks. The maximum values of accelerations are obtained, as well as their distribution fields relative to the supporting structure of the tank container.

The developed models are verified by the Fisher criterion. The research will contribute to the creation of tank containers with improved technical, operational, as well as environmental characteristics and an increase in the efficiency of the liquid cargo transportation process through international transport corridors.

Keywords: tank container, supporting structure, fittings, dynamic loading, maneuvering collisions.

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1. Introduction

Improving the efficiency of the transportation process through international transport corridors makes it necessary to introduce intermodal means into the transport process. It is known that the most common among these are containers or tank containers. Transportation of containers can be carried out by almost all types of transport - rail, road, air or sea. This results in the workload of their structures under various operating conditions.

The study of regulatory documents [1] on the loading of containers in operation led to the conclusion that the greatest force on their design is carried out during carriage on flatcars, namely during a maneuvering collision. It is important to note that the degree of dynamic loading of containers in operation can reach significant values [2–5]. This is due not only to the action on the wagon-platform with tank containers during a maneuvering impact load of 3.5 MN [6–8]. Also, there may be a load arising from the impact of the tank-container fittings with the fittings by the platform-wagon stops [9]. In addition, the movement of bulk cargo in the tank container boiler also causes additional force on the supporting structure [10]. All these factors can contribute to damage to the structural elements of tank containers and wagons.

Therefore, to ensure the strength of tank containers, as well as reducing the cost of manufacture and operation, it is necessary to improve their supporting structures. It will also allow to increase the efficiency of operation of tank containers and to develop recommendations for the creation of new alternative designs with improved technical, economic and environmental characteristics. The aim of research is analysis of the dynamic loading of the improved design of tank containers under operating conditions of load.

To achieve the aim, the following objectives are set:

– to carry out mathematical modeling of the loading of the tank container placed on the wagon-platform during a maneuvering collision;

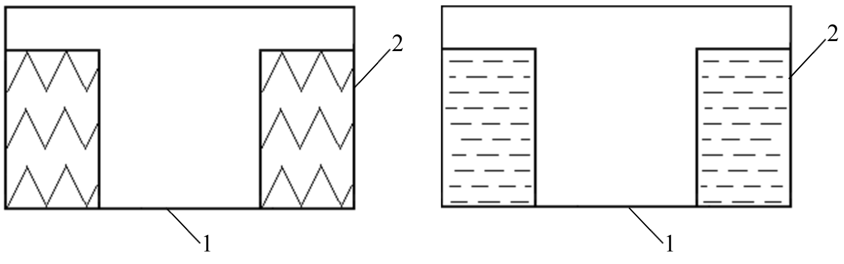
– to conduct a computer simulation of the loading of the tank container placed on the wagon-platform during a maneuvering collision;

– to verify the proposed container loading models.

2. Mathematical modeling of the loading of the tank container placed on the wagon-platform during a maneuvering collision

To reduce the dynamic loading of the tank container in operation, it is proposed to install in the fittings (**Fig. 1, *a***) elastic or viscous elements (**Fig. 1, *b***). The occurrence of a shock load between fittings and fitting stops can occur in the case when the dynamic load P_d exceeds the friction force F_f between their horizontal planes.

To determine the dynamic loading of the tank container during a maneuvering collision, taking into account improvement measures, a mathematical model (1) is compiled, which takes into account the movement of the tank container placed on the wagon-platform. The design scheme is shown in **Fig. 2.**



a *b*

Fig. 1. Improved design of container fittings: *a* – elastic bond; *b* – viscous bond; 1 – fittings; 2 – elastic (a), viscous (b) element

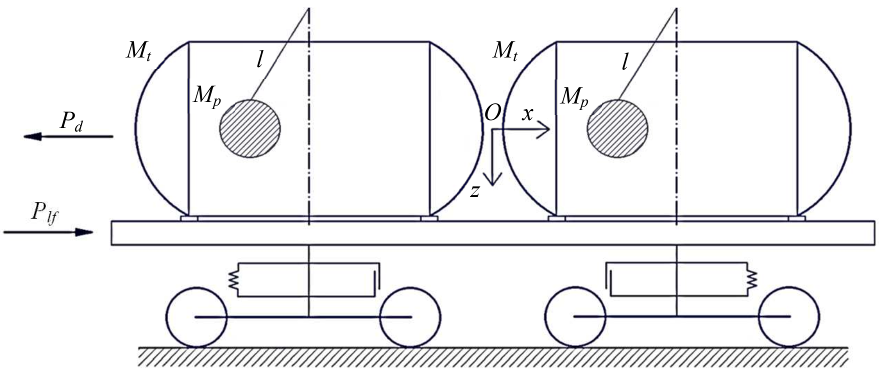


Fig. 2. Diagram of the action of the longitudinal force on the wagon-platform with tank containers placed on it

The wagon-platform model 13-4012M was chosen as the prototype wagon. Investigations were carried out in relation to a tank container of size 1CC.

The model takes into account the dry friction force that occurs when moving the fittings of tank containers relative to the horizontal planes of fitting stops and the elastic bond between fittings stops and fittings [11, 12]. The study of the dynamic loading of the tank container was carried out in a flat coordinate system. The movement of the bulk cargo was described by a set of mathematical pendulums.

As a bulk cargo gasoline is accepted. Determination of the hydrodynamic characteristics of the bulk cargo was carried out taking into account 95 % of the loading of the boiler in bulk. In this case, the value M_P=6.6 t and I_{BC}=250 t·m^2 was obtained.

The solution of the mathematical model (1) is implemented in the MathCad software environment [13]. At the same time, it was reduced to the normal Cauchy form $\dot{y}(t)=Q(t,y)$. Where $q_1=y_1$; $q_2=y_2$; $\dot{q}_1=y_3$; $\dot{q}_2=y_4$.

The solution of the system of differential equations (1) in normal form was carried out by integrating according to the Runge-Kutta method. The initial conditions are assumed to be zero.

$$\begin{cases} M_{PC}^{gw}\cdot\ddot{q}_1=P_{lf}-\sum_{i=1}^{n}\left(F_f\cdot\text{sign}(\dot{q}_1-\dot{q}_2)+S_f(q_1-q_2)\right), \\ M_t\cdot\ddot{q}_2=\sum_{i=1}^{n}\left(F_f\cdot\text{sign}(\dot{q}_1-\dot{q}_2)+S_f\cdot(q_1-q_2)+M_p\cdot l\cdot q_3\right), \\ I_{BC}\cdot\ddot{q}_3=M_p\cdot l\cdot\ddot{q}_2-g\cdot M_p\cdot l\cdot q_3, \end{cases} \quad (1)$$

where M_{PC}^{gw} – gross weight of wagon-platform; P_{lf} – the value of the longitudinal force acting on the coupler; F_f – friction force between fittings stops and fittings; M_t – tank container mass; S_f – stiffness of elastic elements in tank container fittings; M_p – the mass of a pendulum that simulates the movement of a bulk cargo in a tank container; l – the length of the pendulum suspension; I_{BC} – the moment of pendulum inertia; q_1, q_2, q_3 – coordinates that determine the movement, respectively, of the wagon-platform, tank container and bulk cargo relative to the longitudinal axis.

The transition from the system of differential equations of the second order (1) to the system of differential equations of the first order (2) was carried out to apply standard algorithms for solving the system in Mathcad:

$$Q(t,y)=\begin{bmatrix} y_4 \\ y_5 \\ y_6 \\ \dfrac{P_{lf}-\sum_{i=1}^{n}\left(F_f\cdot \mathrm{sign}(y_4-y_5)+S_f(y_1-y_2)\right)}{M_{PC}^{gw}} \\ \dfrac{\sum_{i=1}^{n}\left(F_f\cdot \mathrm{sign}(y_4-y_5)+S_f\cdot(y_1-y_2)+M_p\cdot l\cdot y_3\right)}{M_t} \\ \dfrac{M_p\cdot l\cdot \dot{y}_5-g\cdot M_p\cdot l\cdot y_3}{I_{BC}} \end{bmatrix}, \quad (2)$$

$$Z=\mathrm{rkfixed}\,(Y0, tn, tk, n, Q),$$

where Y0 – a vector containing the initial conditions, tn, tk – the quantities that define the initial and final integration variables, n – a fixed number of steps, Q – a symbol vector.

Based on the calculations made, the acceleration is obtained, which act on the improved design of the tank container placed on the wagon-platform during a maneuvering collision (**Fig. 3**). This acceleration value was about 50 m/s² (≈5g), that is, it exceeds the allowable value [1].

The total stiffness of the elastic elements per tank container was in the range of 420–530 kN/m.

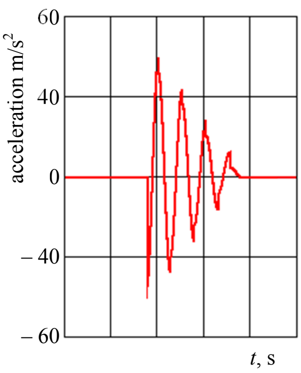


Fig. 3. Acceleration, acting on a tank container with elastic bonds in the fittings, placed on the wagon-platform during a maneuvering collision

To reduce the dynamic loading of the tank container placed on the wagon-platform during a maneuvering collision, a variant of the execution of fittings with viscous bonds was also considered.

A mathematical model of the dynamic loading of a tank container during a maneuvering collision with regard to the presence of a viscous bond in the fittings is given below.

$$\begin{cases} M_{PC}^{gw}\cdot\ddot{q}_1 = P_{lf} - \sum_{i=1}^{n}\left(F_f\cdot \text{sign}(\dot{q}_1-\dot{q}_2)+\beta_f(\dot{q}_1-\dot{q}_2)\right), \\ M_t\cdot\ddot{q}_2 = \sum_{i=1}^{n}\left(F_f\cdot \text{sign}(\dot{q}_1-\dot{q}_2)+\beta_f(\dot{q}_1-\dot{q}_2)+M_p\cdot l\cdot q_3\right), \\ I_{BC}\cdot\ddot{q}_3 = M_p\cdot l\cdot\ddot{q}_2 - g\cdot M_p\cdot l\cdot q_3. \end{cases} \quad (3)$$

The acceleration acting on a tank container with viscous bonds in the fittings placed on the wagon-platform during a maneuvering collision is shown in **Fig. 4**. When the value of viscous resistance in the tank container fittings is inflicted, the acceleration is about 40 m/s^2 (≈4g) and does not exceed the normalized value [1].

$$Q(t,y)=\begin{bmatrix} y_4 \\ y_5 \\ y_6 \\ \dfrac{P_{lf}-\sum_{i=1}^{n}\left(F_F\cdot \text{sign}(y_4-y_5)+\beta_f(y_4-y_5)\right)}{M_{PC}^{gw}} \\ \dfrac{\sum_{i=1}^{n}\left(F_F\cdot \text{sign}(y_4-y_5)+\beta_f(y_4-y_5)+M_P\cdot l\cdot y_3\right)}{M_c} \\ \dfrac{M_P\cdot l\cdot \dot{y}_5 - g\cdot M_P\cdot l\cdot y_3}{I_{BC}} \end{bmatrix}, \quad (4)$$

$$Z = \text{rkfixed}(Y0, tn, tk, n, Q).$$

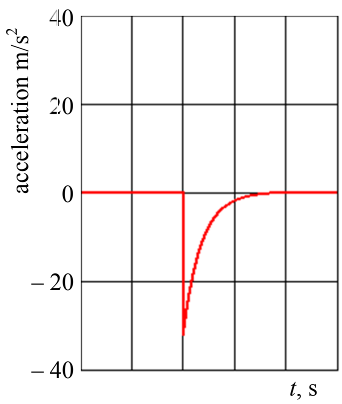


Fig. 4. Acceleration acting on a tank container with viscous bonds in the fittings, placed on the wagon-platform during a maneuvering collision

In this case, the total viscous resistance to the movement of one tank container should be in the range of 9–54 kN s/m.

The case of elastic-viscous bond between fittings and fittings stops is also considered. The mathematical model will look like this:

$$\begin{cases} M_{PC}^{gw}\cdot\ddot{q}_1 = P_{lf} - \sum_{i=1}^{n}\left(F_f\cdot \text{sign}(\dot{q}_1-\dot{q}_2)+c(q_1-q_2)+\beta_f(\dot{q}_1-\dot{q}_2)\right), \\ M_t\cdot\ddot{q}_2 = \sum_{i=1}^{n}\left(F_f\cdot \text{sign}(\dot{q}_1-\dot{q}_2)+c(q_1-q_2)+\beta_f(\dot{q}_1-\dot{q}_2)+M_P\cdot l\cdot q_3\right), \\ I_{BC}\cdot\ddot{q}_3 = M_P\cdot l\cdot\ddot{q}_2 - g\cdot M_P\cdot l\cdot q_3. \end{cases} \quad (5)$$

The solution of equation (5) was sought in the form:

$$Q(t,y)=\begin{bmatrix} y_4 \\ y_5 \\ y_6 \\ \dfrac{P_{lf}-\sum\limits_{i=1}^{n}\left(F_f\cdot \operatorname{sign}(y_4-y_5)+c(q_1-q_2)+\beta_f(y_4-y_5)\right)}{M_{PC}^{gw}} \\ \dfrac{\sum\limits_{i=1}^{n}\left(F_f\cdot \operatorname{sign}(y_4-y_5)+c(q_1-q_2)+\beta_f(y_4-y_5)+M_p\cdot l\cdot y_3\right)}{M_t} \\ \dfrac{M_P\cdot l\cdot \dot{y}_5-g\cdot M_P\cdot l\cdot y_3}{I_{BC}} \end{bmatrix}, \quad (6)$$

$$Z=\text{rkfixed}\,(Y0, tn, tk, n, Q).$$

The acceleration acting on the tank container, taking into account the elastic-viscous bond in the fittings, is shown in **Fig. 5.**

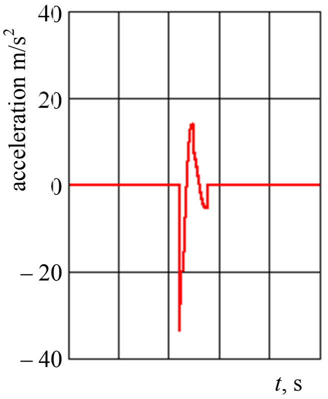


Fig. 5. Acceleration acting on a tank container with viscous and elastic bond in fittings, placed on a wagon-platform during a maneuvering collision

The stiffness of the elastic element is assumed to be 480 kN/m and the viscous resistance coefficient is 30 kN·s/m. The maximum acceleration value is about 40 m/s^2 (≈4g) and does not exceed the normalized value [1].

3. The research results of the loading of the tank container placed on the wagon-platform during a maneuvering collision

3. 1. Computer simulation of the loading of the tank container placed on the wagon-platform during a maneuvering collision

To study the dynamic loading of a tank container with regard to improvement measures, computer simulation was carried out using the finite element method [14, 15] implemented in the CosmosWorks software package (France) [16, 17].

The model for determining the dynamic loading of a wagon-platform with tank containers during a maneuvering collision is shown in **Fig. 6**. The model takes into account that the tank container fittings are affected by the horizontal load P_h, due to the impact of the P_f shock load on the vertical surface of the rear stop of the automatic coupling. Also taken into account are vertical reactions in the supporting areas of the fittings on the fitting stops P_h. It is taken into account that the tank container is affected by pressure from the bulk cargo R_{BC}. On the tank bottom, pressure R_b is applied, due to a longitudinal impact on the rear stop of the automatic coupling of the wagon-platform and movement of the fittings relative to the fitting stops. Fixing the tank container was carried out in the areas of its support on the wagon-platform. It is taken into account that when a dynamic load is applied to the fittings, it is moved relative to the initial position by 30 mm. In the tank container fittings were installed elastic elements, hardness 420 kN/m.

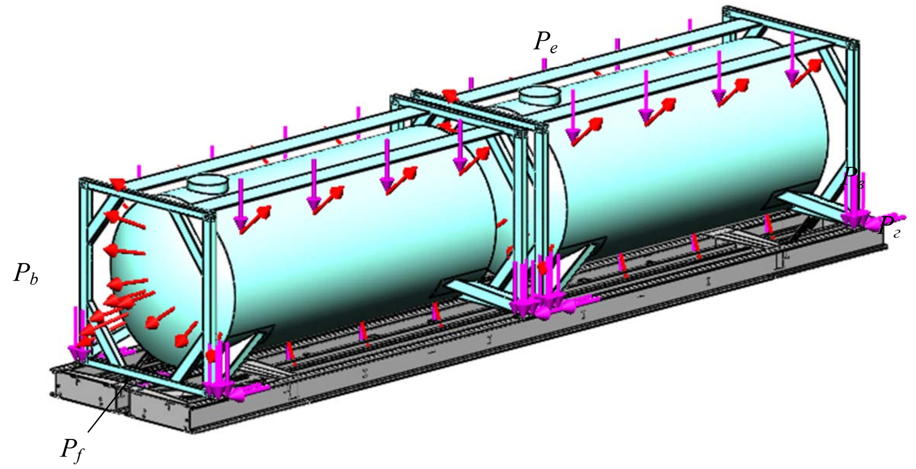


Fig. 6. Model for determining the dynamic loading of a wagon-platform with tank containers during a maneuvering collision

Steel grade 09G2S with the corresponding numerical values of strength and yield strength was used as a construction material [18–20]. The calculation results are shown in **Fig. 7**.

When modeling the dynamic loading of a tank container, taking into account the presence in the fittings of a viscous bond, the total viscous resistance to movement of one tank container should be in the range of 9–54 kN·s/m.

The results of modeling the dynamic loading of the tank container, taking into account the viscous bond between the fittings and the fitting stops, made it possible to conclude that the maximum accelerations acting on the supporting structure of the tank container are 41.4 m/s^2.

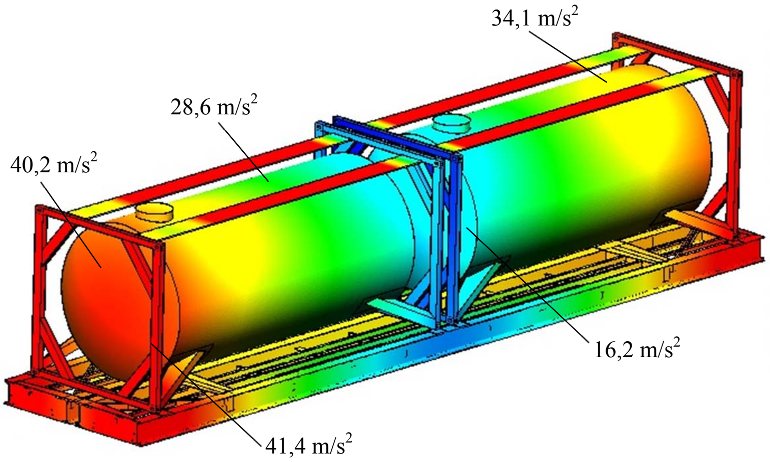


Fig. 7. Distribution of accelerations, operating a wagon-platform with tank containers during a maneuvering collision

So, the maximum accelerations acting on the tank container, taking into account the elastic bond between the fittings and fitting stops do not exceed the permissible [1].

On the basis of the compiled strength model, the values of the critical oscillation frequencies of the tank container were determined (**Table 1**).

Table 1
Numerical values of the critical oscillation frequencies of the tank container of an improved design

Oscillation form	Frequency, rad/s	Frequency, Hz
1	52.25	8.32
2	53.65	8.53
3	57.18	9.1
4	145.6	23.17
5	146.81	23.37
6	150.07	23.88
7	202.65	32.25
8	221.87	35.31
9	278.06	44.25
10	286.44	45.6

The research results show that the values of the critical oscillation frequencies are within the allowable limits [18–20].

3. 2. Verification of loading models of containers placed on a wagon-platform during a maneuvering collision

In order to verify the developed models, the F-criterion was applied [21, 22]. The input parameter of the mathematical and computer model of the dynamic loading of the container is the impact force in the automatic coupling of the wagon-platform, and the output parameter is the acceleration acting on the tank container placed on the wagon-platform (**Table 2**).

The required number of static data was recognized by Student's criterion [23].

When the value of the mathematical expectation is 33.6, the variance is 31.7, the standard deviation is 5.63, it has been established that the optimal number of measurements is 6 and the number of measurements made is sufficient to obtain a reliable assessment of the results.

Table 2
The results of modeling the dynamic loading of the tank container

Impact force, MN	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5
Mathematical model	30	31	32.1	33	34.2	35.2	36	37.4
Computer model	33.1	34.2	35.5	36.7	37.9	39	40.2	41.4

The calculation results show that for the case of viscous interaction of fittings from fittings with dispersion of reproducibility S_y=6.5 and dispersion of adequacy S_{ad2}=8.4, the actual value of the F-criterion F_r=1.3, which is less than the table value of the criterion F_t=3, 07 So the hypothesis about the adequacy of the developed model is not disputed.

The discrepancy between the results of mathematical and computer modeling of the dynamic loading of the tank container is shown in **Fig. 8.**

At the same time, the maximum value of the discrepancy is 10.4 % with the impact force at the automatic coupling of the wagon-platform 3.4 MN, and the smallest – about 9.3 %, respectively, with 2.8 MN.

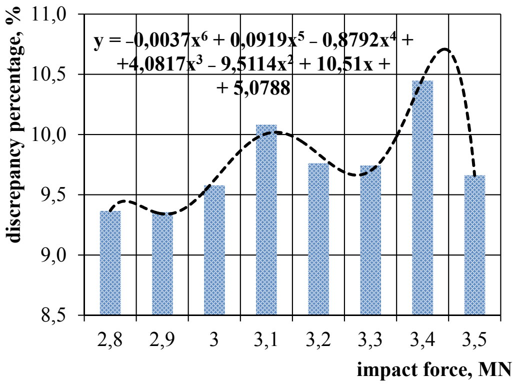


Fig. 8. The discrepancy between the results of mathematical and computer modeling

4. Discussion of the results of the improvement of the supporting structures of tank containers to reduce the dynamic loading in operation

Measures to improve the supporting structures of tank containers to reduce their dynamic loading in operating conditions are proposed. The reduction of dynamic loads is achieved by introducing viscous or elastic-viscous bonds into the tank container fittings.

The peculiarity of the conducted research is that, in contrast to the known solutions, the reduction of the dynamic loading of the tank container is achieved by introducing viscous and elastic-viscous bonds into the design of fittings, rather than by improving the metal structure itself.

It is important to note that in modeling the dynamic loading of a tank container placed on a wagon-platform, it was assumed that there was no oscillation by galloping. That is, the design scheme takes into account only the translational movement of the tank container relative to the longitudinal axis (the equivalent of twitching oscillations in the dynamics of the cars). In addition, the possible eccentricity of the body of the automatic coupling when the impact of shock load on the wagon-platform is not taken into account.

In further studies in this direction, it is necessary to take into account these limitations in order to obtain a more accurate estimate of the dynamic loading of the tank container.

Also an important stage of this research is the experimental determination of the dynamic loading of the tank container of an improved design. Due to the complexity of carrying out a full-scale experiment at the primary stage, it is possible to use the method of similarity theory.

5. Conclusions

A simulation of the loading of the tank container placed on the wagon-platform during a maneuvering collision is carried out. The maximum values of the accelerations acting on the tank container taking into account the improvement measures are determined. It is established that the presence of elastic coupling in the container fittings does not fully compensate for the magnitude of the dynamic load acting on the tank container placed on the wagon-platform during a maneuvering collision. In the presence of a viscous bond in the fittings, the maximum accelerations are about 40 m/s^2 (≈4 g), that is, do not exceed the allowable values. In this case, the total viscous resistance to the movement of one tank container should be in the range of 9–54 kN·s/m.

The case of elastic-viscous bond between fittings and fitting stops is also considered. It is established that with a stiffness of an elastic element of 480 kN/m and a coefficient of viscous resistance of 30 kN s/m, the maximum acceleration value is about 40 m/s^2 (≈4g) and does not exceed the normalized value.

A computer simulation of the loading of the tank container placed on the wagon-platform during a maneuvering collision is carried out. It is established that the maximum accelerations acting on the supporting structure of the tank container are 41.4 m/s^2 and are concentrated in the frame from the cantilever parts of the wagon-platform. The critical oscillation frequency of the tank container is determined. The numerical values of the frequencies do not exceed the permissible.

The proposed tank container loading models are verified. F-criterion are used as a calculated. The optimal number of measurements is determined and the dispersion of adequacy and reproducibility is calculated. The research results show that the hypothesis of adequacy does not deviate. In this case, the calculated value of the criterion below the table is almost 60 %.

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