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Promising technical solutions for integrating Ukrainian and European railway transportation

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A complex of theoretical researches on solving the problems of integration of Ukrainian and European railway transport was carried out. Technical solutions have been developed to create conditions for the safe rolling stock operation on railways of Ukraine and the European Union (EU) countries, as well as for the introduction of effective freight transportation technologies. New wheel tread profiles for railway vehicles are proposed. The use of wheels with these profiles will ensure acceptable indicators of vehicles dynamic qualities and conditions of interaction between wheels and rails on Ukrainian and European railways. It will also reduce wheel and track wear. The methodology of forming disturbances acting on a railway vehicle from the track and causing its spatial vibrations has been proposed to calculate indicators of vehicle dynamic qualities. A new freight transportation technology using wagons with swap bodies has been considered for Ukraine. Recommendations on fastening elements of the swap body to the wagon undercarriage frame have been developed. The implementation of new technical solutions will increase the speed and safety of train motion, improve the interaction of the vehicle running gears with the track, and contribute to the creation of the modern Ukrainian railway complex and its integration into European transport networks.

Keywords: *railway transport, mathematical simulation, wheel-rail interaction, wagons with swap bodies.*

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Introduction. The current trends in the development of railway industry in Ukraine include accelerating integration of Ukrainian and European railway transportations [1], unifying railway interoperability standards, and upgrading the railway rolling stock and infrastructure.

It is necessary to create conditions for the joint operation of rolling stock on Ukrainian and European railways. Rail tracks in Ukraine and in EU countries have different parameters, in particular, the track gauge is 1520 mm and 1435 mm, respectively, the rail inclination is 1/20 and 1/40, the profiles of the track heads are different. Currently, the most effective way to cross borders between countries with different railway track gauges is to use sliding wheelsets, which are able to change the distance between the wheels on special track transfer devices, without stopping the train [2]. The use of sliding wheelsets significantly reduces the time of the train moving from one track to another. However, for the joint operation of rolling stock on Ukrainian and European railways, the compatibility of the “wheel-rail” pair is also required, taking into account the profiles of the P65 (Ukraine) and UIC60 (Europe) rail heads and their inclination. The operational compatibility of the railway transport networks of Ukraine and Europe can be improved with the help of wheels with a new tread profile, which will ensure acceptable indicators of vehicles dynamic qualities and conditions for interaction between wheels and rails on railways of both standards.

Recently, another task for Ukraine has been the implementation of new efficient freight transportation technologies [1], taking into account modern world trends, orientation towards European integration and European standards. Freight wagons with swap bodies for unimodal railway transportation are an innovation in the field of transport services [3, 4]. Switzerland, Austria, Germany are leaders in the development of wagons with swap bodies. Traditionally, universal and specialized railway wagons consist of a frame, running gears, auto coupling and auto braking devices, and a body. Conventionally, it is possible to name the running gears, auto coupling and auto braking devices like an undercarriage part of a wagon, and a body with a frame like a body part of a wagon. As a rule, the undercarriage part is universal. A body part determines the specialization of the wagon. At the same time, the cost of the undercarriage part of the wagon and its body parts is 80 % and 20 % of the cost of the entire wagon, respectively, and the life cycle is 40 and 20 years, respectively. The idea of developing a freight wagon with swap bodies is to separate the frame from the body and assign it to the undercarriage part of the wagon, while the body will be classified solely as the body part. The undercarriage part of such a wagon is a special platform that has a number of swap bodies connecting to it by appropriate removable fasteners. When changing cargo, an empty body of one type can be separated from the undercarriage part of the wagon and can be replaced with an empty body of another type. The newly obtained freight wagon will be operated as a specialized one. The technology of freight transportation by wagons with swap bodies allows: to reduce costs for the purchase and maintenance of rolling stock due to the efficient operation of the platform as the most valuable part of the wagon; to avoid downtime of wagons during seasonal changes of cargoes shipment; to ensure quick replacement of bodies in case of their damage.

The purpose of the article is the development of scientifically based technical solutions for creating conditions for the safe joint rolling stock operation on railways of Ukraine and EU countries, to introduce new effective freight transportation technologies.

New wheel tread profiles for railway vehicles. The task of improving the contact pair “wheel — rail” by determining wheel treads profiles for wagons to provide acceptable indicators of dynamic qualities of railway vehicles and conditions of their interaction with rails on Ukrainian and European railways, as well as to reduce the wear of rolling stock elements and tracks, has been considered.

The work [5] proposed the use of wheels with a new ITM-73EC tread profile for the joint operation of freight wagons. When developing this profile, the task was to ensure freight wagon motion stability on straight track sections at operating speeds and to improve indicators of interaction with the tracks of Ukrainian and European railways on curved sections.

The development of the wheel tread profile has been carried out for a new generation Ukrainian freight wagon with promising model 18-7020 design bogies [6]. This bogie is intended for fixing under freight wagons operated on 1520 mm gauge railways with 0.235 MN load from a wheelset on rails. This bogie design allows its exploitation on 1435 mm gauge railways if the appropriate wheelsets are used and the brake lever transmission is converted.

The spatial mathematical model of the interaction between the railway vehicle and the inertial elastic-dissipative track has been used in theoretical research. This model takes into account the contact patches sizes and the distribution of normal and tangential interaction forces across them [7].

The choice of the wheel tread profile was carried out in accordance with the improved methodology, taking into account the parameters of both railways. The family of wheel tread profiles was developed. The task of contact between wheels and rails has been solved for each variant. Interaction parameters, including the size and position of contact spots, have been analyzed. Calculations of fitting a wagon with such wheels on a small radius circular curve (R = 300 m) with unworn and worn outer rails and its motion along straight sections of the track at speeds from 60 km/h to 140 km/h were fulfilled. The chosen compromise version of the profile has been named ITM-73EC. The use of the chosen profile in freight wagon with Ukrainian bogies of other designs, which have elastically dissipative constant contact slides, has been verified numerically. These are comprehensively modernized bogies (CMB) of model 18-100 (with a normal axle load of 0.235 MN) [8] and prospective bogies of model 18 9817 (with an axle load of 0.25 MN) [9].

The main criterion for the safety of wagon motion is ensuring its stability when empty and loaded within the operating speed range (up to 120 km/h). Calculations of the dynamic indicators of freight wagons with different running gear when moving at speeds of 60 — 140 km/h on straight sections of tracks (Ukrainian and European standards) with small irregularities have been performed. The analysis of the results obtained showed that the wheel tread profiles have the greatest influence on the indicators of the empty wagons motion stability. Dependences of the root-mean-square deviations $\sigma(\ddot{y}_p)$ of body center plate lateral accelerations $\ddot{y}_p$ in the gravity acceleration fractions g on the motion speed of empty wagons with different bogies on tracks with two types of rails (UIC60 and P65) are shown on Fig. 1. The analysis of the curves on Fig. 1 shows that in the case of motion on the European track the indicator $\sigma(\ddot{y}_p)$ of the wagon with CMB bogies and wheels with ITM-73EC tread profile increases most intensively with increasing speed. An intense indicator $\sigma(\ddot{y}_p)$ rise corresponds to the unstable motion of the wagon (there is an intense hunting). In general, wagons with bogies 18-7020, 18-9817 and wheels with ITM-73EC tread profile have stable motion when empty speeds up to 130 km/h. These cars in the loaded state have the stable motion on the tracks of both standards in the speed range up to 140 km/h.

An estimation of the influence of the rail head wear on curved sections on the freight wagons interaction indicators with the tracks was carried out. Calculations showed that the nature of dependences character of intensity indicators of ridge wear of wheels for wagons with different

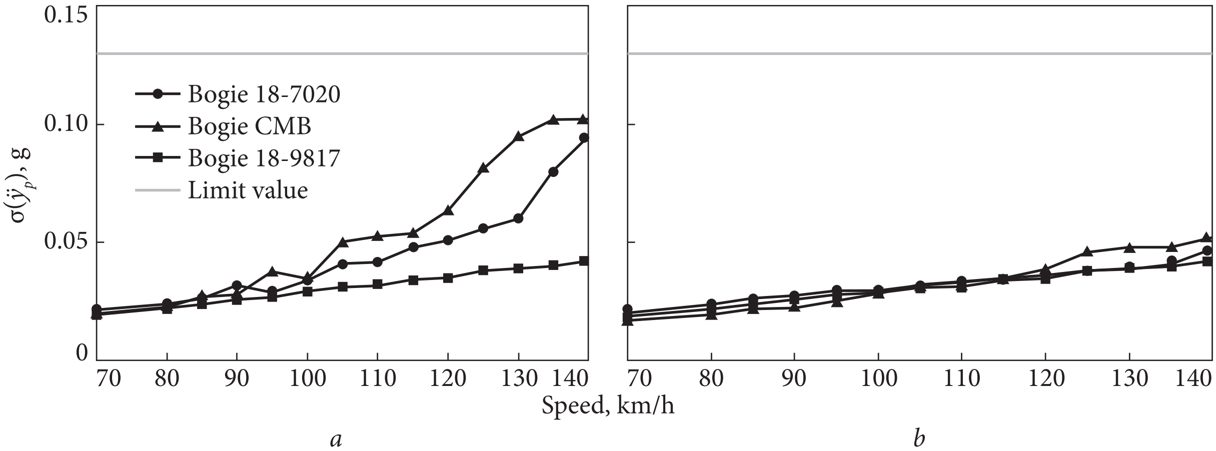

Fig. 1. Dependences of the root-mean-square deviations $\sigma(\ddot{y}_p)$ of the lateral accelerations of the body central plates $\ddot{y}_p$ in the gravity acceleration fractions *g* on the motion speed of empty wagons with different bogies on tracks with different rails: *a* — UIC60 rails; *b* — P65 rails

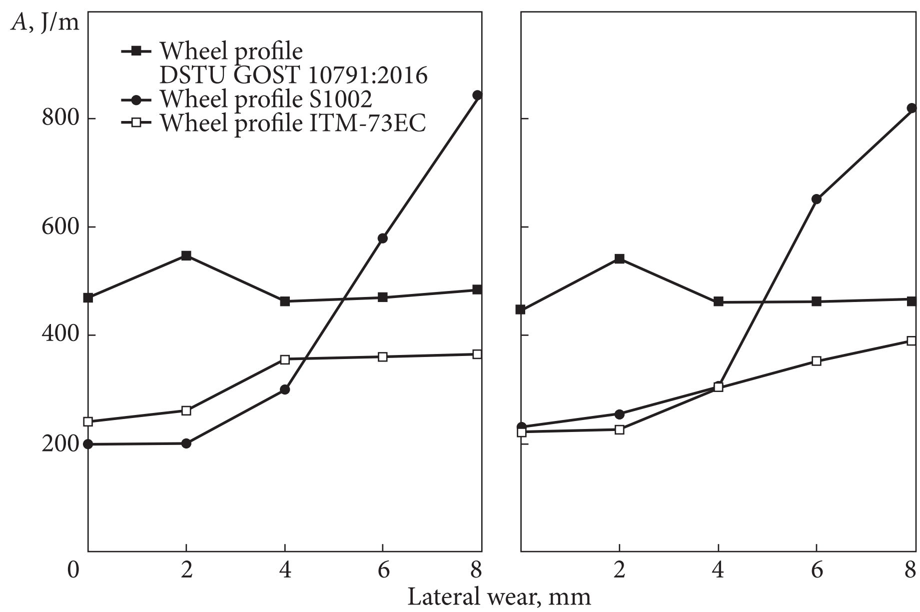

Fig. 2. Dependences of the maximum ridge wear values *A* of wagon wheels running on the outer rail on the degree of lateral wear of P65 rails and UIC60 rails: *a* — P65 rails; *b* — UIC60 rails

bogies is approximately the same. The case when a freight wagon with 18-9817 model bogies is moving in a circular curve with a radius of 300 m at a speed of 60 km/h was considered.

Dependences of the maximum ridge wear values (*A* is unit work of friction forces) of wagon wheels running on the outer rail on the degree of lateral wear of P65 rails and UIC60 rails are shown on Fig. 2. The term "ridge" refers to the wear of the ridge and fillet. The ridge wear indicators of wheels with the standard Ukrainian tread profile (DSTU GOST 10791:2016) and the European profile S1002 are shown on Fig. 2 too.

As one can see, the wear of the standard Ukrainian wheel is high for unworn rails. It changes slightly with the wear growth on the lateral side of both UIC60 and P65 rails. The wear indicator of the wheel with the S1002 tread profile is significantly lower than the wear indicator of the standard Ukrainian wheel in the case of unworn rails. This wear indicator increases intensively and exceeds the wear indicator of the standard Ukrainian wheel even with small lateral wear of rails. It is explained by the changeover of the contact patch on the wheel with the S1002 tread profile from the fillet to the ridge.

The analysis was carried out based on the assumption that the wheels used in the comparative simulations were made of materials with identical chemical composition and mechanical properties suitable for freight operation.

The results obtained show that the intense ridge wear of the wheels can occur when a wagon with Ukrainian bogies and standard wheel tread profiles (both Ukrainian and European) moves in curved sections of railway tracks of both standards. It reduces the resource indicators of wheelsets according to this criterion and requires frequent wheel tread grinding. Wheels with the ITM-73EC profile have the best A indicators on both unworn and worn rails of both types. At the same time, in the case of using prospective bogies of model 18-7020 and 18-9817, these performance indicators are close.

Thus, in the case of using wheels with the ITM-73EC tread profile and bogies of promising 18-7020 model and 18-9817 model at joint operation of freight wagons on Ukrainian and European railways, the wagon motion stability will be ensured, as well as improved interaction with the tracks, including worn rails on these railways.

The methodology of forming disturbances acting on railway vehicles from the track. The main quality criteria of railway vehicles include standardized indicators of dynamics. In calculations to determine these indicators, track-induced disturbances acting on the vehicle are essential input data. Without correct data entry, it is impossible to obtain reliable estimates of the vehicles dynamic qualities indicators. Such forces cause spatial vibrations in the railway vehicle. These disturbances are a combination of vertical and horizontal components. Since the main factors in the occurrence of vibrations in the dynamic system “railway vehicle — track” are track irregularities, it is quite natural to form disturbances for calculations based on information about such unevenness. In the research described in this article, the disturbance components have been based on the scheduled measurements data of the track state on the Prydniprovska railway by a track-measuring wagon (TMW).

Despite the fact that track irregularities are random processes, one possible approach to generating disturbances for calculations in the time domain is to directly use the processes of actual rail irregularities on separate rail sections of the track. In this case, it is advisable to form the components of disturbances based on TMW records in such a section, the technical condition of which does not require motion speed limitation, but the values of irregularities on it are close to their upper limit for this state. The section that best matched the specified conditions has been selected from the available array of TMW records. Components of disturbances have been formed to calculate dynamic qualities indicators of freight wagons on the railways of Ukraine based on the irregularities in this section. The following four processes have been used as disturbance components:

- symmetric vertical irregularities of the rail track (it characterizes the irregularities of the track profile and it is calculated as half the sum of the vertical irregularities of the right and left rails);
- skew-symmetrical vertical irregularities of the track (characterizes the excess of one rail over another and is calculated as the half difference of the vertical irregularities of the rails);
- horizontal irregularities of two rails.

It is also necessary to take into account that the value of vertical irregularities of each rail, measured by the track-measuring wagon, is determined not only by the geometrical irregularities of the track, but also by the action of the load from the moving wagon. In other words, subsidence is the result of the dynamic interaction of the track and TMW. Many parameters affect the level of the dynamic component of irregularities: the masses involved, the elastic characteristics and damping in the suspension and track, the wagon speed, etc. TMW has been manufactured on the basis of a passenger coach. Since the parameters of freight wagons differ from the parameters of the TMW, the vertical components of disturbances must be adjusted to calculate the dynamics of these railway vehicles. Accurate assessment of dynamic interaction is a complex and currently unresolved task, but the effect of the dynamic factor can be roughly taken into account with the help of a correction factor [10]. The weight of the railway vehicle has a decisive influence on its value. For Ukrainian freight wagons, the correction factor for symmetrical vertical irregularities can be approximated by the expression

$$k_{sym} = 0.039m + 0.231 \tag{1}$$

where m is the mass of the wagon in tons.

It varies from 1 (an empty 18.4 t wagon) to 3.9 (a loaded 94 t wagon). In the case of skew-symmetrical vertical unevenness, the value of the correction coefficient k_{sksym} changes much less — from 1 to 1.2, respectively, since this disturbance component characterizes the relative position of the rails and depends primarily on the geometry of the track. Components of disturbances in the horizontal plane are practically independent of the characteristics of the railway vehicle, but they have been determined by the geometry of the track itself, so they do not need to be adjusted. The validity of the proposed methodology has been verified by comparing the results of calculating the dynamic qualities of passenger coach and freight wagons of several types with the results of experiments. For example, the dependences of the body center plate vertical accelerations $\ddot{z}$ maximum values (in fractions of gravity g) on the loaded semi-wagon motion speed is shown on Fig. 3.

It is seen that the calculated values (Line 1) obtained without applying the correction coefficient are too low, while with the coefficients $k_{sym} = 3.6$ and $k_{sksym} = 1.2$ they (Line 2) are in the middle of the experimental data area (the experimental data area on Fig. 3 is limited with Line 3 and Line 4).

Components of disturbances obtained by the methodology described above were used to calculate the dynamics of wagons whose speed is limited to a relatively low design speed (120—140 km/h). When evaluating the dynamic qualities of high-speed trains, in particular when moving on European railways, it is advisable to select track sections for disturbances formation based on the requirements of the DSTU EN 13848-5:2018 [11] (the European standard adopted in Ukraine as a national confirmation method).

In European countries, the documents of the EN 13848 series are the main normative quality documents in the field of railway transport, which regulate the geometric parameters of the track, establish requirements for its condition, and define the safety-related parameter limits for train speeds up to 300 km/h. The requirements for the geometric parameters of the rail track during high-speed motion are more stringent compared to those imposed during motion at normal speeds. However, it can be assumed that among the operating track sections of Ukrainian railways, there are such ones that meet the requirements of the normative part of the standard [11]. Verification of the geometric parameters of track irregularities (both directly measured and their

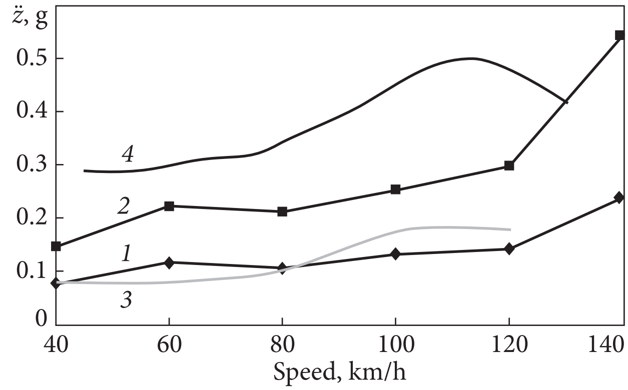

Fig. 3. Dependencies of the body center plate vertical acceleration $\ddot{z}$ maximum values on the loaded semi-wagon motion speed

calculated combinations) regulated [11], confirmed this assumption. Some sections of excellent condition are met with requirements [11]. Components of disturbances have been formed for calculating vibrations of railway vehicles moving at a speed of up to 230—300 km/h, using the records of irregularities obtained for such sections.

A freight wagon with swap bodies. Based on the analysis of world experience [12], proposals regarding the promising design of a Ukrainian freight wagon with swap bodies were developed, in particular:

▪ to use a universal or specialized fitting platform as this type of a wagon undercarriage, which consists of a frame, running gear, auto coupling, auto brake equipment and devices for attaching swap bodies;

▪ to use the experience of the Swiss company "WASCOSA" [3], which developed a flexible freight system (flex freight system) for 1435 mm gauge railways, at designing the structure of the wagon with swap bodies.

Swap bodies usually differ from standard ISO containers in terms of their increased dimensions and load capacity. Special attention in this article is paid to the development of recommendations for swap body to wagon undercarriage frame fastening elements which will ensure the safety of transportation of various cargoes in the respective wagons. The analysis of the existing designs of such fastening elements [12] showed that the platform and the body are equipped with detachable fasteners that should ensure a fixed position of the body on the platform under operational loads during rail transportation. For example, in the patent CH 700850 A1, it is proposed to fasten the swap body to the platform with standard mounting pins designed for fixing ISO containers. The mounts on the body consist of two clamping jaws providing rigid connection to the mounting pins on the platform.

Due to current lack of projects to create wagons with swap bodies in Ukraine, a railway wagon which undercarriage part is model 13-7133 wagon-platform with 16 fitting pins for container transportation [13] was taken as a basis. The mass of the wagon-platform is 16.1 t. The mass of the bogie is m_{ib} = 4.68 t. The dimensions of the swap body correspond to the 45-foot container dimensions. The load capacity of such a container is 30.48 t. However, the load capacity of swap body is equal to the wagon-platform load capacity. It is 73.6 t. The total load capacity of the wagon with the swap body is m_b = 89.7 t.

Recently, the strength of freight rolling stock structures in Ukraine has been regulated by the normative document DSTU EN 12663-2:2018 [14].

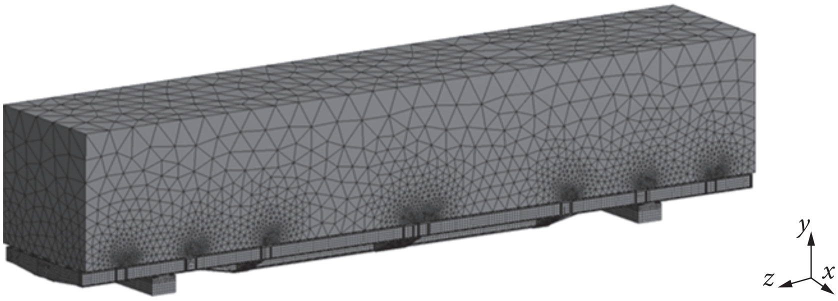

Fig. 4. The calculation scheme for a wagon with the swap body

Finite-element models have been developed to study the elements strength of the wagon with the swap body under standard loads [14], taking into account various schemes of connections of the body with the wagon undercarriage part frame, presence and absence of clearances in these connections. The calculation scheme for a wagon with the swap body is shown on Fig. 4.

The undercarriage part frame has been modeled using special plate elements with three nodes, each of which has three linear and three angular displacements. Auto couplings absorbers, fitting pins, bogies, and a swap body have been simulated by solid elements with three linear displacements in each node. A surface-to-surface contact was selected, and the extended Lagrange method was used to model the contact interaction between the elements of the structure under consideration.

Volumetric loads in the form of accelerations (a_x, a_y, a_z), and longitudinal inertial forces of the bogies (F_{ib}, (i = 1,2)) act on the considered mechanical system. The mass of the bogie is m_{ib}. The total load capacity of the wagon with a swap body is m_b. The gravity acceleration value is g. Normative loads according to [14] for mode 1 (the mode of static loads superposition for the evaluation of strength in operation): the compressive longitudinal force value F = 2 MN, $a_x = 0$, $a_y = 1.3g$, $a_z = \frac{F}{m_b}$, $F_{ib} = m_{ib} \cdot a_z$. Normative loads for mode 2 (fatigue load mode): $a_x = \pm 0.2g$, $a_y = (1 \pm 0.3)g$, $a_z = 0$, $F_{ib} = 0$. Permissible stresses for strength evaluation of the 09G2S steel design is [σ] = 325 MPa for mode 1 and [σ] = 323 MPa for mode 2.

The results of the conducted research showed that four fitting connections with clearances ensure the frame design strength of the wagon-platform with a 45-foot container in accordance with regulatory requirements. The undercarriage part frame strength of a wagon with a swap body does not meet DSTU EN 12663-2:2018 requirements. To ensure the undercarriage part frame strength, it is proposed to increase the number of connections transferring operational loads from the body to the frame, in particular by using clearance-free fasteners. It was assumed that the corner fitting pins are fixed, and the intermediate ones are hinged.

Different schemes of connections between the body and the undercarriage part frame were considered (Fig. 5).

In the schemes under consideration, all fitting connections have additional clamping elements, making them clearance-free in the transverse direction x from outsides of the frame of the undercarriage part. In addition, all fitting connections, with the exception of connections of group 4, have additional elements making them clearance-free in the longitudinal direction z. Fitting connections of group 4 are clearance-free in the longitudinal direction only on the outer sides of this group, while on their inner sides there are clearances between fittings and pins.

The results of calculations for various schemes and loading modes showed that the Scheme 2

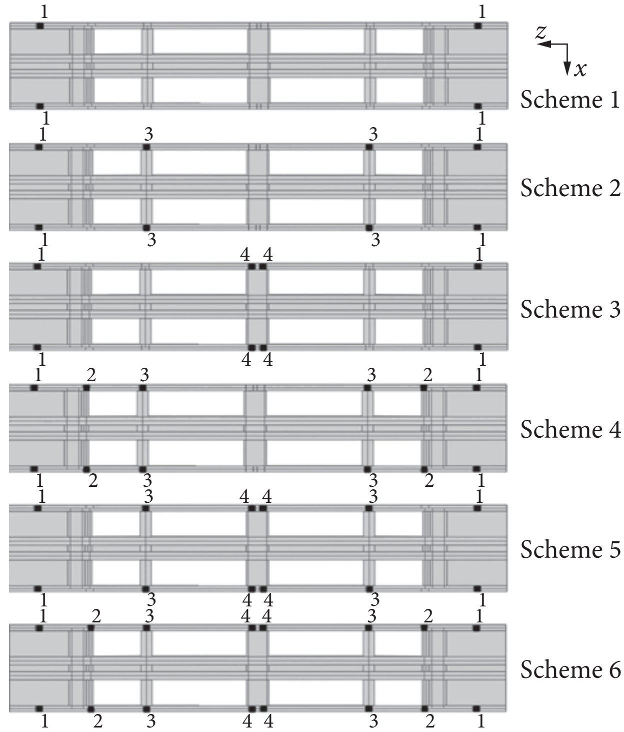

Fig. 5. Schemes of connections between the body and the undercarriage part frame: 1 — a group of fitting pins for placing one 45-foot container; 2 — a group of fitting pins for placing one 30-foot container; 3 — a group of fitting pins for placing one 20-foot container; 1 and 4 — groups of fitting pins for placing two 20-foot containers

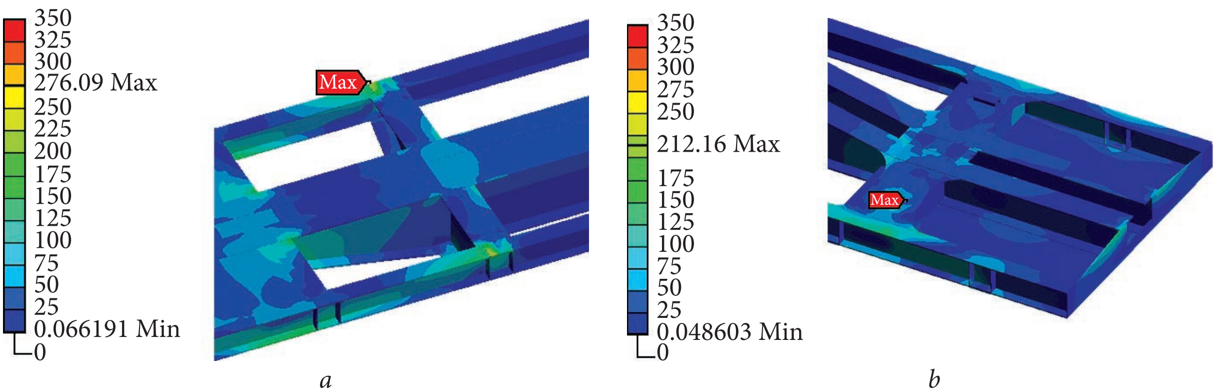

Fig. 6. Maximum stresses in the zone of the front fitting pins (Scheme 2): *a* — load mode 1; *b* — load mode 2. The stress value is given in MPa

is the rational scheme. Maximum stresses in the frame elements (Scheme 2) are located in the area of the front fitting pins. Maximum stresses values do not exceed the permissible values (Fig. 6).

Recommendations have been developed for fastening elements that ensure the cargo transportation safety in wagons with swap bodies in accordance with requirements [14]. When designing wagons with swap bodies, it is recommended to pay special attention to the development of special detachable clearance-free connections of the body with the undercarriage part frame, ensuring the safe operation of such wagons. The designs of such connections depend on the type of the undercarriage part, its load capacity, mass and dimensions of the swap body. If the undercarriage part is a fitting platform and the swap body mass does not exceed the mass of a 45-foot container, four ordinary fitting connections are sufficient. If the mass of the swap body exceeds the mass of the 45-foot container, it is necessary to install more fitting pins on the frame of the wagon's undercarriage part (preferably hinged) and install on the swap body fittings with adjustable clamping elements, which will allow to ensure clearance-free fitting connections. In accordance with normative requirements, it is advisable to fasten 73.6 t swap body to model 13-7133 wagon-platform frame using 8 fitting connections located according to scheme 2 (see Fig. 5), with additional clamping elements to ensure that these connections without clearances in the longitudinal direction and in the transverse direction of outer frame side. If the wagon undercarriage part is not a fitting wagon-platform, then the clearance-free connection between its frame and the swap body can be carried out by special elements provided in their designs with the appropriate forms of contact surfaces and additionally installed clamping elements.

Conclusions. With the use of the developed mathematical models and methodologies, a complex of theoretical studies was carried out, the results of which will contribute to ensuring the operational compatibility and efficiency of Ukrainian and European railway transport. The theoretical studies used a spatial mathematical model of the interaction between a railway vehicle and an inertial elastic-dissipative track. The choice of wheel tread profile was carried out in accordance with an improved methodology taking into account the parameters of both railways. The methodology of forming disturbances acting on a railway vehicle from the track has been proposed to calculate indicators of vehicle dynamic qualities. Finite-element models have been developed to study the elements strength of the wagon with the swap body under standard loads (DSTU EN 12663-2:2018), taking into account different schemes of connections of the body with the undercarriage part frame, as well as the presence or absence of clearances in these connections. Based on the results of these researches, scientifically based technical solutions have been developed to create conditions for the safe joint rolling stock operation on railways of Ukraine and the countries of the European Union, and to introduce new effective freight transportation technologies.

1. New wheel tread profile using for freight wagons has been proposed. The use of such wheels will provide acceptable indicators of vehicle dynamic qualities and conditions of their interaction with rails on Ukrainian and European railways, as well as reducing the rolling stock elements and track wear.

2. The methodology of forming disturbances acting on wagon from the track and causing its spatial vibrations has been proposed for calculating the indicators of vehicle dynamic qualities.

3. A new for Ukraine technology of freight transportation using wagons with swap bodies has been considered. The strength of the elements of such wagon under standard loads (DSTU EN 12663-2:2018) has been investigated, and recommendations for fastening elements of the swap body to the wagon undercarriage frame have been developed.

The implementation of these solutions will have a significant economic effect. It will allow for increased speed and safety of train motion, improve the interaction of the wagon running gears with the railway track, and contribute to the creation of the modern Ukrainian railway complex and its integration into European transport networks.

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ПЕРСПЕКТИВНІ ТЕХНІЧНІ РІШЕННЯ ДЛЯ ІНТЕГРАЦІЇ УКРАЇНСЬКИХ ТА ЄВРОПЕЙСЬКИХ ЗАЛІЗНИЧНИХ ПЕРЕВЕЗЕНЬ

Проведено комплекс теоретичних досліджень щодо вирішення проблем інтеграції українського та європейського залізничного транспорту. Розроблено технічні рішення щодо створення умов для безпечної експлуатації рухомого складу на залізницях України та країн Європейського Союзу (ЄС), впровадження ефективних технологій перевезення вантажів. Запропоновано нові профілі протектора коліс залізничного транспорту. Застосування коліс із цим профілем забезпечить прийнятні показники динамічних якостей транспортних засобів та умов їх взаємодії з рейками на залізницях України та Європи. Це також зменшить знос коліс і гусениць. Для розрахунку показників динамічних якостей транспортного засобу запропоновано методику формування збурень, що діють на залізничний транспортний засіб з боку колії та спричиняють його просторові коливання. Розглянуто нову для України технологію перевезення вантажів вагонами зі змінними кузовами. Розроблено рекомендації щодо кріплення елементів змінного кузова до рами ходової частини вагона. Впровадження нових технічних рішень дасть змогу підвищити швидкість і безпеку руху поїздів, покращити взаємодію ходових частин вагона з колією, сприятиме створенню сучасного залізничного комплексу України та його інтеграції в європейські транспортні мережі.

Ключові слова: *залізничний транспорт, математичне моделювання, взаємодія колеса з рейкою, вагони зі змінними кузовами.*