The dynamics and strength of the carrying structure of a flat wagon while conducting fire from it

O Fomin¹, A Lovska²,5, Ya Kichuk³, N Urum⁴

¹Department of Cars and Carriage Facilities, State University of Infrastructure and Technologies, Kyrylivska str., 9, Kyiv, Ukraine, 04071
²Department of wagons, Ukrainian State University of Railway Transport, Feuerbach sq., 7, Kharkiv, Ukraine, 61050
³Izmail State University of Humanities, Repin str., 12, Izmail, Ukraine, 68600
⁴Department of Navigation and Technical Systems Operation in Water Transport, The Danube Faculty of Marine Transport of the State University of Infrastructure and Technologies, Fanagoriyska str., 7, Izmail, Ukraine, 68600

⁵alyonalovskaya.vagons@gmail.com

Abstract. The dynamic loading of the flat wagon supporting structure during the military equipment transportation and conducting fire from it is investigated. A flat wagon model 13-401 by the construction of Dniprodzerzhirsk Car Building Plant (Ukraine) was chosen as a prototype. It was taken into account that the flat wagon was loaded with two anti-aircraft systems of muzzle energy of 89 kJ. The accelerations acting on the supporting structure of the flat wagon are determined using mathematical simulation. At the same time, it was taken into account that a simultaneous shot from two anti-aircraft systems is carried out. The solution of the mathematical model was carried out in the MathCad software. It has been found that the longitudinal accelerations of the flat wagon supporting structure were about 36 m/s², and the vertical ones were about 5 m/s². The obtained accelerations were taken into account when determining the equilibrium stability of the flat wagon, considering the conducting fire. The stability factor in this case was about 9. The calculation results of the strength of the flat wagon supporting structure are presented. The calculation was carried out in a quasi-static state. It has been established that the maximum equivalent stresses occur in the areas of frontal stops of the automatic coupling and amount to about 300 MPa. The results of the research will contribute to the creation of innovative flat wagon load-bearing structures for the military equipment transportation with the possibility of firing while moving.

1. Introduction
Nowadays Ukraine, with its significant machine-building and transit capacity and also with well-developed transport infrastructure, faces acute economic, social, engineering and national defence and security challenges. And the country must solve all of them. Thus, for rail transportation, which plays a key role in solving problems in the transport industry, the innovative resource-saving car structure is of crucial significance. And the national defence capability can be increased with special cars intended for transporting military equipment, which is of primary importance. And while designing such cars, there is a need to take into consideration refined dynamic loads from transported military equipment in combat activity (fire).

Some features of designing cars for transporting heavy loads are considered in [1]. Dynamics and capacity of a car were calculated in ProMechanica and CosmosWorks software suites. The study deals
with designing the carrying structure for a car of various materials. But it does not touch the possibility to transport military equipment while conducting fire. The structure of a car for intermodal transportation is analyzed in [2]. The special feature of such a car is a lowered middle part and reversible sectors. The car structure allows loading/unloading automobiles by gravity. The study does not consider the possibility to transport military equipment while conducting fire.

The strength of the carrying capacity of a flat wagon with a motor semi-trailer on is modeled in [3]. The study suggests a design diagram for obtaining refined values of stresses in the carrying structure of a flat wagon. Some features of a car to transfer transport means and containers are presented in [4]. The car structure provides an easy loading and unloading of freight without any infrastructure or terminal facilities.

The study presents the dynamic characteristics obtained. The calculation is made in MSC Adams software. It should be noted that the studies do not consider the dynamic loading on a car under transporting military equipment. Research into the dynamics of a flat car under the most unfavorable operational modes is presented in [5, 6]. The study defines the maximum accelerations on the carrying structure of a flat wagon. The authors define the main strength characteristics of the carrying structure. They do not consider the dynamics under transporting military equipment.

The strength of a flat wagon under static and dynamic loading on the carrying structure is defined in [7]; the authors use experimental methods, in particular strain measurements. Dynamics characteristics of a flat wagon calculated with multibody methods are presented in [8]. Equations of motion for a flat wagon are given in the absolute coordinates with Lagrange’s equations of the first kind. But strength of a flat wagon for transporting military equipment is not considered in the studies.

The spatial oscillations of a flat wagon with long cargo moving over rail joint and harmonic irregularities in horizontal and vertical planes are studied in [9]. Oscillations of the mechanic system are described by composing a twenty-differential-equation system. The authors do not define the dynamics and strength of a flat wagon loaded with military equipment.

The objective of the study presents special approaches in defining dynamics and strength of the carrying structure of a flat wagon while conducting fire. The following tasks were set to achieve the objective:

- to make a mathematical model of dynamic loads on the carrying structure of a flat wagon while conducting fire;
- to define the strength coefficient of a flat wagon while conducting fire;
- to define the strength characteristics of the carrying structure of a flat wagon while conducting fire.

2. Mathematical simulation of the dynamic loading of the flat wagon supporting structure

To define the dynamic loads on the carrying structure of a flat wagon while conducting fire the authors applied a mathematical model presented in [10]. However, the model was improved by an additional degree of freedom – oscillations in the longitudinal plane (recoils). The design diagram of a flat wagon loaded with two anti-aircraft systems is given in Figure 1.

In this case, a flat wagon is considered as a system of three solid bodies - a supporting structure and two bogies of model 18-100 with spring sets that have stiffness and a relative friction coefficient.

It is taken into account that the following links are imposed on the system:

1. the movement of the body and bogies of the flat wagon along the track center are the same: \( q_i = q_s = q_f \).
2. wheelsets move without sliding: \( \Psi_{mn} = x_n / R, \) where \( R \) is the wheel radius;
3. due to the absence of elastic elements in the axle-box suspension, the bouncing and pitching of the bogies are determined by the bouncing of the wheelsets.

The study did not consider displacements of the anti-aircraft systems while conducting fire, as they were restricted due to applying multi-screw fixation elements. Authors considered the most unfavorable loading on the carrying structure of a flat wagon, particularly, movement of the car over a joint track irregularity with simultaneous firing.
Figure 1. Design diagram of a flat wagon loaded with two anti-aircraft systems.

The equation of motion for the design model is as follows:

\[
M_1 \cdot \frac{d^2 q_1}{dt^2} + M_2 \cdot \frac{d^2 q_3}{dt^2} = P_1 + P'_e, \tag{1}
\]

\[
M_1 \cdot \frac{d^2 q_2}{dt^2} + C_{zz} \cdot q_2 + C_{zz} \cdot q_e + C_{zz} \cdot q_e = P_e, \tag{2}
\]

\[
M_1 \cdot \frac{d^2 q_4}{dt^2} + C_{zz} \cdot q_4 + C_{zz} \cdot q_e + C_{zz} \cdot q_e = P_e, \tag{3}
\]

\[
M_1 \cdot \frac{d^2 q_6}{dt^2} = H_t, \tag{4}
\]

\[
M_2 \cdot \frac{d^2 q_2}{dt^2} + C_{zz} \cdot q_2 + C_{zz} \cdot q_e + C_{zz} \cdot q_e + B_{zz} \cdot \frac{d q_3}{dt} = P_e', \tag{5}
\]

\[
M_2 \cdot \frac{d^2 q_4}{dt^2} + C_{zz} \cdot q_4 + C_{zz} \cdot q_e + B_{zz} \cdot \frac{d q_3}{dt} = P_e', \tag{6}
\]

\[
M_2 \cdot \frac{d^2 q_6}{dt^2} = H_t, \tag{7}
\]

\[
M_2 \cdot \frac{d^2 q_2}{dt^2} + C_{zz} \cdot q_2 + C_{zz} \cdot q_e + C_{zz} \cdot q_e + B_{zz} \cdot \frac{d q_3}{dt} = P_e', \tag{8}
\]

\[
M_2 \cdot \frac{d^2 q_4}{dt^2} + C_{zz} \cdot q_4 + B_{zz} \cdot \frac{d q_3}{dt} = P_e', \tag{9}
\]

\[
P_e = -F_{rz} \cdot \left( \text{sign} \left( \frac{d}{dt} \delta_1 \right) + \text{sign} \left( \frac{d}{dt} \delta_2 \right) \right) + P'_e, \tag{10}
\]

\[
P_o = F_{rz} \cdot \left( \text{sign} \left( \frac{d}{dt} \delta_1 \right) + \text{sign} \left( \frac{d}{dt} \delta_2 \right) \right) + 2T, \tag{11}
\]

\[
P'_e = F_{rz} \cdot \text{sign} \left( \frac{d}{dt} \delta_1 \right) + k(\eta_1 + \eta_2) + \beta \left( \frac{d}{dt} \eta_1 + \frac{d}{dt} \eta_2 \right), \tag{12}
\]
\[
P_{\psi}^i = -k (\eta_i - \eta_s) - \beta \cdot a \cdot \left( \frac{d}{dt} \eta_i - \frac{d}{dt} \eta_s \right), \quad (13)
\]
\[
P_{\psi}^2 = F_{rn} \cdot \text{sign} \left( \frac{d}{dt} \delta \right) + k (\eta_i + \eta_s) + \beta \left( \frac{d}{dt} \eta_i + \frac{d}{dt} \eta_s \right), \quad (14)
\]
\[
P_{\psi}^3 = -k \cdot a \cdot (\eta_i - \eta_s) - \beta \cdot a \cdot \left( \frac{d}{dt} \eta_s - \frac{d}{dt} \eta_s \right), \quad (15)
\]
\[
M' = M_i + (M_s + M_s) + \frac{n \cdot M_w}{R^2}, \quad (16)
\]
\[
M' = M_i \cdot h, \quad (17)
\]

where \( M_i, M_s \) – the mass and moment of inertia of the flat wagon supporting structure respectively; \( M_s, M_e \) – the mass and moment of inertia of the first bogie in the direction of travel respectively; \( M_s, M_s \) – the mass and moment of inertia of the second bogie in the direction of travel respectively; \( C_{i,j} \) – elasticity characteristic of the vibration system elements defined according to the values of stiffness factors of springs \( k_s \); \( B_{i,j} \) – pattern density function; \( a \) – half bogie wheelbase; \( k \) – track stiffness coefficient; \( \beta \) – damping factor; \( \eta_i (x) \) – function that describes the track irregularity; \( \delta \) – deformation of elastic elements of spring suspension; \( F_{rn} \) – absolute friction force in a spring complex; \( P_{i} \) – longitudinal loading on the automatic coupling supports; \( P_i', P_h' \) – loads on the carrying structure in vertical and horizontal planes in firing, respectively; \( n \) – the number of bogie wheelsets; \( M_w \) – the wheelset moment of inertia; \( H_i, H_s \) – values of horizontal forces applied to body plates; \( T_f \) – moment on the carrying structure of a flat wagon in firing; \( h \) – height of the center of gravity of the carrying structure of a flat wagon (Figure 1).

The output parameters of the model were technical characteristics of the carrying structure of a flat wagon, spring suspension of bogies, perturbation action, and engineering characteristics of the anti-aircraft systems. It was considered, that a flat wagon was loaded with two anti-aircraft systems of muzzle energy of 89 kJ each. Besides, it was considered that two anti-aircraft systems were conducting fire.

The initial displacement and speeds were taken equal to zero [11-14]. The calculation was made in the plane coordinates; it considered the event of firing while the wagon was passing over a joint track irregularity. Differential equations (1)-(9) were reduced to standard Cauchy problems. Then they were integrated by the Runge-Kutta method [15, 16]. On the basis of the calculation the authors defined accelerations on a flat wagon in firing from anti-aircraft systems at various fire angles in horizontal and vertical planes. The maximum acceleration was about 36.0 m/s² and almost independent of the fire angle (Table 1).

| Fire angle, degree | 30   | 35   | 40   | 45   | 50   | 55   | 60   |
|-------------------|------|------|------|------|------|------|------|
| Acceleration, m/sec² | 35.75 | 35.75 | 35.75 | 35.75 | 35.74 | 35.74 | 35.74 |

The pattern of change in accelerations on the carrying structure of a flat wagon at a fire angle of 30° is given in Figures 2 and 3.
3. Determination of the stability factor of the flat wagon

The strength of a flat wagon in firing was defined with the sustainability coefficient. The design diagram is presented in Figure 4.

The balance condition of a flat wagon in firing from anti-aircraft systems is:

\[ k_f \geq \frac{T_{rest}}{2T_f} \]  \hspace{1cm} (18)

where \( T_{rest} \) – restoring torque, kN \cdot m; \( T_f \) – breakdown torque, kN \cdot m.

The restoring torque is defined as:

\[ T_{rest} = P_{gw} \frac{B}{2} + P'_c \cdot h' \]  \hspace{1cm} (19)

where \( P_{gw} \) – gross weight of a wagon; \( B \) – half-width of a wagon; \( P'_c = P_c / 4 \); \( h' \) – height of the wheel flange of a bogie.

The breakdown torque is defined as:

\[ T_f = P_c \cdot h' \]  \hspace{1cm} (20)

where \( P_c \) – load on the carrying structure in firing; \( h' \) – distance from the weight center of an anti-aircraft system to the top level of a railhead.

On the basis of the calculation the authors obtained the restoring torque \( T_{rest} = 466.3 \text{ kN} \cdot \text{m} \), and the breakdown torque \( 2T_f = 54.4 \text{ kN} \cdot \text{m} \), from where \( k_f = 8.6 \). Therefore, the equilibrium stability of a wagon in firing was ensured.
4. Determination of strength indicators of the flat wagon supporting structure

The accelerations on the carrying structure of a flat wagon in firing were taken into account in the strength calculation. The calculation was made by the finite element method [17-19] in CosmosWorks software suite. Spatial tetrahedrons were used as finite elements for the finite element model. The optimal number of elements was calculated with the graphical analytical method. Steel 09G2S was used as structural material for a flat wagon. The design diagram considered that the longitudinal load $P_\parallel$ 2.5 MN impacted frontal supports of the automatic coupling (Figure 5).

The vertical load $P_v$ from the gross weight of anti-aircraft systems, and also loads in fixation areas impacted the carrying structure of a flat wagon. Due to angular location of fixation elements, the load $P_\parallel$ decomposed. The model was fixed in the areas where the model leaned on the gear parts. The results of the calculation are given in Figure 6.

![Figure 5. Design diagram of a flat wagon.](image)

![Figure 6. Stressed state of the carrying structure of a flat wagon.](image)

On the basis of the calculation it was established that the maximum equivalent stresses emerged in the areas of frontal stops of the automatic coupling and were about 300 MPa. Therefore, the maximum equivalent stresses did not exceed the admissible values [20]. The maximum displacements were about 3.0 mm. The maximum deformations were $3 \times 10^{-3}$. Thus, it is possible to keep firing from anti-aircraft systems under rail transportation.

5. Conclusions

- The dynamic loading of the flat wagon supporting structure when conducting fire from two anti-aircraft systems placed on it has been determined. The calculation was carried out in a flat coordinate system. It was found that the longitudinal accelerations of the flat wagon supporting structure were about 36 m/s$^2$, and the vertical ones were about 5 m/s$^2$. Moreover, the acceleration rate is almost independent of the firing angle;
- The stability factor of the flat wagon while conducting fire has been determined. It has been established that the stability factor has a value of about 9. That is, the equilibrium stability of the flat wagon supporting structure while conducting fire from it is ensured;
- The main strength indices of the flat wagon supporting structure while conducting fire from it have been determined. The maximum equivalent stresses were about 300 MPa and concentrated in the area of the frontal supports of the automatic coupling, the maximum displacements were about 3.0 mm, and the maximum deformations were $3 \times 10^{-3}$. So, it is possible to conduct fire from anti-aircraft systems of given muzzle energy when transported on a flat wagon. The results of the research will contribute to the creation of flat wagon supporting structures for the transportation of military equipment and firing when moving.

Acknowledgments

This study was conducted in the framework of a scientific theme "Development of conceptual frameworks for restoring the efficient operation of obsolete freight cars" (Project registration number: 2020.02/0122).
References

[1] Divya Priya G and Swarnakumari A 2014 Modeling and analysis of twenty tonne heavy duty trolley Intern. J. of Innovative Technology and Research 2 6 pp 1568–1580

[2] Krason W and Niezgoda T 2014 FE numerical tests of railway wagon for intermodal transport according to PN–EU standards Bulletin of the Polish Academy of Sciences Technical Sciences 62 4 pp 843–851

[3] Bondarenko A I and Panin A Yu 2014 Teoreticheskaya i eksperimentalnaya otsenka prochnosti vagona-platformyi dlya perevozki avtomobilnykh polupritsepow Transp. Ros. Federatsii 3 pp 33–35

[4] Niezgoda T, Krasoń W and Stankiewicz M 2015 Simulations of motion of prototype railway wagon with rotatable loading floor carried out in MSC Adams software J. of Kones Powertrain and Transport 19 4 pp 495–502

[5] Okorokov A M, Fomin O V, Lovska A O, Vernigora R V, Zhuravel I L and Fomin V V 2018 Research into a possibility to prolong the time of operation of universal semi-wagon bodies that have exhausted their standard resource Eastern-European journal of enterprise technologies 3/7 93 pp 20–26

[6] Fomin O, Lovska A, Pišťek V and Kučera P 2020 Research of stability of containers in the combined trains during transportation by railroad ferry MM Science Journal 1 pp 3728–3733

[7] Sandu N and Zaharia N L 2014 Static and dynamic tests performed on a flat wagon Problemy kolejnictwa 163 pp 67–77

[8] Wójcik K, Malachowski J, Baranowski P, Mazurkiewicz L, Damaziak K and Krason W 2012 Multi-body simulations of railway wagon dynamics J. of Kones Powertrain and Transport 19 3 pp 499–506

[9] Anisimov P 2013 Model prostranstvennyh kolebaniy platformyi s dlinnomernyim gruzom Mir transporta 4 pp 6–13

[10] Domin Yu V and Chernyak G Yu 2003 Osnovi dinamiki vagoniv (Cham: Kiyiv KUETT) p 269

[11] Fomin O, Lovska A, Radkevych V, Horban A, Skliarenko I and Gurenkova O 2019 The dynamic loading analysis of containers placed on a flat wagon during shunting collisions ARPN Journal of Engineering and Applied Sciences 14 21 pp 3747–3752

[12] Fomin O, Lovska A, Pišťek V and Kučera P 2019 Dynamic load computational modelling of containers placed on a flat wagon at railroad ferry transportation Vibroengineering Procedia 29 pp 118–123

[13] Kondratiev A V, Gaidachuk V E and Kharchenko M E 2019 Relationships between the ultimate strengths of polymer composites in static bending, compression, and tension Mechanics of Composite Materials 52 2 pp 259–266

[14] Pištek V, Klimes L, Mauder T and Kucera P 2017 Optimal design of structure in rheological models: An automotive application to dampers with high viscosity silicone fluids Journal of Vibroengineering 19 6 pp 4459–4470

[15] Dyakonov V 2000 MATHCAD 8/2000: spetsialniy spravochnik (Cham: SPb. Piter) p 592

[16] Alyamovskiy A A 2010 COSMOSWorks Osnovy rascheta konstruktsiy na prochnost v srede SolidWorks (Cham: Moscow DMK Press) p 785

[17] Vatulia G, Falendysh A, Orel Y and Pavluchenkov M 2017 Structural improvements in a tank wagon with modern software packages Procedia engineering 187 pp 301–307

[18] Kitov Y, Verevicheva M, Vatulia G, Orel Y and Deryzemlia S 2017 Design solutions for structures with optimal internal stress distribution MATEC Web of Conferences 133(1–3) 03001

[19] Fomin O, Lovska A, Kulbovsksyi I, Holub H, Kozarchuk I, Kharuta V 2019 Determining the dynamic loading on a semi-wagon when fixing it with a viscous coupling to a ferry deck Eastern-European Journal of Enterprise Technologies 8 2/7 98 pp 6–12

[20] GOST 33211-2014 2014 Vagonyi gruzoviyie. Trebovaniya k prochnosti i dinamicheskim kachestvam p 54