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PROSPECTIVE CONCEPT OF THE DRAFT SYSTEM OF OPEN BOXCARS

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Purpose. Integration of Ukraine into the world freight transportation and transport engineering systems suggests the need to create the rolling stock which will be competitive at the world transportation market. The solution of this scientific-and-technological problem requires development and implementation of new generation rail cars with considerably improved characteristics of power, reliability and possibility to increase speeds. It can be achieved by implementing creative and ingenious solutions in the rail car structure. Therefore, the present stage of railway industry demands production and implementation of progressive approaches to the 21st century rolling stock design. **Methodology.** It has been used the following modern methods in the research: the method of the wagon dynamics and the theory of vibrations for a mathematical model designing to define accelerations in the supporting structure of the car body with viscous materials, the theoretical and applied mechanics for dynamic processes modeling in a new draft system, designing in modern engineering software applications for creating of an adequate spatial virtual model of the supporting system of an open boxcar, finite elements for calculations of accelerations occurring in the supporting structure of an open boxcar under longitudinal loading, and the F-test for the model adequacy. Generally, the algorithm of the research included the mathematical model designing for the prospective supporting system of an open boxcar to ground the parameters of the viscous material used. Then the computer simulation of maximum longitudinal working loads has been conducted for the new open boxcar body. And the results have been analyzed. **Results.** The comprehensive theoretical research has proved the efficiency of implementation of the draft system concept for open boxcars. Its full-scale implementation will provide substantial reduction of construction and maintenance cost of freight cars. The designed models are adequate and can be used for further similar research. **Originality.** For the first time a new concept of the draft system of open boxcars has been proposed and scientifically based. The longitudinal working loads are distributed to the centre sill, not to a separate absorbing device (rather expensive one); the centre sill has been made of a circular pipe where the draft arms are filled with viscous material of damping characteristics. For comprehensive theoretical investigations of possibility to implement the proposed idea it has been developed a mathematical and finite-element models for defining accelerations in the supporting structure of the car body, which considered viscous connection, the adequacy of the models have been checked. **Practical value.** The results of theoretical pre-design scientific substantiation of the proposed concept make it possible to proceed to the next design stages. Besides, such results will become the base for further dynamics and power calculations of the supporting structure of car bodies while implementing the proposed innovative trend.

Key words: open boxcars, construction, dynamics, acceleration, load, strength.

ПЕРСПЕКТИВНИЙ КОНЦЕПТ УПРЯЖНОЇ СИСТЕМИ ЗАЛІЗНИЧНИХ НАПІВВАГОНІВ

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В результаті проведеного комплексу теоретичних досліджень з’ясовано ефективність впровадження запропонованого концепту упряжної системи залізничних напіввагонів. Його використання дозволить суттєво знизити собівартість виготовлення та експлуатації вантажних вагонів. Розроблені в ході досліджень моделі є адекватними, що доводить доцільність їх використання в відповідних подальших науково-дослідних та дослідно-конструкторських роботах. Вперше запропоновано та науково обґрунтовано новий концепт упряжної системи залізничних напіввагонів, де функції по поглинанню поздовжніх експлуатаційних навантажень замість окремого поглинального апарату виконує хребтова балка шляхом виконання її із круглої труби з заповненими консольними частинами в’язким матеріалом з демпфуючими властивостями. Для комплексного теоретичного дослідження можливостей реалізації запропонованого напрямку розроблено математичну та скінчено-елементну моделі для визначення прискорень у несучій конструкції кузова вагона з урахуванням наявності в’язкого зв’язку у ній, та перевірено їх адекватність.

Ключові слова: залізничний транспорт, вантажний вагон, концепт упряжної системи, впровадження в’язких матеріалів, динамічна навантаженність конструкції.

PROBLEM STATEMENT. One of the key problems in rail transport development is designing samples of rolling stock with improved technical, economic and operational characteristics.

According to transport experts in Ukraine and other countries the coming years will witness increased volume of rail transportation. It explains the need to create the rolling stock which will provide maximal effectiveness and safe operation of railways. And the key role is fulfilled by freight cars. Therefore, development and operation of freight cars of the best performance characteristics will become the ground of economic prosperity for the rail transport in the world freight transportation market. It is especially acute for Ukraine being a machine building country (over 10 machine building plants) with a considerable domestic freight turnover and transit potential; though over two third of the rolling stock being obsolete both morally and physically. But to achieve the highest efficiency of freight cars with conventional approaches without developing absolutely new designs is an impossible task.

The experience in operating freight rolling stock in European countries and Ukraine, according to transport experts, indicates the absence of innovative knowledge-based structures and technologies. Most of innovative solutions are aimed at modernization of existing projects (car trucks, car bodies, unloading and braking systems, elastic and dissipative vibration control systems). It is obvious that such a situation can have a detrimental effect to the rail transport in its competition against other transportation modes. A conventional modern car cannot meet the requirements for the 21st century rolling stock.

Analysis of results of recent studies and stating the problem which has not been solved.

So that to reduce the construction and operational cost of cars the supporting structures are made of circular pipes while meeting requirements for power capacity and operational reliability [1–3]. Optimal parameters of circular pipes, proposed to use as supporting elements of car bodies, can be defined on the base of the power reserve of standard structural elements. The results of the capacity calculations for improved supporting structures of car bodies have shown that requirement for the power capacity is fulfilled considering the solutions proposed. The analysis of construction materials for new generation car bodies presented in study [4] lists the advantages of the innovative materials for some car elements. Besides, the next stage in designing innovative cars [1–4] lays in the investigation into reduction of dynamic loads of the supporting structures.

The measures aimed at improvements in the supporting structure of the open boxcar body so that to provide their reliable fixation on the desk of railway ferry is given in [5]. The results of the body capacity calculations including their fixation on the desk in the proposed construction points in the conditions of sea dusting have confirmed the efficiency of the proposed solutions.

Investigation into dynamic loads of flatcars with containers in the conditions of shunting impacts is given in [6]. The investigation made it possible to obtain accelerations influencing the flatcar and containers taking into account possible shifts of container fittings relative to the fixed fittings located on the flatcar.

The investigation into dynamics of rail flatcars is given in [7]. The calculation has been carried out in MSC Adams software. The stability test against car rollover has been made on a 250 m radius curve at different speeds. The results of the above-mentioned studies [1–7] are a sufficient basis for solving the problem, which has been posed for the first time and regards improvements in freight cars. The aim of the improvements is to decrease the car dynamic load by implementing the new draft system concept where longitudinal working loads are carried by the center sill, not by a separate device (by the way, a rather expensive one); the centre sill being made of a circular pipe where the draft arms are filled with viscous material of damping characteristics.

The objective of the study. The study reveals the peculiarities and results of research into implementation of the innovative draft system for automatic couplers of open boxcars. Such a system is alternative to an existing one, where energy of longitudinal loads are absorbed by draw gears, the main working elements of which are absorbing devices. The concept of the new system is based on the above-mentioned functions performed by the centre sill of an open boxcar, made of a circular tube the draft arms of which are filled with viscous material of damping properties.

EXPERIMENTAL PART AND RESULTS OBTAINED. The concept proposed suggests replacing a modern draft gear consisting of separate parts (absorbing devices, yokes, follower blocks, etc.) so that to reduce construction and maintenance cost of open boxcars. The advantages mentioned are achieved due to higher effectiveness of the centre sill of the open boxcar, namely, its ability to absorb tensile and compressive loads associated with impacts during shunting operations and transition operational modes. It is especially important in the conditions of higher train speeds, intensive shunting operations and for ensuring safety.

General operational algorithm:

1. Theoretical estimation of dynamic load of the supporting structure of the open boxcar body under longitudinal loads during shunting impacts (the most extreme operational conditions) using modern research methods for investigation into the wagon dynamics and the theory of vibrations;
2. Computer simulation of dynamic loads on the supporting structure of the open boxcar body under the influence of longitudinal loads during shunting impacts with the use of engineering software;
3. Theoretical model verification to provide the theoretical substantiation of necessity to create a prospective concept of the draft system of open boxcars.

So that to reduce dynamic loads influencing the supporting structure of the open boxcar body the study proposes to remove draft gears of automatic couplers and transfer their function of absorbing energy associated with operational loads to the centre sill and upper and lower coverings of side walls; they are proposed to be made of circular pipes and filled with materials of damping and anticorrosion properties, that will allow a lower material consumption for the car, an increased carrying capacity and loading volume of the body, as well as a longer repair-free service life.

So that to define dynamic loads influencing the car body during shunting impacts, as the most intensive loads on its supporting structure in operation, the mathematical model presented in [8] has been used. The model is designed for defining accelerations being components of the dynamic loads on the flatcar loaded with container tankers during shunting impacts. Therefore, it has been improved for defining accelerations as components of the dynamic loads on the car under longitudinal impact forces.

$$M'_C \cdot \ddot{x}_B + M_C \cdot h \cdot \ddot{\varphi}_B = S_a, \quad (1)$$

$$I_C \cdot \ddot{\varphi}_B + M_C \cdot h \cdot \ddot{x}_B - g \cdot \varphi_B \cdot M_C \cdot h =$$

$$= l \cdot F_{FR}\left(sign\dot{\Delta}_1 - sign\dot{\Delta}_2\right) + l\left(k_1 \cdot \Delta_1 - k_2 \cdot \dot{\Delta}_2\right), \quad (2)$$

$$M_C \cdot \ddot{z}_B = k_1 \cdot \Delta_1 + k_2 \cdot \Delta_2 - F_{FR}\left(sign\dot{\Delta}_1 - sign\dot{\Delta}_2\right), \quad (3)$$

$$M'_C = M_C + 2 \cdot m_B + \frac{n \cdot I_W}{r^2}; \ \Delta_1 = z_B - l \cdot \varphi_B; \ \Delta_2 = z_B + l \cdot \varphi_B$$

where M_C is the mass of the supporting structure of the car; I_C is the inertia moment of the car relative to the longitudinal axis; S_a is the value of the longitudinal impact force upon the automatic coupler; m_B is the body mass; I_W is the inertia moment of the wheel set; r is the radius of the half worn wheel; n is the number of the body's axes; l is the half of the bogie center distance; F_{FR} is the absolute value of the dry friction force in the spring group; k_1, k_2 are the rigidities of springs in the spring suspension of the car bodies; x_B, φ_B, z_B are the coordinates corresponding to longitudinal, angular around the lateral axis and vertical displacement of the car respectively.

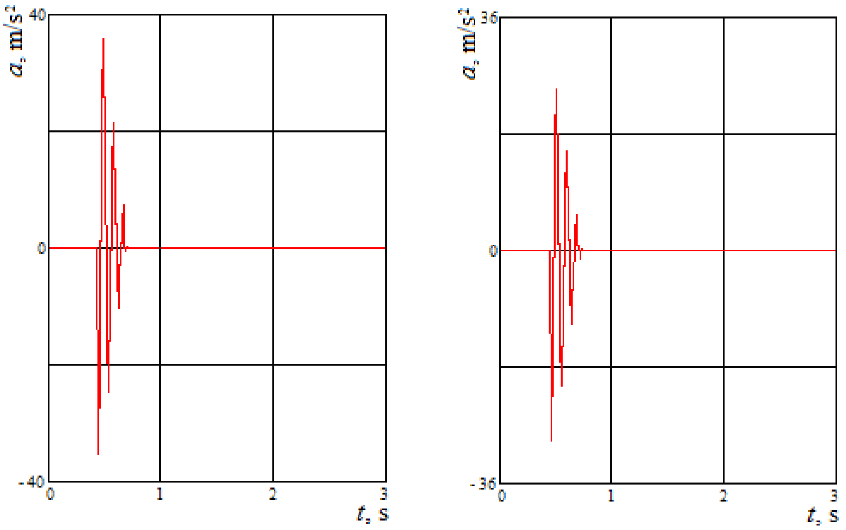
The solutions of the differential equations have been found in the MathCad software, where they have been reduced to a normal Cauchy-Euler equation, and then integrated with the Runge-Kutta method.

The initial displacements and speeds have been taken equal to zero. The input parameters of the mathematical model are technical characteristics of the car body, parameters of spring suspension, and also values of longitudinal impact force upon the automatic coupler.

The 12-757 open boxcar has been taken as a basic model taking into account its supporting structure made of circular pipes. The spring suspension parameters considered in the calculations have been taken the same as for a standard bogie of the 18-100 model.

The longitudinal impact force influencing the vertical surface of the rear draft lug of the coupler is taken equal to 3.5 MN [9].

The results of the research made it possible to conclude that the acceleration influencing the supporting structure of the car during shunting co-impacts is approximately 40 m/s^2 (Fig. 1, a)).



a) b)

Figure 1 – The accelerations influencing the car during shunting co-impacts:
a) for the standard scheme of carrying loads by the center sill of the car;
b) for the scheme of carrying loads by the center sill filled with viscous material

So that to define accelerations influencing the supporting structure of the car body with consideration of circular pipes filled with elastomeric material of damping and anticorrosion properties, the mathematical model mentioned above is reduced to:

$$M_C' \cdot \ddot{x}_B + M_C \cdot h \cdot \ddot{\varphi}_B = S_a - \beta \cdot \dot{x}_B, \quad (4)$$

$$I_C \cdot \ddot{\varphi}_B + M_C \cdot h \cdot \ddot{x}_B - g \cdot \varphi_B \cdot M_C \cdot h =$$

$$= l \cdot F_{FR}\left(sign\dot{\Delta}_1 - sign\dot{\Delta}_2\right) + l\left(k_1 \cdot \Delta_1 - k_2 \cdot \dot{\Delta}_2\right), \quad (5)$$

$$M_C \cdot \ddot{z}_B = k_1 \cdot \Delta_1 + k_2 \cdot \Delta_2 - F_{FR}\left(sign\dot{\Delta}_1 - sign\dot{\Delta}_2\right), \quad (6)$$

where β is the viscous resistance coefficient of the material inside the supporting structure elements of the car.

The investigations of accelerations influencing the supporting structure of the car body with viscous material inside its supporting elements made it possible to conclude that efficiency of this solution can be achieved at the viscous resistance coefficient values lower than 120 kN·s/m.

The results of the research considering the viscous resistance coefficient values of the material 120 kN·s/m made it possible to conclude that the acceleration influencing the supporting structure of the car during shunting co-impacts is about 34 m/s^2 (Fig.1, b), and lower by 10 % than the values of accelerations achieved for a standard loading scheme and exerted on the center sill of the car.

It should be mentioned that the value of the acceleration obtained can be reduced by selecting the best parameters of viscous materials used in industry.

In order to implement the proposed scheme for carrying longitudinal loads by the centre sill of the car, structural changes in automatic coupling devices are suggested, namely, removal of draft gears, as well as follower blocks and transfer their functions to less structurally complicated elements (Fig. 2) that considerably reduce construction and repair cost of such open boxcars.

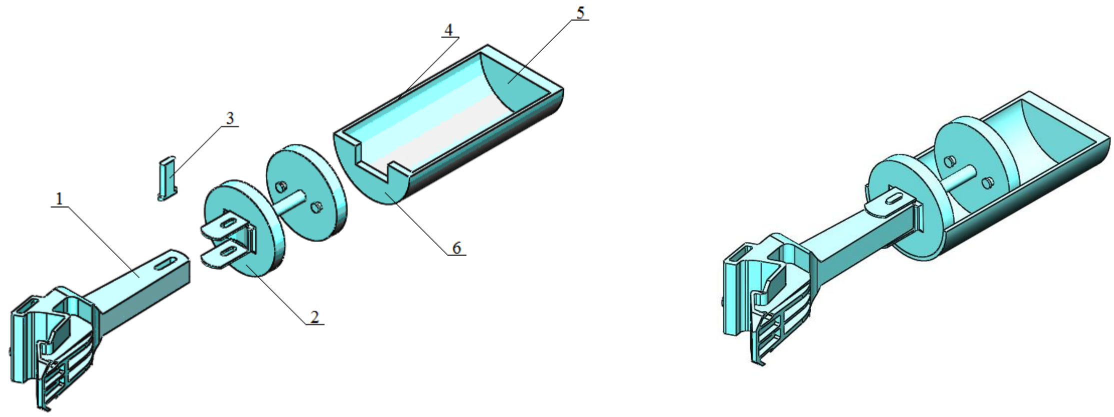


Figure 2 – Structural peculiarities of the automatic coupling device considering implementation of viscous materials as springs for longitudinal forces on the supporting structure of the car body: a) the assembly with element separation; b) the assembly (overview); 1 – body of the automatic coupler; 2 – adaptor; 3 – key; 4 – centre sill made of circular pipe; 5 – bottom

The automatic coupler consists of CA-3 standard frame 1 interacting with the intermediate adapter 2 consisting of the front follower with a standard follower block on. Through the rod the front follower of the adaptor is connected with the piston with two throttle valves – input and output. The viscous material is located to the right and left of the piston. To create the pressure in the viscous material when the piston moves during impact force in centre sill 4, bottom 5 is provided. To limit the movements of the adaptor during jerks and stretches the limiter 6 is provided.

The structural peculiarities of the adaptor are presented in Fig. 3.

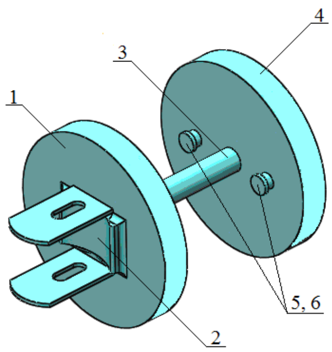


Figure 3 – The structural peculiarities of the adaptor: 1 – front follower; 2 – follower block; 3 – rod; 4 – piston; 5, 6 – throttle valves

Considering the viscous materials as springs for longitudinal forces on the supporting structure of the car body the automatic coupling device operates as follows (Fig. 4). Through automatic coupler body 1 the loads are transferred to adaptor's front follower 2 through the shark end. Under the loads the adapter moves in longitudinal direction and presses the viscous material located in the gap between piston 3 and bottom 4. It provides the flow through the throttle valve to the gap between the front follower of the adapter and the piston. At the backspacing of the piston the viscous material flows through the other throttle valve. The energy generated dissipates in the environment. Thus the work of the viscous material is similar to the work of a hydraulic shock absorber (damper).

So that to improve the efficiency of the proposed draft system of the car it is necessary to provide the air-tightening (absence of possible outputs of the viscous material out of the centre sill).

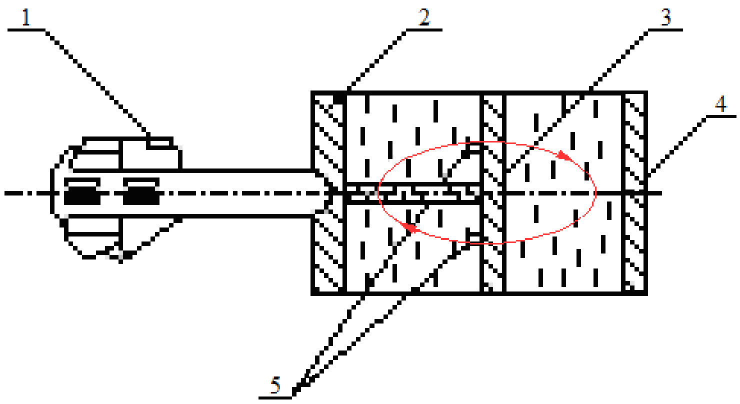


Figure 4 – The operation of the automatic coupling device considering implementation of viscous materials as springs for longitudinal forces to the supporting structure of a car body

In order to theoretically check the obtained results of mathematical modelling and investigations into acceleration field distribution in the supporting structure of the open boxcar made of circular pipes, the spatial computer model in SolidWorks software was designed (Fig. 5) with subsequent dynamics modelling in CosmosWorks software. The accelerations were defined by the finite-element method [10].

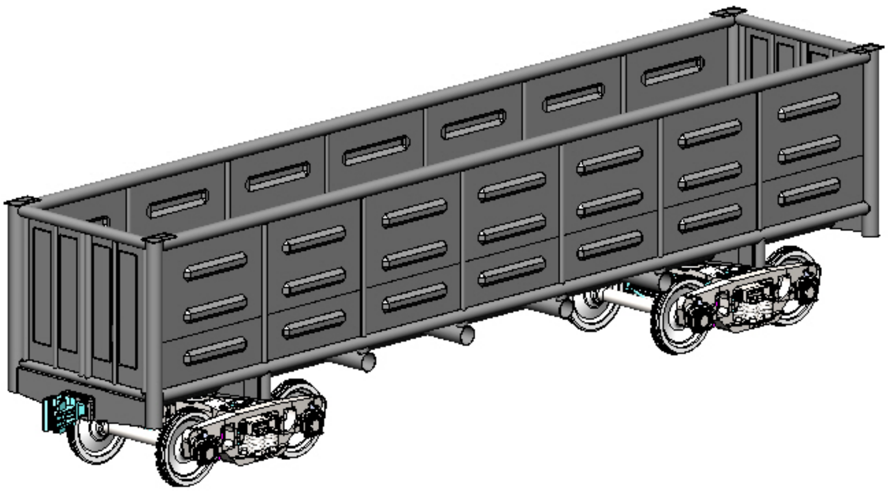


Figure 5 – The computer model of the supporting structure of the open boxcar body made of circular pipes

The finite-element model (FEM) of the body of an open boxcar considering implementation of viscous materials as springs for longitudinal forces to the supporting structure is presented in Fig. 6.

The optimal number of elements of the grid (which provides the level of adequacy of research findings) has been defined by the graphic analytical method. Isoperametric tetrahedrons have been used as finite elements. And the number of grid elements was 640,829, joints – 204,116. The maximum size of the grid element is 93.5 mm, the minimum size is 18,7 mm, the maximum ratio of sides of the elements is 598,26, the percentage of the elements with the ratio of sides lower than three is 27,8, higher than ten is 10,9. The minimum number of elements in the circle is 15; the ratio of growth of the size of the element is 1,9.

The capacity model of the promising supporting structure of the open boxcar body is given in Fig. 7 a).

The values of loads influencing the supporting structure of the open boxcar body for calculation mode I as the most intensive mode for the body is given in Table 1.

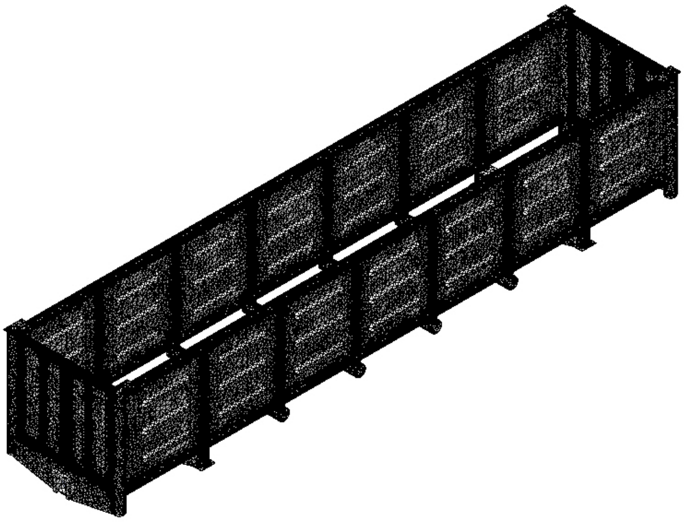


Figure 6 – The finite-element model of the open boxcar body considering implementation of viscous materials as springs for longitudinal forces upon the centre sill

It was taken into account that the total freight capacity of the car was used. Black coal was used as the bulky freight being the most frequently transported in Ukraine. In the Table the sign * marks the pressure of the bulky load on the lower part of the studs and the sign ** marks the pressure on the upper part of the studs.

The longitudinal impact force was applied to the vertical surface of the front follower of the adaptor (Fig. 7, b)) and the opposite end was fixed for simulating the maximum pressure on the supporting structure.

The model was also fixed in the areas of its support on riding parts, namely, body centrals and crossbars.

In order to model properties of the viscous material the study uses the spring-damper link taken from the fastening examples presented in the software, and installs it between the piston and the bottom. The coefficient of viscous resistance of the material was taken 120 kNH·s/m and the spring rigidity was taken equal to zero, because the proposed scheme of carrying longitudinal loads does not consider spring linkage.

The calculations have demonstrated that the shift of the adaptor under a longitudinal impact force of $3{,}5 \cdot 10^3$ kN and an impact force speed of 0,03 m/s is 875 mm.

The supporting structure was made of the 09Г2С steel.

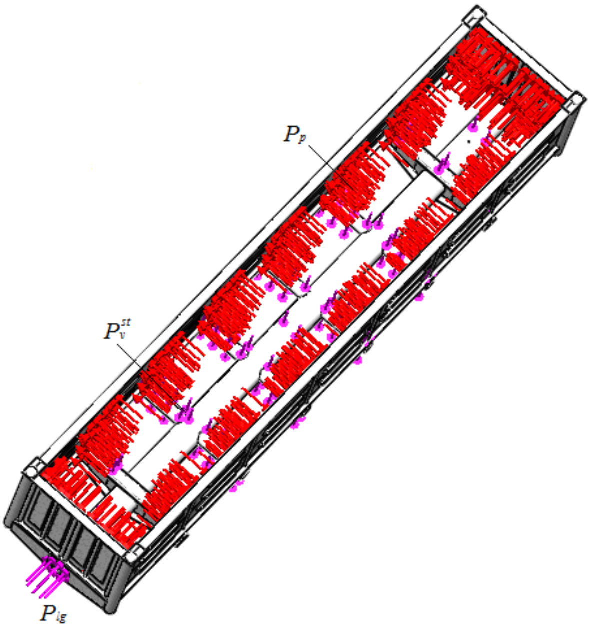
While designing the model a possible difference in levels of interacting automatic coupler castings of the cars was not considered.

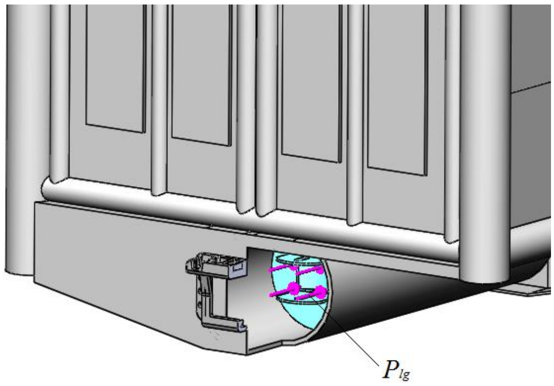
The calculation results are given in Fig. 8.

The research conducted makes it possible to conclude that maximum accelerations of the car body occur in the area from the arm to the area where the centre sill interacts with the bolster beam and are about 50 m/s^2 (≈5g). In the area between the bolster beam to the middle part of the centre sill the value of accelerations decreases and is about 30 m/s^2 (≈3g).

Table 1 – The values of loads influencing the supporting structure of the open boxcar body

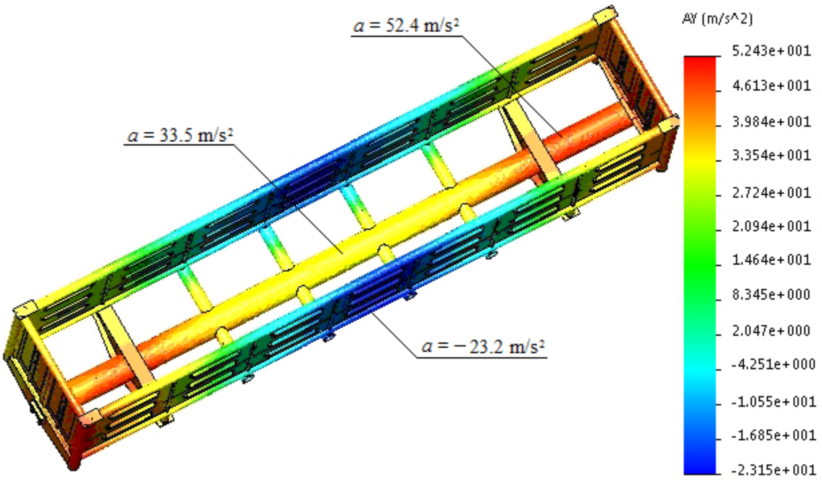
Loads	Values
Vertical static, kN	829,926
Pressure from bulky load, kPa	
Side wall stud:	
angular	7,083
the first from the arm	13,03
the second from the arm	11,895
the third from the arm	8,92
Front (end) wall stud:	
angular	50,06* 44,98**
intermediate	100,12* 89,96**
middle	50,06* 44,98**



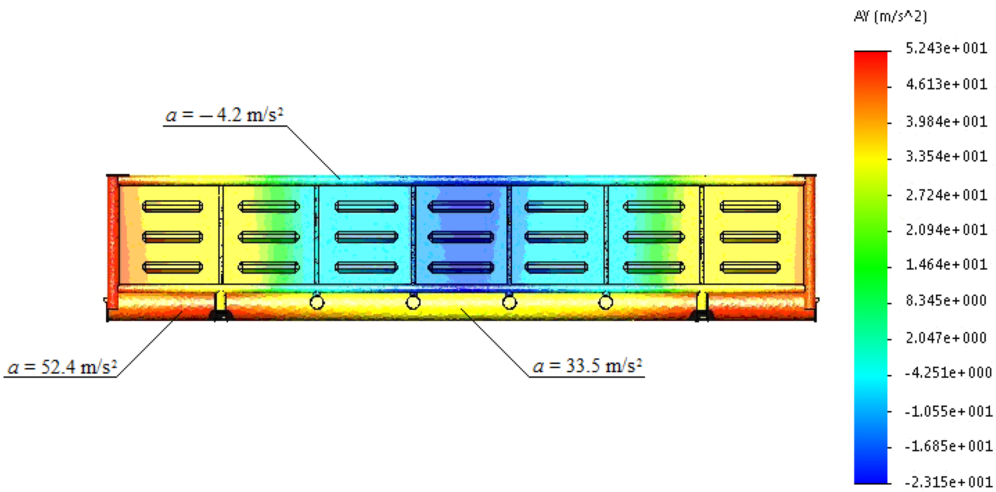


a) b)

Figure 7 – The capacity model of the open boxcar body considering implementation of viscous materials as springs for longitudinal forces upon the centre sill:
P_v^{st} is the vertical static load; P_p is the pressure from the bulky load; P_{lg} is the longitudinal impact force:
a) – overview; b) – scheme of the longitudinal force exerted upon the adapter



a)



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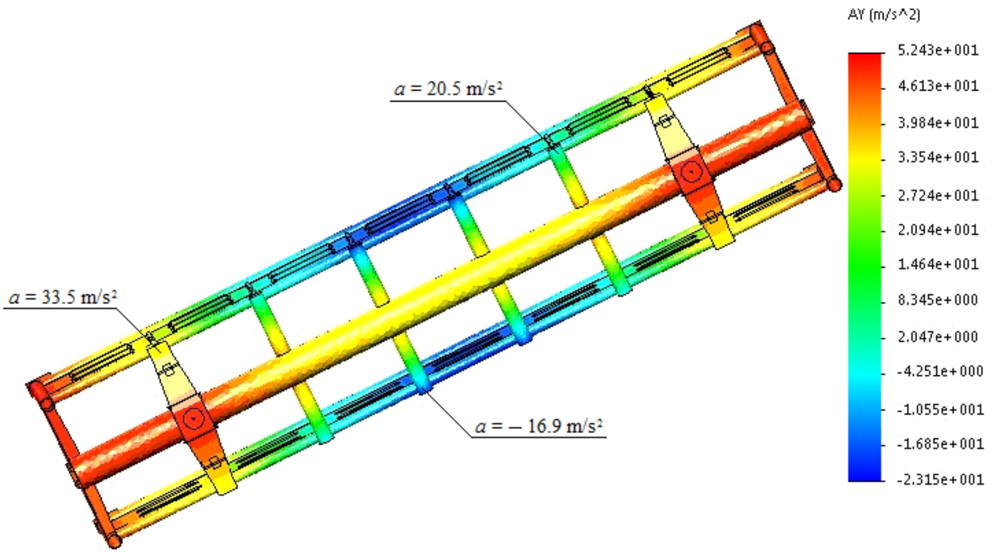

c)

Figure 8 – The distribution of acceleration fields influencing the supporting structure of the body of an open boxcar considering implementation of viscous materials as springs for longitudinal forces upon the centre sill:
a) top view; b) side view; c) bottom view

The distribution of accelerations along the centre sill of an open boxcar frame is given in Fig. 9.

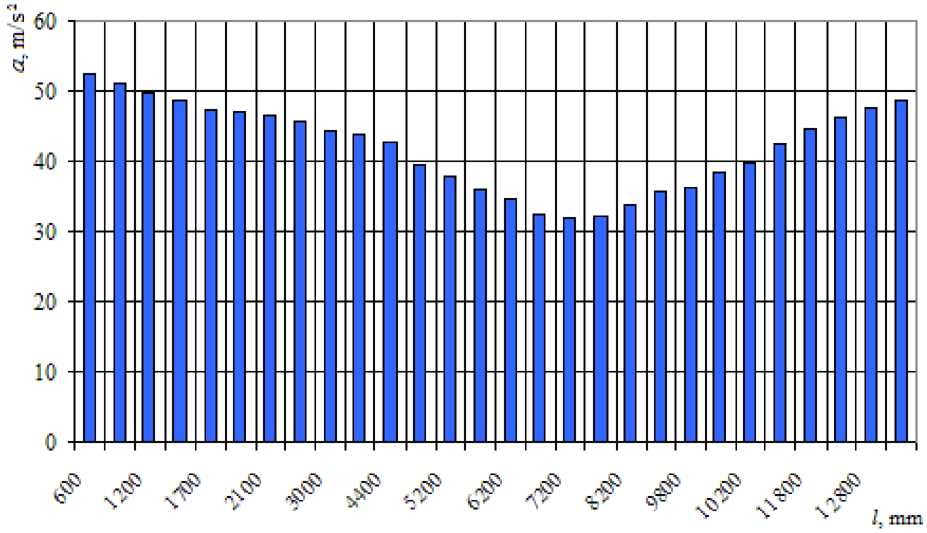

Figure 9 – The distribution of accelerations along the centre sill of an open boxcar frame under the impact force on the adapter

The comparative analysis of accelerations occurring in an open boxcar frame as the most important element of the construction during shunting impacts with viscous materials and without them is given in Table 2.

Table 2 – The comparative analysis of accelerations in the open boxcar frame

Frame elements	Accelerations m/s^2		Difference %
	without viscous material in the centre sill	with viscous material in the centre sill	
Centre sill (central part)	50,3	33,5	33,4
Bolster beam	42,5	38,4	9,6
Frontal beam	21,7	48,3	55,1
Intermediate beam (the first from the bolster beam to the center of the centre sill)	35,1	33,5	4,6
Intermediate beam (the second from the bolster beam to the center of the centre sill)	38,2	32,4	15,2

Thus, maximum accelerations in the open boxcar frame with viscous materials under the impact force occur in the zone from the frontal beam to the bolster beam, and without viscous materials – in the central area of the centre sill. It is conditioned by the fact that kinetic energy of the impact force is dampened by the draft system and turns into the dissipative energy.

In order to test the adequacy of the designed model the F-test has been applied.

$$F_p = \frac{S_{ad}^2}{S_r^2}, \quad (7)$$

where S_{ad}^2 – is the dispersion of adequacy; S_r^2 – is the dispersion of restorability.

The dispersion of adequacy can be defined by the formula:

$$S_{ad}^2 = \frac{\sum_{i=1}^{n}\left(y_i - y_i^p\right)}{f_i}, \quad (8)$$

where y_i^p – is the calculated value obtained by modelling; f_i – is the number of freeness.

$$f_i = N - q, \quad (9)$$

where N – is the number of tests in the planning matrix; q – is the number of equilibrium ratios.

The dispersion of restorability is defined by the formula:

$$S_r^2 = \frac{1}{N}\sum_{i=1}^{n} S_i^2, \quad (10)$$

where S_i^2 – is the dispersion in each line, where parallel tests were conducted.

It has been stated that the model under consideration is a linear one and characterizes the change in the car accelerations due to the longitudinal force exerted upon the adaptor. Here, the number of freeness at $N = 5$ N=5 will be $f_1 = 3$.

While defining the adequacy of the model it has been established that if the dispersion of restorability is $S_y^2 = 1.95$ and the dispersion of adequacy is $S_{ao}^2 = 2.0$, the actual value of the F-test is $F_P = 1.03$, which is lower than the table value of the test, namely, $F_t = 5.41$. Thus, at a significance level of p=0.05 the hypothesis about adequacy of the model designed is not denied. The approximation accuracy is 8,76 %.

During preliminary exploratory research the possible variants have additionally been studied regarding filling the lower and upper covering of walls of open boxcars with viscous materials, though at present such variants have not provided a sufficient level of economic justification.

CONCLUSIONS. The results of the research have demonstrated that implementation of the proposed concept regarding construction of the draft system for open boxcars allows to improve dynamic operational qualities of their structure, promoting their preservation during shunting impacts, and also reducing construction and operational cost.

The proposed concept of the draft system for the open boxcar makes it possible to reduce the maximum equivalent stresses exerted on its supporting structure during shunting impacts over 15 %. Besides, viscous material in the structural elements of an open boxcar leads to reduction of their corrosion in operation. Among disadvantages one should mention technological approaches in its implementing for the supporting structure of a car.

Further development and implementation of the proposed concept require investigations of peculiarities of operating regimes (besides the extreme one considered), as well as further bench and field tests.

According to the results of the study the application for a patent has been submitted which also considers other possible wagon structural variants with implementation of units filled with viscous material.

The proposed engineering solution of the draft system of an open boxcar can be applied in structures of other freight cars made in Ukraine and other countries, as well as for wagon pilot samples.

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ПЕРСПЕКТИВНЫЙ КОНЦЕПТ УПРЯЖНОЙ СИСТЕМЫ ЖЕЛЕЗНОДОРОЖНЫХ ПОЛУВАГОНОВ

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В результате проведенного комплекса теоретических исследований установлено эффективность внедрения предложенного концепта упряжной системы железнодорожных полувагонов. Его использование позволит существенно снизить себестоимость изготовления и эксплуатации грузовых вагонов. Разработанные в ходе исследований модели адекватны, что доказывает целесообразность их использования в соответствующих дальнейших научно-исследовательских и опытно-конструкторских работах. Впервые предложено и научно обоснован новый концепт упряжной системы железнодорожных полувагонов, где функции по поглощению продольных эксплуатационных нагрузок вместо отдельного поглощающего аппарата выполняет хребтовая балка путем выполнения ее с круглой трубы с заполненными консольными частями вязким материалом с демпфирующими свойствами. Для комплексного теоретического исследования возможностей реализации предложенного направления разработана математическая и конечно-элементной модели для определения ускорений в несущей конструкции кузова вагона с учетом наличия вязкого связи в ней, и проверено их адекватность.

Ключевые слова: железнодорожный транспорт, грузовой вагон, концепт упряжной системы, внедрение вязких материалов, динамическая нагруженность конструкции.

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