Research into the dynamic loading on the carrying structure of a flat wagon with lower center of gravity when transporting firing equipment

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Abstract. The article presents the study results of the dynamic loading of a flat wagon with a lower gravity center. The authors built a mathematical model that takes into account displacements of a flat wagon loaded with an anti-aircraft installation firing in motion. The solution of the differential equations of motion is carried out by using the Runge-Kutta method. The maximum vertical acceleration was about 5 m/sec² and almost independent of the fire angle. The horizontal acceleration was about 37 m/sec². The acceleration values obtained did not exceed the normative ones. The study defined the natural oscillation frequencies for the frame of a flat wagon with lower gravity center. It was established that the critical oscillation frequencies were within the admissible values. The results of the work will contribute to the creation of recommendations on the transportation of military equipment on wagons and the possibility of conducting military operations from them.

1. Introduction

The current development of transport infrastructure requires a higher operational efficiency for the railway transport being a leading industry. In terms of their structure, railway vehicles must not only ensure efficient freight transportation, but also be strategic reserve. One of the priority tasks for the railway transport is national defense. This can be achieved by introducing special-purpose wagons, the design of which allows them to carry equipment firing in motion.

Transportation of military equipment by rail is carried out mainly on flat wagons. In order for military equipment to be able to fire from a flat wagon in motion, appropriate research is required. Theoretically, the use of flat wagons with lower gravity center is the rational approach as such wagons have a better stability factor in comparison with that of standard wagons.

Therefore, it is important to do relevant research in this direction with the possibility of further implementation in the design of innovative carrying structures of wagons.
The structural features of the wagon for combined transport are described in [1]. The general requirements for ensuring the safety of combined transport are given. Analysis of a new generation flat wagon design is given in [2]. A special feature of a wagon is the possibility to adjust the effective length according to the dimensions of the freight transported.

It is important to note that in that research no attention was paid to the issues of wagon adaptation for use in military-strategic purposes.

A study of the freight wagon dynamics during their transportation by rail ferry is carried out in [3, 4]. The results of mathematic modelling are proven by computation. The issues of wagon dynamic loading and strength in using them for military-strategic purposes have not been considered in these papers.

Some requirements for carrying systems of railway wagons are presented in [5]. These requirements are suggested for the manufacture of new wagon structures, and also for ones under modernization. However, the requirements for dynamic loads on wagons transporting military equipment are not presented in this study.

The strength of wagon for transportation of timber freight (Model 17-494-01) is studied in [6]. The case of shock loading of a flat wagon was taken into account. However, the authors did not perform the mathematic modelling of dynamic loads on the flat wagon.

The strength of the frame for a rapid articulated flat wagon is estimated in [7]. Strength calculation was carried out by using modern software tools. The paper also presents the results of the fatigue strength calculation of a wagon frame.

The dynamic loads on wagons in train ferry transportation are defined in [8]. The dynamic loading values obtained were taken into account for calculation of the strength of wagon carrying structures. The dynamic loading of the wagons with firing military equipment is not studied.

The features of the strength simulation of a flat wagon for container transportation in the Nastran software are described in [9]. The main operating load conditions have been taken into account when doing this. The rationale for the operation of flat wagons for the removable rolling stock transport is carried out in [10]. This wagon is designed to carry heavy removable units.

However, these studies did not cover the specifics of the wagon loading during conditions above permitted standard, including military-strategic purposes.

The aim of the article is to describe the dynamic features of a flat wagon with a lower gravity center with an anti-aircraft installation firing from it in motion. To do this, the following tasks are set:

- to study the dynamics of a flat wagon with a lower gravity center with an anti-aircraft installation firing from it;
- to calculate the natural oscillation frequencies of the flat wagon frame with a lower gravity center with an anti-aircraft installation firing from it.

2. The main part of the research

To study the dynamics of a flat wagon with a lower gravity center with an anti-aircraft installation firing from it, mathematical simulation has been carried out. The studies were carried out in the XZ plane (figure 1). Three stages of freedom were taken into account: longitudinal plane oscillations, jumping oscillations and galloping oscillations.

It is taken into account that an anti-aircraft installation has muzzle energy of 89 kJ. It was assumed that the anti-aircraft installation did not move while conducting fire, and the carrying structure rested on two bogies of Model 18-100. The authors used the model created by Prof. Domin and Assoc. Prof. Chernyak, which is designed for an open wagon loaded with conditional cargo when using full carrying capacity [11]. Therefore, this model has been redone and takes into account the movement of a flat wagon with the anti-aircraft installation (1) – (6).
The movement of a flat wagon with the anti-aircraft installation is described by second-order differential equations:

\[ M_1 \frac{d^2}{dt^2} q_1 + M_1' \frac{d^2}{dt^2} q_3 = P_l + P_h' \]  

\[ M_1 \frac{d^2}{dt^2} q_2 + C_{2,2} q_2 + C_{2,5} q_5 + C_{2,8} q_8 = P_z \]  

\[ M_2 \frac{d^2}{dt^2} q_3 + C_{3,3} q_3 + C_{3,5} q_5 + C_{3,8} q_8 = P_\varphi \]  

\[ M_3 \frac{d^2}{dt^2} q_4 = 0 \]  

\[ M_3 \frac{d^2}{dt^2} q_5 + C_{5,2} q_2 + C_{5,3} q_3 + C_{5,5} q_5 + B_{5,5} \frac{d}{dt} q_5 = P_{z,T_1} \]  

\[ M_4 \frac{d^2}{dt^2} q_6 + C_{6,6} q_6 + B_{6,6} \frac{d}{dt} q_6 = P_{\varphi,T_1} \]  

\[ M_5 \frac{d^2}{dt^2} q_7 = 0 \]  

\[ M_5 \frac{d^2}{dt^2} q_8 + C_{8,2} q_2 + C_{8,3} q_3 + C_{8,8} q_8 + B_{8,8} \frac{d}{dt} q_8 = P_{z,T_2} \]  

\[ M_6 \frac{d^2}{dt^2} q_9 + C_{9,9} q_9 + B_{9,9} \frac{d}{dt} q_9 = P_{\varphi,T_2} \]
\[ P_z = -F_{FR} \left( \text{sign} \left( \frac{d}{dt} \delta_1 \right) + \text{sign} \left( \frac{d}{dt} \delta_2 \right) \right) + P'_v; \]  
\[ P_\varphi = F_{FR} l \left( \text{sign} \left( \frac{d}{dt} \delta_1 \right) + \text{sign} \left( \frac{d}{dt} \delta_2 \right) \right) + T_f; \]  
\[ P_{z1}^{T_1} = F_{FR} \text{sign} \left( \frac{d}{dt} \delta_1 \right) + k_1 (\eta_1 + \eta_2) + \beta_1 \left( \frac{d}{dt} \eta_1 + \frac{d}{dt} \eta_2 \right); \]  
\[ P_{\varphi}^{T_1} = -k_1 (\eta_1 - \eta_2) - \beta_1 a \left( \frac{d}{dt} \eta_1 - \frac{d}{dt} \eta_2 \right); \]  
\[ P_{z2}^{T_2} = F_{FR} \text{sign} \left( \frac{d}{dt} \delta_2 \right) + k_1 (\eta_3 + \eta_4) + \beta_1 \left( \frac{d}{dt} \eta_3 + \frac{d}{dt} \eta_4 \right); \]  
\[ P_{\varphi}^{T_2} = -k_1 a (\eta_3 - \eta_4) - \beta_1 a \left( \frac{d}{dt} \eta_3 - \frac{d}{dt} \eta_4 \right); \]

where \( M_i \) are the inertial coefficients of the oscillatory system elements (wagon frame and two bogies); \( C_i \) is the elasticity characteristic of the oscillatory system elements; \( B_i \) is the dispersion function; \( l \) is half of the distance between truck centres; \( a \) is a half of the bogie wheelbase; \( q_i \) are the generalized coordinates corresponding to the translational displacement relative to the longitudinal and vertical axes and the angular displacement around the vertical axis; \( k_T \) is a stiffness of spring set coils; \( \beta_i \) is the damping factor; \( F_{FR} \) is the absolute friction force in spring set coils of bogies; \( P_l \) is the longitudinal load acting on the front stops of the automatic coupling; \( P'_v, P'_h \) are the loads that are transmitted to the wagon frame when firing in the vertical and horizontal planes; \( T_f \) is the moment acting on the wagon frame when firing.

The input parameters to the mathematical model are given in table 1.

| Parameter | Dimension | Value |
|-----------|-----------|-------|
| \( M_1 \) | t         | 11.85 |
| \( M_2 \) | t·m²      | 201.3 |
| \( M_3, M_5 \) | t | 4.3 |
| \( M_4, M_6 \) | t·m² | 3.0 |
| \( l \) | m | 4.86 |
| \( a \) | m | 0.925 |
| \( k_T \) | kN/m | 8000 |
| \( k_i \) | kN/m | 100000 |
| \( \beta_i \) | kN·sec/m | 200 |
| \( P_l \) | kN | 2500 |

It is taken into account that the wagon moves along the track with irregularities. At the same time, an anti-aircraft installation is firing. The mathematical model was solved by using the Runge-Kutta method [12 – 14]. The initial displacement and speeds were taken to be equal to zero.

The accelerations acting on the flat wagon when firing from an anti-aircraft installation in vertical and horizontal planes are determined. The maximum vertical acceleration was about 5 m/sec²; it was nearly independent on the fire angle (figure 2). And the horizontal acceleration was about 37 m/sec² (figure 3).
The acceleration values obtained did not exceed the normative values [15 – 17].

Also, within the framework of the study, a modal analysis of the supporting structure of a flat wagon has been carried out. The purpose of this analysis is to determine the natural frequencies of bending oscillations of the flat wagon supporting structure. In this case, as it is known, to ensure the safety of the flat wagon movement, the first natural frequency of bending oscillations of the supporting structure must be at least 8 Hz in the vertical plane at maximum load. The calculation was made with the finite element method [18 – 20] in CosmosWorks software [21, 22].

The finite element model of the flat wagon frame is shown in figure 4. Tetrahedrons were used to create it. The design diagram of the flat wagon frame is shown in figure 5.
It is taken into account that the load $P_r$, equal to 2500 kN, acts on the front stops of the automatic coupling. The vertical load $P_v$ initiated by the weight of the anti-aircraft installation and by the load $P_f$ in the areas of fixing of the anti-aircraft installation to the wagon frame is also taken into account. The numerical values of the loads are shown in table 2. The model was fixed in the areas where it leaned on the gear parts. Steel 09G2S was used as structural material for a flat wagon. The calculation was carried out in quasi-statics, taking into account the application of dynamic loads obtained by mathematical simulation to the spatial model. The results of the calculation are given in table 3.

### Table 2. The input parameters of the model.

| The parameter | Dimension | Value |
|---------------|-----------|-------|
| $P_l$         | MN        | 2.5   |
| $P_v$         | kN        | 9.32  |
| $P_f$         | kN        | 10.2  |
| a horizontal component |       | 1.18  |
| a vertical component |     |       |

Table 3 demonstrates that the natural oscillation frequencies are within the admissible values.

### Table 3. The values of the natural oscillations frequencies of the carrying structure of a flat wagon of lower center of gravity.

| Frequency number | Frequency, Hz | Frequency, rad/sec. |
|------------------|---------------|---------------------|
| 1                | 15.21         | 95.57               |
| 2                | 16.60         | 104.36              |
| 3                | 19.94         | 125.33              |
| 4                | 20.70         | 130.07              |
| 5                | 21.93         | 137.83              |
| 6                | 24.54         | 154.19              |
| 7                | 25.17         | 158.16              |
| 8                | 28.14         | 176.71              |
| 9                | 29.23         | 183.56              |
| 10               | 32.14         | 201.84              |

In subsequent studies in this direction, the authors plan to carry out a calculation of wagon dynamics taking into account the effect of track irregularities, as well as the stochastic behavior of shots from the anti-aircraft installation placed on it.

Based on the created computer model (figure 5), the dislocation fields of the acceleration acting on the flat wagon supporting structure with a tank firing from it are determined. It was found out that the maximum acceleration is concentrated in the middle part of the flat wagon supporting structure and is $4.3 \text{ m/s}^2$ (figure 6). The discrepancy between the values of acceleration obtained by mathematical and computer simulation in the vertical plane is 14%. In this case, the assessment of wagon motion can be characterized as “excellent” [15, 16].
Figure 6. Accelerations acting on the flat wagon supporting structure.

The work results will contribute to the creation of recommendations for the transportation of military equipment on wagons, and the possibility for the equipment to fire from it.

3. Conclusions

- The dynamics of a flat wagon with a lower gravity center with an anti-aircraft installation firing from it has been studied. The maximum vertical acceleration was about 5 m/sec²; the maximum horizontal acceleration was about 37 m/sec². The accelerations obtained did not exceed the normative values.
- The natural oscillation frequencies of the flat wagon frame with a lower gravity center with an anti-aircraft installation firing from it has been calculated. When doing this, CosmosWorks software which implements the finite element method was used. The first natural frequency is 15.2 Hz. So, the critical oscillation frequencies are within acceptable limits. The dislocation fields of accelerations, which act on the flat wagon supporting structure with the equipment firing from it have been determined by computer simulation. The maximum acceleration was 4.3 m/s². The assessment of the wagon motion is “excellent”.

The paper findings will contribute to the creation of recommendations for the transport of military equipment on wagons and the possibility for it to fire, as well as to the increase the efficiency of using railway transport for military strategic purposes.

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