Determination of the strength of a flat wagon by elastic viscous interaction with tank containers

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Abstract. The article highlights the peculiarities of the mathematical modelling for dynamic load of the bearing structure of a flat wagon by elastic-viscous interaction with tank containers. It was established that the presence of viscous or elastic-viscous connections between fittings and fitting stops, taking into account the possible movements of tank containers in relation to the frame, provides the dynamic load of the bearing structure of the flat wagon within normal range. The conducted researches will provide efficiency increase of combined transportations and develop recommendations for designing modern constructions of railway rolling stock.

1. Introduction

The increase in the pace of integration of the Eurasian countries into the system of international transport corridors results in putting container transportations into operation. This is due to the possibility of transportation containers in almost all transport modes. The use of tank containers became widespread in international traffic for enabling transportation of liquid bulk cargo.

Study of the dynamic load of a flat wagon with tank containers by shunting collision allowed concluding that there are higher tensions in their bearing structures. This results in damage to flat wagons, as well as tank containers and as a consequence the need for unscheduled repairs (figure 1).

At the present stage of the development of the transport industry it is important to implement innovative solutions in the construction of railroad vehicles, their production materials and schemes of interaction with each other for increasing the efficiency of operating railroad vehicle. The development of these issues will provide design of a new generation of vehicles with improved characteristics, as well as recommendations for their design.
2. Analysis of recent research

Study of dynamics of a flat wagon using multibody methods is given in [1]. The calculation was made in the MSC Adams software environment for the flat wagon with rotating middle section. The equations of the movement of the flat wagon were formulated in absolute coordinates using the Lagrange method of the first kind.

New railway tank wagon type Zans, which was developed by University of Žilina and Tatravagónka Inc. Poprad Results of calculations and prototype tests prove, that new designed construction of the tank wagon satisfies strength conditions [2].

In order to address the question of the possibility of further safe operation of tank cars in the over-term period, their technical diagnostics and control tests are carried out [3–6]. In this case, the control of the technical condition includes visual inspection of the tank wagon, measurements of the thickness of the metal at the control points of the boiler and the frame of the car, conducting of the magnetopowder, ultrasonic and acoustic emission control of the bearing metal constructions. Control tests include static vertical load tests, test for a low cyclic load by boiler pressure, typical, resource shock tests, and possible emergencies testing.

The study of the strength of a flat wagon with static and dynamic load of its construction is given in [7]. In this case the experimental methods were used, namely electrical strain gauge measurement.

In this case, attention to the study of the dynamic load of flat wagons by shunting collision was not paid in these works.

The issue of designing a railway rolling stock for transportation of heavy loads is considered in [8]. The study of dynamics and strength was conducted using modern software environments such as ProMechanica and CosmosWorks. During designing the bearing structure of a carrier, the study was conducted on the possibility of its constructing from various types of materials.

Peculiarities of the development of high-speed articulated flat wagon for the transportation of containers are given in [9]. The technical solutions adopted in the design of the flat wagon allow simultaneous transportation of two 40- or 45-foot or four 20-foot containers.

Measures to reduce the dynamic load of railway rolling stock under the most adverse operating conditions are not highlighted in these works.

Dynamic load of the bearing structure of a wagon during combined transportation is determined in [10, 11]. The mathematical models which allow obtaining accelerations acting on the bearing structure of a wagon during movements of the railroad ferry were presented. The results of mathematical modelling were verified by computer modelling.

The results of computer modelling of the bearing structure dynamics of the wagon body during transportation by railroad ferry in conditions of sea disturbance are given in [12]. The researches were conducted in the CosmosWorks software environment using the finite element method.
The issue of determining the strength of bearing structures of wagons in is not considered in these works.

Peculiarities and results of the cataloguing of bearing systems of freight wagon and the requirements that they must meet at the present stage of development of the railroad industry are given in [13]. However, the requirements for the dynamic load of wagons by shunting collision are not highlighted in this paper.

Strength of the frame of the flat wagon, taking into account a road semi-trailer placed on it, is modelled in [14]. The paper proposes an analytical model that allows obtaining the specified values of stress in the bearing structure of the flat wagon.

Attention to the research of the dynamics of the flat wagon at operating load conditions is not paid in this paper.

Spatial movements of the “subframe - track” system is modelled in [15]. The calculation is based on the finite element method implemented in the Ansys software environment.

Peculiarities of the mathematical modelling of the flat wagon dynamics are not considered in the work.

Obtaining samples of high density and analysis of mechanical strength characteristics of ZrO₂-WC nanopowders composite is considered in [16]. However, the peculiarities of the application of this material in bearing structures of the railway rolling stock are not highlighted in this paper.

3. Purpose and objectives of the article

Determination of the strength indexes of the flat wagon by elastic viscous interaction with tank containers. In order to achieve this aim the following tasks are defined:

- To develop a mathematical model of the dynamic load of a flat wagon with elastic, viscous and elastic-viscous connections between fitting stops and fittings of tank containers by shunting collision;
- Determine the dynamic load of the flat wagon with elastic, viscous and elastic-viscous connections between the fitting stops and fittings of tank containers by shunting collision.

The main body of the article. One of the directions for providing the strength of flat wagons and tank containers under operating load conditions is the improvement the design of fittings (figure 2).

![Figure 2. Tank container fittings: a) general view; b) placed on a tank-container.](image-url)

It is proposed to set into the fittings of the tank container the elastic, viscous, as well as elastic viscous elements (figure 3) for reducing the dynamic load of the flat wagon by the most unfavourable operating mode – shunting collision.

Dynamic load was mathematically modelled (figure 4) taking into account the proposed scheme of the interaction of fitting stops and fittings for determining the stressed condition of the flat wagon.

Consideration was given at the initial stage of the research to the existence of an elastic connection between the fitting stops of the flat wagon and tank container fittings (1).

Calculations were made for the 13-4012M model of flat wagon loaded with TK25 tank containers. It was assumed that each tank container was loaded with petrol using 95 % of the boiler volume. The
determination of the hydrodynamic characteristics of the liquid bulk cargo was made in accordance with [17]. In this case, the values of $M_p = 6.6$ t and the $I_p = 250$ t m$^2$ were obtained.

![Image](https://via.placeholder.com/150)

**Figure 3.** Improved design of tank container fittings: a) with elastic elements; b) with viscous elements; c) with elastic viscous elements.

![Image](https://via.placeholder.com/150)

**Figure 4.** Diagram of longitudinal force on a flat wagon with tank containers placed on it.

Model (1) takes into account the presence of dry frictional force between fitting stops and fittings when moving tank containers relative to the frame of the flat wagon. The movement of liquid bulk cargo was described by a set of mathematical pendulums [18].

\[
\begin{align*}
M_{\text{gross}} \cdot \ddot{q}_1 &= P_l - \sum_{i=1}^{n} (F_{fr} \cdot \text{sign}(\dot{q}_i - \dot{q}_j) + C_f (q_i - q_j)), \\
M_e \cdot \ddot{q}_1 &= \sum_{i=1}^{n} (F_{fr} \cdot \text{sign}(\dot{q}_i - \dot{q}_j) + C_f (q_i - q_j) + M_p \cdot \dot{l} \cdot q_i), \\
I_p \cdot \ddot{q}_1 &= M_p \cdot \dot{l} \cdot \dot{q}_1 - g \cdot M_p \cdot \dot{l} \cdot q_i, \\
\end{align*}
\]

where $M_{\text{gross}}$ – gross weight of the flat wagon; $P_l$ – the magnitude of the longitudinal force acting on the automatic coupler; $F_{fr}$ – friction force between fitting stops and fittings; $M_e$ – weight of the tank container; $C_f$ – stiffness of elastic elements in tank container fittings; $M_p$ – mass of the pendulum simulating the displacement of the liquid bulk cargo in the tank container; $l$ – length of the pendulum suspension; $I_p$ – moment of inertia of the pendulum; $q_1, q_2, q_3$ – coordinates determining respectively the movement of the flat wagon, tank container and liquid bulk cargo relative to the longitudinal axis.
The system of differential equations (1) was solved by integrating using the Runge-Kutta method in the MathCad software environment [19]. Initial conditions were assumed to be zero.

General stiffness of the elastic elements per one tank container was in the range of 420–530 kN m\(^{-1}\). The calculation results are shown in figure 5.

\[ Z = \text{rkfixed}(Y0, \text{tn}, \text{tk}, n, Q) \]

where \( Y0 \) – vector which contains the initial conditions, \( \text{tn}, \text{tk} \) – magnitudes which determine the initial and final integration variables, \( n \) – fixed number of steps, \( Q \) – symbolic vector.

In the presence of viscous connection between fittings and fitting stops, the mathematical model of the dynamic load of the flat wagon will look like:

\[ Q(t, y) = \begin{bmatrix} y_i \\ y_j \\ y_k \end{bmatrix} \]

\[ \begin{align*}
    P_i - \sum_{i=1}^{\infty} \left( \frac{F_p \cdot \text{sign}(y_i - y_j) + C_f (y_i - y_j)}{M_{\text{pot}}} \right) \\
    \sum_{i=1}^{\infty} \left( F_p \cdot \text{sign}(y_i - y_j) + C_f (y_i - y_j) + M_p \cdot l \cdot y_j \right) \\
    \frac{M_k}{M_p \cdot l \cdot y_j - g \cdot M_p \cdot l \cdot y_j} \\
    \frac{I_p}{l_p}
\end{align*} \]
where $\beta_v$ – coefficient of viscous resistance in fittings of tank container.

The solution of the mathematical model (3) was sought in the form:

$$
T = r\text{fixed} \left( Y_0, t_n, t_k, n', G \right).
$$

By viscous resistance to the movement of the tank container of $9–54 \text{ kN s m}^{-1}$ the acceleration acting on the flat wagon is about $40 \text{ m s}^{-2} (\approx 4 \text{ g})$ and does not exceed the standard values [20–23].
Mathematical model for determining the dynamic load of the bearing structure of the flat wagon taking into account the elastic viscous connection between fittings and fitting is written as:

\[
\begin{align*}
M_{grav} \cdot \ddot{q}_i &= P_i - \sum_{k=1}^{x} \left( F_p \cdot \text{sign}(\dot{q}_i - \dot{q}_k) + c_r (q_i - q_k) + \beta_1 (\dot{q}_i - \dot{q}_k) \right), \\
M_e \cdot \ddot{q}_2 &= \sum_{k=1}^{x} \left( F_p \cdot \text{sign}(\dot{q}_i - \dot{q}_k) + c_r (q_i - q_k) + \beta_1 (\dot{q}_i - \dot{q}_k) + M_p \cdot I \cdot q_i \right), \\
I_e \cdot \ddot{q}_3 &= M_p \cdot I \cdot \dot{q}_2 - g \cdot M_p \cdot I \cdot q_i.
\end{align*}
\]

Then,

\[
F(t, y) = \begin{bmatrix}
y_4 \\
y_5 \\
y_6 \\
\frac{P_i - \sum_{k=1}^{x} \left( F_p \cdot \text{sign}(y_i - y_k) + c_r (y_i - y_k) + \beta_1 (y_i - y_k) \right)}{M_{grav}} \\
\sum_{k=1}^{x} \left( F_p \cdot \text{sign}(y_i - y_k) + c_r (y_i - y_k) + \beta_1 (y_i - y_k) + M_p \cdot I \cdot y_k \right) \\
\frac{M_e \cdot I \cdot \dot{y}_i - g \cdot M_p \cdot I \cdot y_i}{I_e}
\end{bmatrix}
\]

\[K = rkfixed(Y0, tn, tk, n', F).\]

Accelerations that act on the carriage platform, taking into account the elastic viscous connection between the fittings and fittings, are shown in figure 7.

![Figure 7](image.png)

**Figure 7.** Accelerations acting on a flat wagon by elastic-viscous interaction of fittings with fitting stops.
From figure 5 it is evident that the accelerations acting on the flat wagon do not exceed the permissible values [20–23]. In this case, the stiffness of the elastic element should be 360–480 kN m⁻¹, and the coefficient of viscous resistance: 9–32 kN s m⁻¹.

4. Conclusions
The following conclusions of the conducted research can be drawn:
1. Mathematical model of dynamic load of a flat wagon with elastic, viscous and elastic viscous connections between fitting stops and fittings of tank containers by shunting collision is developed. The model takes into account the presence of dry frictional force between fittings and fitting stops in movement of tank containers relative to the frame of the flat wagon, as well as the flow of liquid bulk cargo in the boiler described by a set of mathematical pendulums;
2. Dynamic load value of the flat wagon with elastic, viscous and elastic-viscous connections between the fittings and fittings of tank containers by shunting collision was determined.

It was established that the elastic connection between fittings and fitting stops in this analytical model does not fully compensate the dynamic load of a flat wagon. Accelerations acting on the flat wagon is about 40 m s⁻¹ (≈ 4 g) by viscous resistance to the movement of the tank container of 9–54 kN s m⁻¹ and do not exceed the standard values.

The maximum accelerations acting on the flat wagon by elastic viscous interaction of fitting stoppers with fittings are 40 m s⁻¹ (≈ 4g) and do not exceed the permissible values. In this case, the stiffness of the elastic element is assumed to be 360–480 kN m⁻¹, and the coefficient of viscous resistance is 9–32 kN s m⁻¹.

Determining the strength parameters of the flat wagon with elastic viscous connections between the fitting stops and fittings by shunting collision taking into account the obtained values of dynamic load is the next stage of the research in this direction.

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