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Study of the Possibility of Railway Transportation of Tracked Vehicles in an Open Wagon

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Abstract

In this paper a study of the possibility of using open wagons for the transportation of tracked vehicles is presented. At the initial stage, the author's team carried out mathematical modelling of the longitudinal load of an open wagon when transporting tracked equipment in it. The option of fixing it in an open wagon through fastening brackets is considered. The determined acceleration is considered when calculating the strength of the open wagon body. It was established that the stresses in the body of the open wagon are almost 30% higher than permissible. Therefore, the transportation of tracked machinery according to such a scheme is inadmissible. In this regard, the concept of a removable module for attaching tracked equipment in an open wagon is proposed. This concept is a frame that works as an intermediate adapter between the open wagon body and the tracked transport unit. The peculiarities of determining the performance profile of the removable module, as well as its strength calculation under static and dynamic loads, are highlighted. The results of these calculations proved that the strength of the removable module under the considered operating load schemes is ensured. Mathematical modelling of its vertical load was carried out to evaluate the dynamics of the open wagon, considering the proposed technical solutions for securing the tracked machinery. The results of the calculation showed that the movement of the open wagon is rated as "excellent". The conducted research will contribute to the improvement of the efficiency of railway transport operation and will be useful developments in the design of modern concepts of removable modules of multifunctional purpose.

Keywords: transport mechanics, open wagon, dynamic load, combined transportation, strength analysis, structure loading

1 Introduction

Prospects of technical and economic development of European countries, as well as strengthening of their national security and defence, lead to an increase in the efficiency of operation of railway rolling stock, as a leading branch of the transport system. Therefore, it is necessary to put into operation highly efficient interoperable rolling stock. To ensure the sustainable development of the economy of European countries, the issue of creating specialized railway vehicles for transportation of tracked machines (agricultural, military, etc.) needs to be resolved (Figure 1).

a)

b)

Figure 1: Platform wagons loaded by tracked machines:
a) agricultural and construction machines [1]; b) military tanks [2]

Replenishment of the wagon fleet in many European countries in recent years is insignificant. In this regard, there is a need to implement effective structural solutions of railway rolling stock for cargo transportation. One of the most relevant options among these is the situational adaptation of the existing fleet of wagons to the relevant operating conditions. It is known that one of the most common types of wagons used for the transportation of tracked vehicles are platform wagons.

Loading of the tracked machinery onto a platform wagon is carried out by a scooter through an inclined ramp.

Fastening on platform wagons of the tracked machines is carried out in the following ways [3]:

- universal multi-turn fasteners (the first method);
- metal spurs (the second method);
- wooden support bars and wire (report card) stretchers (the third method);
- metal thrust shoes and wooden inserts (the fourth method);
- wooden support bars and inserts (the fifth method);
- stretch clamps and clamps (the sixth method).

Multi-rotating means of fastening, which are used to fasten tracked machinery on platform wagons, are shown in Figure 2. All fastening means are removable and can fasten the tracked machines of various dimensions on the supporting structure of the platform wagon. Regarding brake shoes, they can be made of metal or wood. It is also possible to use wooden bars or inserts. There are brake shoes that can be turned or folded.

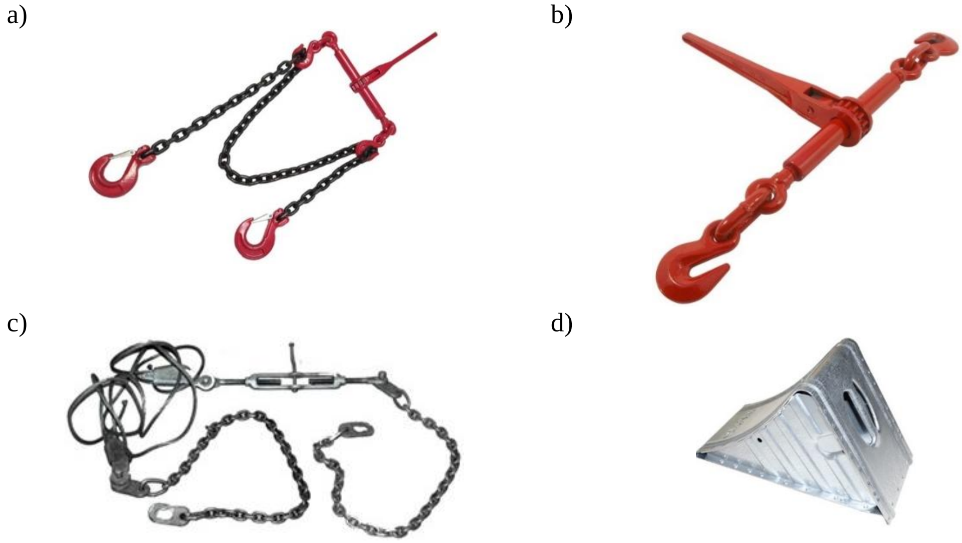

Figure 2: Multi-rotating fastening means: a) chain screed; b) metal stretch; c) wire stretching; d) metal shoe.

At the same time, the lack of platform wagons in operation for the transportation of tracked equipment can cause it to be simply waiting for transportation. One of the solutions to this issue is the adaptation of other types of wagons for the transportation of tracked vehicles. Therefore, the issue of situational adaptation of freight wagons for the transportation of tracked equipment is urgent.

2 Analysis of the recent research and publications

The issue of situational adaptation of wagons to the transportation of the assigned cargo nomenclature is quite urgent. For example, in the scientific publication [4] modernization of the railway vehicle is proposed, which will facilitate the possibility of transporting containers on it. The structural features of the proposed modernization are highlighted, as well as the results of the calculation of the strength of the frame, which confirmed the effectiveness of its use. However, the authors of this work limited themselves to one type of wagon - a platform wagon and did not conduct research on the possibility of adapting its design to the transportation of tracked vehicles.

To adapt the open wagon to the transportation of goods whose height exceeds the height of the body, its improvement is proposed in [6]. This improvement consists in the use of a retractable element - a bar with adjustable height. It is noted that this improvement will increase the safety of cargo transportation by railway. At the same time, the authors did not consider the possibility of securing tracked equipment according to this scheme.

To enable the transportation of containers in semi-trailers, the publication [6] proposed the use of an intermediate adapter for their fastening in the body. This adapter is a removable frame that can function as a modular transport unit. The paper presents the results of calculating the strength of the body of a open wagon under the condition of transportation of containers in it, fixed with the help of an adapter. It has been proven that such a scheme of securing containers is expedient. However, the authors did not consider the issue of situational adaptation of open wagons to the transportation of tracked vehicles.

The publication [7] highlights the peculiarities of tests of a railway vehicle adapted to transport removable vehicles. The study was carried out on the example of carriage of containers by wagon. The test results confirmed the reliability of the proposed improvement. Along with this, the study of the possibility of transporting tracked vehicles on this wagon was not considered by the authors.

Features of the design of a railway vehicle intended for the transportation of heavy goods are covered in the article [8]. Hypotheses and assumptions adopted during the design of this wagon are specified. The results of determining its stress state under the main modes of operation are presented. However, the possibility of transporting tracked vehicles on this wagon is not indicated, which would increase the efficiency of its use.

The design of a freight wagon for the transportation of wheeled equipment was proposed by the authors of the paper [9]. The interestingness of the design of this wagon is that it is possible to overload wagons using the ACTS system. For this purpose, the wagon has a special rotating frame. Along with several advantages of this wagon design, the authors did not specify the possibility of transporting tracked vehicles on it.

The rationale for the modernization of railway vehicles for the transportation of the assigned cargo nomenclature is covered in the article [10]. At the same time, the authors considered the possibility of modernizing not only universal, but also specialized wagons. The results of the determination of the strength of the wagons, considering the proposed modernization, are given. At the same time, the authors carried out not only calculation, but also experimental research. It is important to say that this modernization does not provide for the possibility of transporting tracked equipment on railway vehicles, which necessitates additional scientific research on this issue.

The analysed literary sources allow to conclude that the research devoted to the situational adaptation of open wagons to the transportation of tracked vehicles is relevant and needs development.

3 The purpose and main tasks of the research

The purpose of the research is scientific substantiation of the possibility of railway transportation of tracked vehicles in open wagons. To achieve this goal, the following tasks are set:

- to carry out mathematical modelling of the longitudinal load and calculation of the strength of the supporting structure of the open wagon when transporting tracked machinery in it;
- propose the concept of a removable module for placing crawler equipment on an open wagon;
- to carry out a mathematical modelling of the vertical load of an open wagon loaded with tracked machinery.

4 Presentation of the main material of the research

For transportation of tracked machinery by railways, it is possible to use open wagons with end doors for these purposes. In this way, loading of crawler equipment can be carried out through the open-end door. Along with this, it is necessary to provide special fastening brackets (rims) for its fastening on an open wagon. To study the possibility of tracked machines transportation on an open wagon, appropriate calculations were made. An open wagon model 12-753-01 was considered as a prototype. The end walls of this open wagon are formed by double-leaf doors. As an example, it is considered that the transported tracked unit (TTU) has a mass of 22.6 tons and a width of 2.71 m.

To determine the dynamic loads that will act on the supporting structure of the open wagon loaded with tracked machines, mathematical modelling of its dynamic load in the longitudinal plane was carried out. The movement of the wagon in the trainset is considered in the calculation mode "jerk" [11]. It is considered that a longitudinal load of 2.5 MN acts on the front stop of the auto coupling. The study was carried out in a flat coordinate system - the *XZ* plane. The calculation diagram of the open wagon is shown in Figure 3.

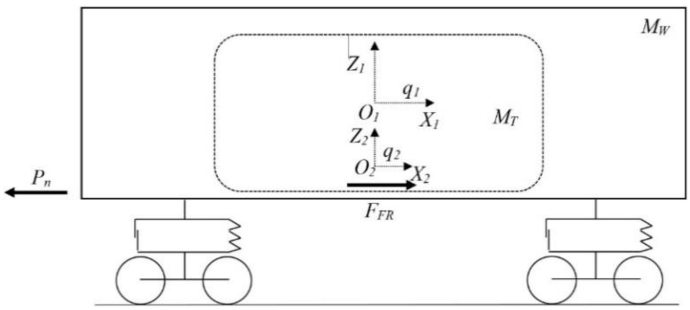

Figure 3: A calculation scheme of a half-wagon model.

The mathematical model that characterizes the movement of the system in the longitudinal plane during a "jerk" has the form:

$$\begin{cases} M_W \cdot \ddot{q}_1 = P_n - \left[F_{FR} \cdot sign(\dot{q}_1 - \dot{q}_2)\right] \\ M_T \cdot \ddot{q}_2 = \left[F_{FR} \cdot sign(\dot{q}_1 - \dot{q}_2)\right] \end{cases} \quad (1)$$

where M_W is the gross mass of the open wagon; P_n is the force that acts on the front stops of the automatic coupler during a "jerk"; F_{FR} is the friction force between the floor of the open wagon and the tracks of the transport unit; M_T is the mass of TTU.

The mathematical model was solved in MathCad using the Runge-Kutta stepwise iteration method [12]. Initial conditions, displacements and velocities were set close to zero [13, 14]. Based on the calculations, the acceleration that acts on the open wagon during a "jerk" was obtained (Figure 4). The maximum value of the acceleration was close to 25 m/s^2.

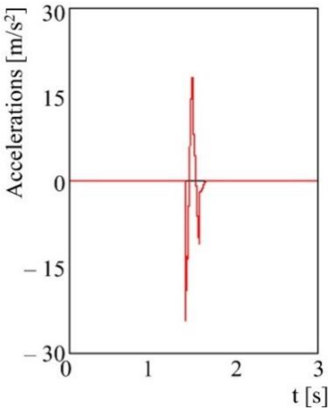

Figure 4: Accelerations acting on the supporting structure of the open wagon at "jerk".

The calculated acceleration value is considered when determining the strength of the supporting structure of the open wagon. For this, a spatial model of the supporting structure of the open wagon 12-753-01 was created.

Three dimensional models were created in SolidWorks software [15, 16]. At the same time, overlays were installed on the floor of the open wagon, imitating the zone of interaction between the tracks of the TTU and the open wagon. When drawing up the calculation scheme (Figure 5), the vertical load P_b from the gross weight of the TTU, as well as the friction force P_{tr} that occurs between the tracks and the floor of the open wagon, was applied to these overlays.

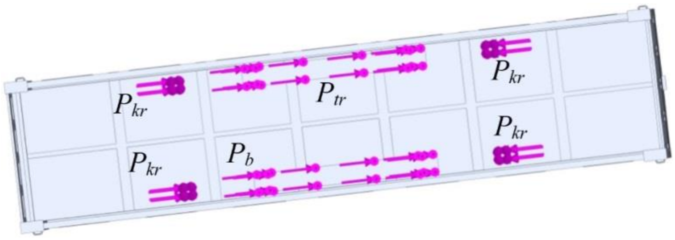

Figure 5: A spatial model of the load-bearing structure of the open wagon

Also, four rectangular pads were installed on the floor, imitating plates of fastening brackets for fixing the slings that keep the TTU from moving during transient modes of train movement. The load from the P_{kr} slings was applied to these slabs, which was divided into two components – vertical and horizontal. The angle of inclination of the sling is assumed to be equal to 45°. The longitudinal load of 2.5 MN was applied to the front stops of the automatic coupler, which simulated the "jerk" mode. On the opposite side of the wagon, this load was balanced by corresponding reactions applied to the front stops of the automatic coupler.Ties were attached to the horizontal surfaces of the wagon's heels, imitating its leaning on the bogies. At the same time, a hard pinching was used. The finite element model was created using the tetrahedral element. The model is formed by 390767 elements and 127755 nodes. The maximum size of the element was 100 mm, and the minimum was 20 mm. The optimal value of the model elements is determined graphical analytically. Low-alloy steel 09G2S is proposed as material of the supporting structure of the open wagon. This kind of steel is typical to produce the load-bearing structures of wagons.

Based on the results of the calculations, it was established that the maximum stresses in the supporting structure of the open wagon occur in the areas where the fastening brackets are installed (Figure 6). The values of these stresses exceed the permissible values by almost 30% and amount to 298.4 MPa.

The maximum movements in the supporting structure of the open wagon were also recorded in the areas where the fastening brackets are placed from the direction opposite to the direction of movement and amounted to about 6.4 mm.

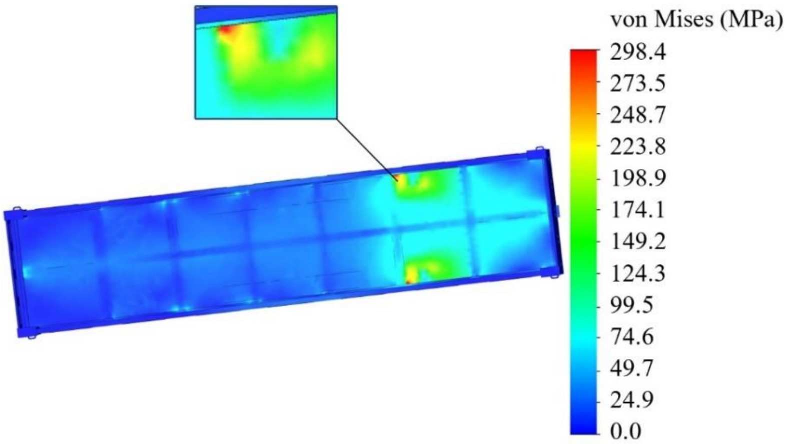

Figure 6: The stress distribution in the supporting structure of the open wagon.

To ensure the possibility of transporting light tracked vehicles in open wagons, it is proposed to use an intermediate adapter in the form of a removable module between the floor of the open wagon and the chassis of the TTU (Figure 7). The design of the module includes longitudinal beams 1, which are designed to absorb the main vertical load caused by a tracked machine, cantilever beams 2 and several intermediate transverse beams 3 connect the longitudinal beams to each other. The module is equipped with staples for attaching slings. The module is fixed in the body by corner parts that have fittings identical to those used on containers. For this, it is necessary to equip the open wagon with fitting stops.

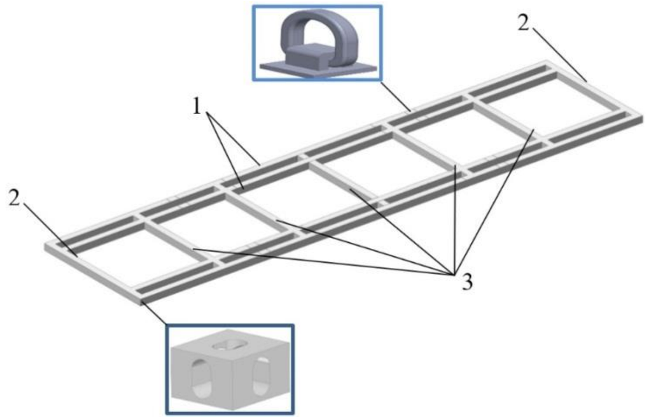

Figure 7: A module for a placement of a TTU on the open wagon.

To determine the performance profile of the removable module, appropriate calculations were made in the "Lira-Sapr" software [17]. The removable module is considered as a rod system. When carrying out calculations, the longitudinal load of the removable module was considered. At the same time, a force was applied to the longitudinal beams (Figure 8), which considers the acceleration determined according to the mathematical model (1). Fixing of the system was carried out at the corners, that is, in the areas where the fittings are located.

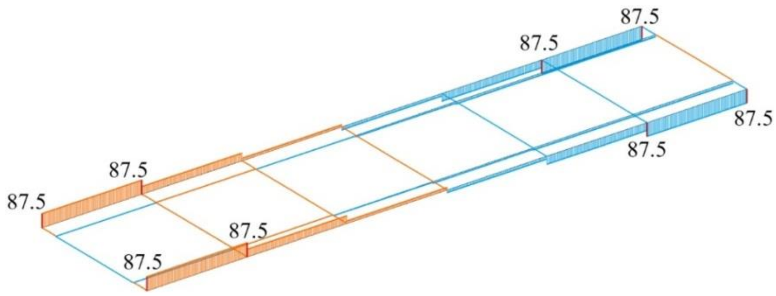

Figure 8: A graph of the longitudinal forces (kN).

Based on the known value of the longitudinal force F and the permissible stresses σ of the material module (09G2S steel), its cross-section is determined as following [18, 19]:

$$S = \frac{F}{[\sigma]}. \tag{2}$$

According to the cross-sectional area, the profile of the module was selected – a tube with a square cross-section profile, which has the following parameters: the height of the pipe and width – 160 mm; the pipe wall thickness – 4 mm.

This profile was chosen not only from the point of view of the minimum material consumption of the module design, but also the manufacturability of its manufacture, as well as maintenance.

To verify the correct selection of the tube profile, the strength of the removable module was calculated using two calculation schemes: action on the removal module of static loads; action on the removal module of dynamic loads.

The finite element method was used to determine the strength of the removable module. The finite element model is formed by tetrahedral. Their number was 52,965. At the same time, the model has 17,121 nodes. Fixing of the model was carried out using corner fittings. The calculation scheme of the removable module, when it is subjected to static loads, is shown in Figure 9. It considers the following loads: the vertical load of P_v is determined by the weight of the TTU, as well as the load from fastening means. Because they are placed at an angle to the horizontal plane, this load was divided into two components: vertical - P_c^v and horizontal - P_c^h. At the same time, it is considered that the angle of inclination of the fastening means to the horizontal plane is of 45°.

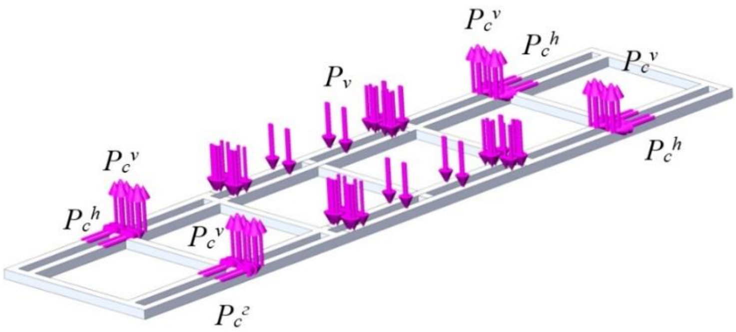

Figure 9: A calculation scheme of the removable module (action of the static loads)

Based on the calculations, the maximum stresses in the removable module occur in the TTU attachment zones and amount to the value of 98.4 MPa (Figure 10).

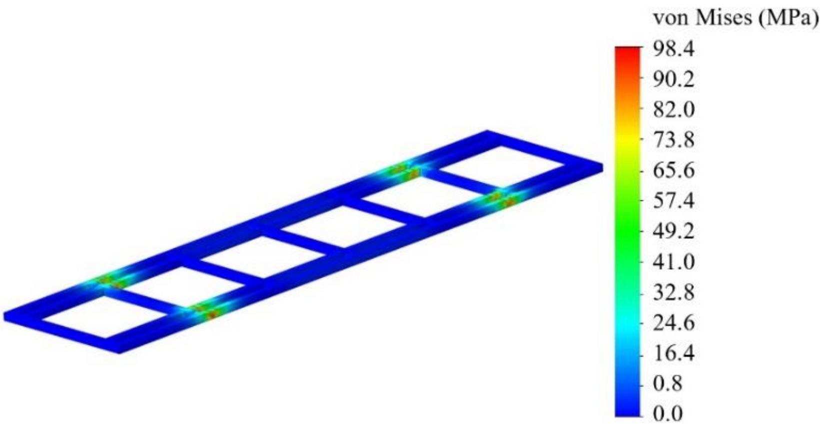

Figure 10: A stress distribution in the removable module (action of the static loads).

The stress data are 53.1% less than the permissible stresses [11]. The maximum movements in the nodes of the removable module were also recorded in the TTU attachment zones. Their value was of 2.1 mm.

To determine the strength of the removable module when it is subjected to dynamic loads, the calculation model shown in Figure 11. The loads acting on the removable module are identical to those considered when it perceives static loads but considering their corresponding numerical values.

The calculation also considers the frictional force P_{tr} that occurs between the tracks of the transport equipment and the module.

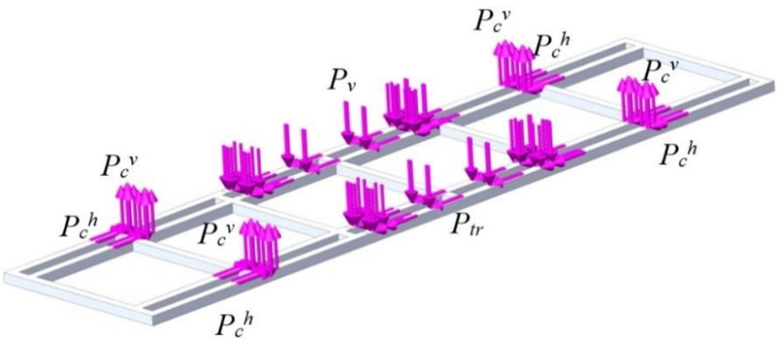

Figure 11: A calculation scheme of the removable module (action of the dynamic loads).

The results of the calculation showed that the maximum stresses occur in the TTU attachment zones from the opposite side of the removable module in terms of movement (Figure 12).

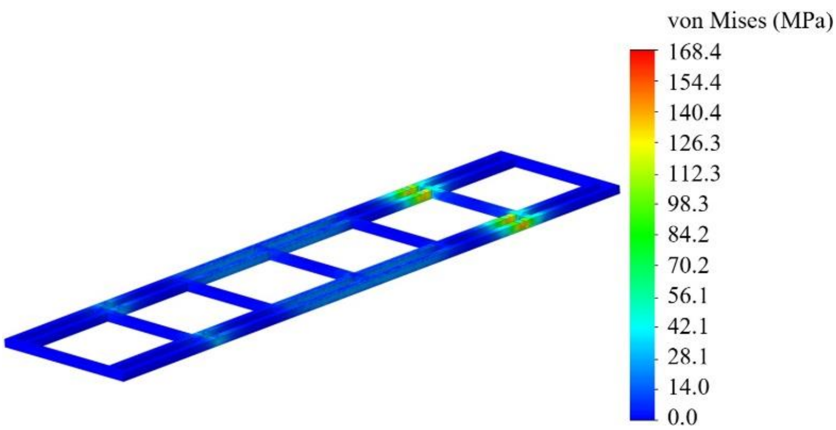

Figure 12: A stress distribution of the removable module (action of the dynamic loads).

These stresses amounted to 168.4 MPa and are 19.8% less than permissible value [11]. The maximum displacements also occur in the TTU fastening zones from the opposite side of the removable module in the direction of movement and amount to

2.6 mm. The performed calculations prove that the strength of the removable module under operational loads is ensured.

In connection with the fact that when transporting TTU in an open wagon, its useful carrying capacity is underutilized, mathematical modelling of the dynamic loading of the open wagon was carried out. The research was carried out when the open wagon was moving along a rail track with irregularities.

The presence of two degrees of freedom of the open wagon in the vertical plane is considered (Figure 13). It is considered that the TTU is rigidly fixed on the wagons and repeats the trajectory of its movements. It does not have its own degree of freedom in the vertical plane.

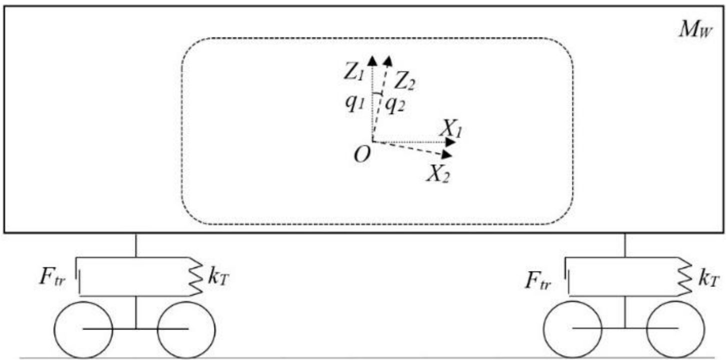

Figure 13: A calculation scheme of the open wagon.

The study was carried out in the considered coordinate system. At the same time, the mathematical model of oscillations looks like this:

$$\begin{cases} M_1 \cdot \dfrac{d^2}{dt^2} q_1 + C_1 \cdot q_1 = -F_{TP} \cdot \left[sign\left(\dfrac{d}{dt}(q_1 - l \cdot q_2) \right) + sign\left(\dfrac{d}{dt}(q_1 + l \cdot q_2) \right) \right], \\ M_2 \cdot \dfrac{d^2}{dt^2} q_2 + C_2 \cdot q_2 = F_{TP} \cdot l \cdot \left[sign\left(\dfrac{d}{dt}(q_1 - l \cdot q_2) \right) - sign\left(\dfrac{d}{dt}(q_1 + l \cdot q_2) \right) \right], \end{cases} \quad (3)$$

where M_1 is the mass of the supporting structure of the open wagon; M_2 is the moment of inertia of the supporting structure of the open wagon; q_1 is a generalized coordinate that corresponds to the translational movement of the open wagon relative to the vertical axis; q_2 is a generalized coordinate that corresponds to the angular movement of the open wagon relative to the vertical axis; $C_{1,2}$ are non-zero elements of the matrix of elastic coefficients, which are determined by the stiffness of the springs of the spring suspension k_T; F_{tr} – the friction force in the spring suspension of the bogie; l indicates semi-base of the wagon.

The solution of the system of differential equations of motion was carried out in the MathCad software under the initial conditions close to zero. The calculation result are shown in Figure 14. The maximum accelerations in the centre of mass of the open wagon were about 1.7 m/s^2 (0.17g).

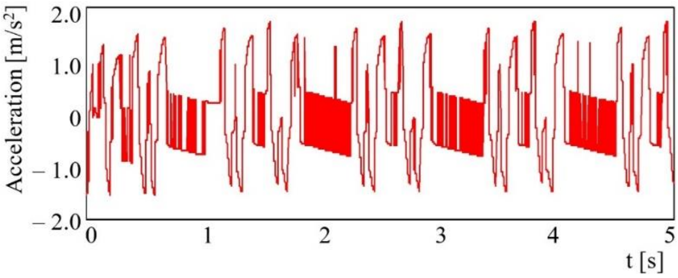

Figure 14: Acceleration of the supporting structure of the open wagon in the centre of mass.

Analysis of the obtained dependencies, it can be concluded that the movement of the open wagon in accordance with [11] is evaluated as "excellent".

5 Conclusions and Contributions

1. Mathematical modelling of the longitudinal loading of an open wagon during the transportation of TTU was carried out. The mode of movement of the open wagon as part of the train - "jerk" - is considered. The maximum value of the acceleration acting on the supporting structure of the open wagon was about 25 m/s^2. The obtained acceleration value is considered when calculating the strength of the supporting structure of the open wagon.

The results of strength calculations of the supporting structure of the open wagon showed that the maximum stresses occur in the areas where the fastening brackets are installed and amount to 298.4 MPa. The resulting stresses exceed the permissible by almost 30%. The maximum movements in the supporting structure of the open wagon were also recorded in the areas where the fastening brackets are placed from the direction opposite to the direction of movement and amounted to about 6.4 mm.

2. The concept of a removable module for placing crawler equipment in an open wagon is proposed. This concept is a frame that is equipped with fastening brackets for fixing the TTU. Fastening of this module in the open wagon is carried out with the help of corner fittings. For this, it is necessary to install fitting stops on the floor of the open wagon. The performance profile of the removable module is determined based on the plot of the longitudinal forces that arise in it. To justify the chosen manufacturing profile of the removable module, its strength was calculated using the finite element method. The calculation is carried out for the case of static loads acting on the removable module, as well as dynamic loads.

Based on the performed calculations for the case of action on the module of static loads, it was established that the maximum stresses occur in the TTU fastening zones and amount to 98.4 MPa, which is 53.1% lower than the allowable one.

The maximum movements in the nodes of the removable module were also recorded in the TTU attachment zones and amounted to 2.1 mm. The results of the calculation of the removable module for the case of dynamic loads acting on it established that the maximum stresses occur in the TTU fastening zones from the side opposite to the direction of movement. These stresses amounted to 168.4 MPa and are 19.8% less than permissible. The maximum displacements also occur in the TTU fastening zones from the opposite side of the removable module in terms of movement and amount to 2.6 mm. The performed calculations prove that the strength of the removable module under the considered operating load schemes is ensured.

3. Mathematical modelling of the vertical load of an open wagon loaded with a tracked machine was carried out. It was established that the maximum accelerations in the centre of mass of the supporting structure of the open wagon are about 1.7 m/s^2 (0.17g). The evaluation of the movement of the open wagon was carried out based on the accelerations that act in its centre of mass. In accordance with this, the movement of the open wagon is rated as "excellent".

The conducted research will contribute to the improvement of the efficiency of railway transport operation and will be useful developments in the design of modern concepts of removable modules of multifunctional purpose.

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