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ESTIMATION OF DYNAMIC PERFORMANCES OF THE SAFE OPERATION OF HIGH-SPEED ELECTRIC TRAIN

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Abstract: *The process of implementation of new developments, in particular, new generation rolling stock holds a prominent place among the range of measures for organization of high-speed passenger rail transportation in Ukraine. The example of permission for use and the initial phase of work with interregional NRCS2 dual-mode electric trains produced by Hyundai-Rotem Corporation is the illustrative one in this context. Due to the detection of macro-cracks in bolster beams of the car body frames of these electric trains, namely in the areas of mounting of anti-yaw dampers, these trains were taken out of service until the completion of the modernization of problematic nodes. The comprehensive study on the determination of the safety parameters of electric trains was conducted to determine the causes of destruction of bolster beams. At the same time, bolster beams loading was estimated depending on the characteristics of anti-yaw dampers by means of computer simulation of the dynamics of motion of trailing and motor cars. The feasibility of selection of parameters for anti-yaw dampers mounted on electric train cars was assessed. The results of work will improve the safe operation of high-speed trains and increase the efficiency of estimates regarding the loading of bearing structures of underframes of the of rolling stock.*

Key words: *high-speed electric train, safe operation, computer simulation, dynamic performances, anti-yaw dampers.*

1. Introduction

The experience in operating HRCS2 electric trains in the conditions of Ukrainian railways showed their low reliability. The number of failures of these trains, especially at the beginning of operation, greatly exceeds the number of ordinary failures that occurred in traction rolling stocks of other manufacturers at the stage of finalization in the conditions of Ukrainian railways. Shortly after commissioning macro-cracks in bolster beams of the car body frames in the areas of mounting of anti-yaw dampers were found (Domin et al., 2014).

The areas of bolster beams directly in the zone of cracks occurrence were studied in details by means of non-destructive metallography method using replicas (imprints of structures) in order to detect micro-cracks (Domin et al., 2016). At microscopic examination of replicas taken from the elements of body frames of one of the cars under laboratory conditions few micro-cracks approximately 50 mm from macro-cracks were found. In further operation they may cause the development of macro-cracks. The preliminary analysis of causes of fatigue cracks occurrence in bolster beams of the car body frames of high-speed trains that was conducted based on the method of expert estimations (Domin, et al., 2015) provided the basis for in-depth studies of dynamic performances of the safe operation and assessment of characteristics of dynamic loading of bolster beams of the car body frames of high-speed trains using the computer simulation.

2. Analysis of the prerequisites for the promotion of destruction of bearing elements of body frames

2.1. General description

The situation related to technical failures of NRCS2 electric trains is largely caused by structural features of underframes and shortcomings in the process of admission of trains to the operation.

2.2. Structural features of underframes

Generally, the design of underframes of NRCS2 electric trains is based on typical schemes adopted for rolling stock with a maximum speed of 160 km / h. However, according to the results of analysis of features of running gears construction, significant differences in design and characteristics of central spring suspension and other devices for cars coupling with bolster structure were found in comparison with standard technical solutions used in modern high-speed trains. For example, at the central level of the spring suspension of NRCS2 electric train there is no vertical shock absorber, although, as a rule, such absorbers are installed in the second level of the spring suspension of high-speed rolling stocks. The lack of vertical hydraulic shock absorbers in the central level of the suspension can be explained by damping properties of the air suspension; however such data were not identified during the testing for electric trains' admission to operation. Furthermore, there are no devices that must additionally limit inclinations of bodies during the curve negotiation with unbalanced accelerations (torsion systems).

The technical solution for mounting brackets for anti-yaw dampers is atypical. Such brackets are usually mounted on longitudinal beams of body frames, whereas in NRCS2 electric train cars such brackets are mounted on bolster beams (Fig. 1).

Specified significant differences in design and characteristics of central spring suspension and other devices for cars coupling with bolster structure that were found in comparison with the standard technical solutions used in modern high-speed trains did not get adequate justification at the stage of design works. In particular, the rationality of adopted technical solution in terms of the structure of attachment points for anti-yaw dampers remained unsubstantiated due to the lack of appropriate strength calculations.

2.3. Procedural shortcomings of admission to operation

In analyzing the conditions that contributed to the appearance of some technical failures of electric trains, it should be noted that Ukrainian railways did not have sufficient experience in the organization of high-speed traffic until recently. In addition, the relevant regulatory system, under which the works on the design and modernization of the rolling stock for 1520 mm track are carried out, is such that guides the vehicle manufacturers to outdated approaches to production quality management system and admission of locomotives and cars to operation (Diomin Yu. and Diomin R., 2013). It is obvious that these circumstances have affected the quality of previous and acceptance tests and technical evaluation of calculation works. For example, running strength tests and impact tests remained outside the program of experimental part of the works on the admission to operation. There were no tests under conditions when air suspension is in the emergency mode, as well as tests on dropping of the cars from wedges.

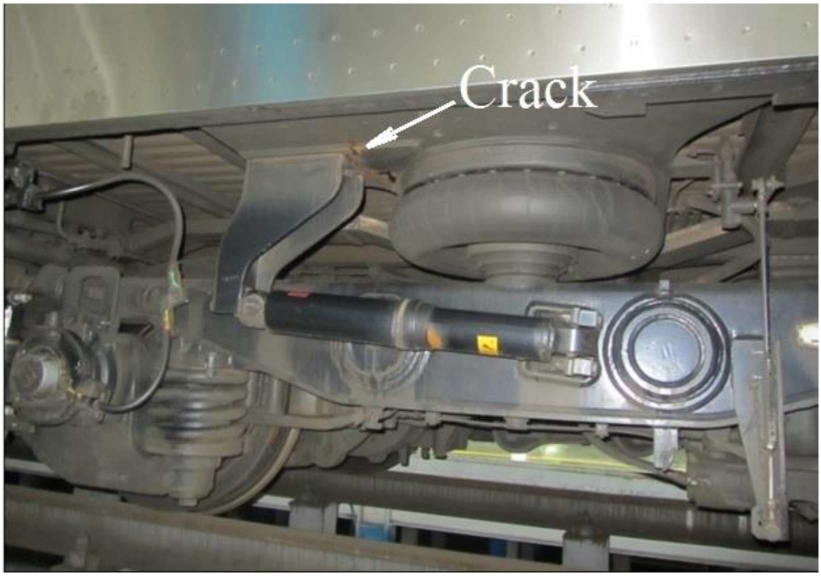

Fig. 1. Bogie of the NRCS2 electric train car

The technical examination of fatigue strength of the body frame was made with fundamental shortcomings, which, in turns, did not contribute to the reliability of predictive evaluation of fatigue strength performances for supporting structures. Thus, according to the requirements specifications for the electric train design, dynamic characteristics of the bogie in different operating modes must meet UIC 518 OR (UIC, 2009) requirements, and, in accordance with UIC 615-4 (UIC, 2003), the bogie frame strength has to be confirmed by calculation and fatigue test.

Relevant verifications have not been conducted.

In the operation bolster beams of body frames are subjected to stresses according to the complex scheme: in vertical direction - due to air suspensions; in horizontal transverse direction - due to swaying shock absorbers and air suspensions; in longitudinal direction - due to air suspensions and anti-yaw dampers. These components of forces must be taken into account in the design, but it was not implemented in full.

The load on the body frame arising from the operation of anti-yaw dampers was not taken into account in the strength calculations of designers. It is these stresses that together with the defective design concept of the attachment point for anti-yaw dampers at the bolster beams have led to fatigue destruction of the latter.

As a result, after 1.5 years of operation all NRCS2 electric trains were sent back for further improvement, namely, development and implementation of recommendations to eliminate and prevent occurrence of cracks in bearing elements of bolster beams. Destruction of bolster beams of body frames has necessitated urgent works on modernization of attachment points for anti-yaw dampers.

3. Simulation of motion dynamics of cars of electric trains

3.1. General provisions

Computer simulation of the dynamics of the rolling stock has become an integral part of projects related to sustainable development of new technologies for railway transport. The use of computer simulation helps designers and engineers in addressing a wide range of technical problems. The virtual experiment appears to replace expensive field tests, and it allows us to investigate almost unlimited number of design variants, choose the best of them and spend much less time and money.

The simulation model should be developed using the program of dynamic analysis of the railway vehicle, subject to obtaining consistent results. Where possible, parameters of components of the simulation model should be determined based on the results of the tests. Where it is not possible, the calculations for obtaining used values shall be provided.

It is important to carry out simulations in the same conditions as field tests. For this purpose, it is necessary to withstand tests conditions, including, for example, orientation of the vehicle, its modification and loadings. The conditions of interaction between wheels and rails are verified, data on the structure and condition of the track are checked in order to evaluate the dynamic properties of the railway rolling stock.

For dynamic running tests sensors should be located so as to measure the dynamic characteristics of the vehicle that are necessary for the validation process. Normally, the main source of data for validation of simulation models is vertical and lateral acceleration of underframe.

The comparison must be based on time dependences and power density spectra (PDS). PDS should have a carrying capacity of about 0.05 Hz (± 0005 Hz). The task of dynamic analysis is to create matrices of maximum values of quantities at certain speeds of trains.

3.2. Problems of railway rolling stock mechanics related to safe operation

The significant progress in the development of methods and tools for simulation modeling became possible due to fundamental researches in the field of dynamics and strength of rolling stock. This is confirmed by a set of scientific work in this field, and this, for example, is reflected in the works (Garg and Dukkipati, 1984; Lozia and Kardas-Cinal, 2016). Various mathematical models that describe spatial oscillations of railway rolling stocks are used to determine the dynamic performances of safety of operation by means of calculations. With the development of methods of the mathematical modeling with respect to railway rolling stock dynamics simulation models changed from relatively simple linear systems to essentially nonlinear with dozens of variables (Iwnicki, 2006).

The stability problem of undisturbed motion holds a special place in studies of conditions of the safe operation of railway rolling stocks.
The loss of stability of motion leads to self-induced oscillations, i.e. auto-oscillations (Diomin, et al., 1994). These self-oscillations associated with intensive twisty motion of the railway rolling stock. Speeds at which there is a loss of motion stability and intense hunting oscillations are developed have come to be known as critical speeds – v_c. F. W. Carter was the first who used the concept of critical speed as the speed of translational motion of the rolling stock, the excess of which causes continuous hunting oscillations (Carter, 1928). In contrast to the resonant critical speeds that produce small ranges of sharp changes in performances of the vertical dynamics, critical speeds with a relation to hunting divide the whole range of operating speed of the railway rolling stocks into zones of stable motion and auto-oscillations zones.
If critical speeds are in the operating range of speeds of the railway rolling stock, it is, at best, can lead to accelerated wear of elements of running gears and track that interact. With a substantial degree of instability there is a real threat to the safe operation. Furthermore, additional energy of the traction unit is spent on maintenance of constant speed of the train with cars the motion of which is accompanied by self-oscillations.
The experience of the creation and implementation of new types of the rolling stock intended for advanced operative conditions confirms the importance of solving the problem of elimination of auto-oscillations from normal operation modes of railway rolling stocks. Only self-oscillations elimination defines necessary conditions to ensure the safe operation and soft riding of new-generation railway rolling stock. It is therefore necessary to establish the main principle of obtaining high dynamic properties of the railway rolling stock: critical speed should be higher than the design one. High-speed rolling stock is equipped with anti-yaw dampers exactly for prevention of the development of auto-oscillations.

3.3. Computer model

The corresponding computer model was built for determination of performances of the safe operation of electric train cars and dynamic loading of bolster beams of body frames by means of numerical simulation modeling.
The tested object – car of the HR CS2 electric train – structurally is an integrated system which consists of separate subsystems of solids interconnected by joints and load-bearing elements. For illustrative purposes, individual elements of the computer model, namely, axle box, bogie frame, body and elements of current collecting device, were designed in Solid Works software as three-dimensional graphical objects, which are imported into a computer model of the car (Alyamovskii, 2007).
The model of the motion dynamics of the car contains solid object – car body – that is combined with elements of the current collecting device in case of trailing car, and includes two subsystems of bogies, each of them contains two subsystems of wheel sets (WS) that are formed from the standard subsystem of the wheel set, provided by PC UM, and two solids - left and right axle boxes.
The general structure of the model of motion dynamics of the car is shown in Fig. 2.

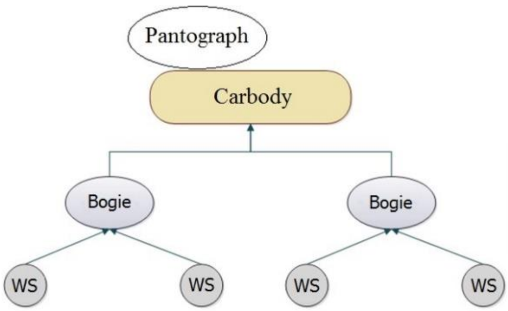

Fig. 2. The structure of the model of motion dynamics of the car

The model of car dynamics combines the body and elements of the current collecting device, involves two subsystems of bogies, each of which contains a frame and wheel sets. Geometric and inertial parameters of the model were defined according to the technical documentation of the car equipped with the current collecting device.
Power elements represented by S. Nishimura model were used to simulate the operation of air suspensions, which are included in the system of the second level of the suspension. The stiffness and damping factors of load-bearing elements are set according to the relevant parameters of air suspension. Non-linear load-bearing elements were

used in the model to show the operation of transversal shock absorbers and anti-yaw dampers.
The general computer model of the trailing car dynamics developed in UM software complex includes 10 subsystems, 19 solids, 19 joints and 50 degrees of freedom, it also includes 20 bipolar, 20 linear elastic-viscous and 2 contact load-bearing elements and 91 indicators.
The graphical format of the computer model of the car dynamics is shown in Fig. 3.

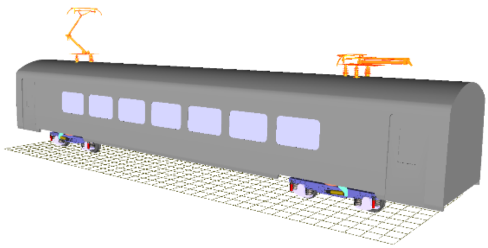

Fig. 3. General view of the model of the car dynamics

The dynamic model of the motor car is made based on the similar procedure. The verification of developed computer models was made by means of comparison of results of calculations with the results of approval running tests of cars. The adequacy of computer models of motion dynamics of cars was confirmed by satisfactory compliance of calculations results with the experimental data.

3.4. Formation of random disturbances due to track irregularities

The state of the track, which is determined by the existing irregularities, could significantly affect dynamic performances of the rolling stock. The algorithm of formation of the realization of a random process in accordance with the provided spectral density functions was used for the simulation of track irregularities (Cherniak, 2003)).
Disturbances represented in the temporary realm as multiplicative equivalent irregularities or random process are used at the dynamic calculations for cars for 1520 mm track (Bolotin, 1978). The spectral density function is used as one of the most important characteristics of random process. It characterizes the distribution of the process dispersion over different frequencies. It is proposed to use the spectral density function of the equivalent calculated irregularity in the form analytic expression:

$$\bar{G}\eta(f) = \frac{b_i V^{\gamma_i - 1}}{f^{\gamma_i}} + \\ + \frac{1}{2\sqrt{\pi}} \sum_{j=1}^{m} \frac{a_j}{\alpha_j V} \exp\left[-\frac{(f - \beta_j V)^2}{4\alpha_j^2 V^2} \right] \quad (1)$$

where:
$\bar{G}\eta(f)$ is the spectral density function of the equivalent irregularity for the mean state track , mm/Hz;
V is the running speed in m/s;
f is the oscillations frequency in Hz (frequency change range - 0 ... 100 Hz).

In the expression (1) numerical values for the coefficients of disturbances acting in horizontal and vertical directions are different. In practical application there is the task of forming disturbances in the temporary realm according to available spectral density function of the irregularity.
There are different types of algorithms by which discrete realizations of a random process with specified probabilistic characteristics may be implemented (Bendat and Piersol, 1971). In this case we use an algorithm based on the representation of the modeled process as an expansion:

$$U(t) = \sum_{k=1}^{N} A_k \cos(\omega_k t + \varphi_k) \quad (2)$$

The values included in the expression (2) are defined as follows:

$$A_k = \sqrt{2S_k \cdot \Delta f} \quad (3)$$

$$\omega_k = 2\pi \cdot k \cdot \Delta f \quad (4)$$

where:
Δf is the frequency sampling interval;
$S_k = \bar{G}\eta(f_k)$ is the value of spectral density at a frequency of $f_k = k \cdot \Delta f$;
φ_k is the random variable with probability density of $p(\varphi_k) = (2\pi)^{-1}$.

It is known that the spectral density of harmonic oscillation with the amplitude A and frequency f_0 equals to infinity at a frequency of this oscillation:

$$G(f) = \frac{A^2}{2}\delta(f - f_0), \quad (5)$$

where:
A and f_0 are amplitude and frequency of harmonic oscillation;
$\delta(f - f_0)$ is the Dirac delta function.

At the same time, energy spectrum integral (spectral density) taken within any limits that include frequency of harmonic oscillation has a finite value equal to the mean-square value, i.e. equal to $A^2/2$. The integral of the spectral density of the process formed by the $k = \overline{1, N}$ total of harmonic oscillations taken within the whole range of frequencies is equal to $\sum_{k=1}^{N} \frac{A_k^2}{2}$. On the other hand, the integral of the spectral density taken within the whole range of frequencies can be approximately calculated as $\sum_{k=1}^{N} S_k \cdot \Delta f$. Equating these amounts we get the formula (3).

Hence, the simulation of the random process with a given spectral density reduces to the calculation $A_k, \omega_k, \varphi_k (k = \overline{1, N})$ and subsequent summation according to the formula (2). It should be noted that the above algorithm satisfies the compliance of frequency response values, alongside with that the spectral density function does not contain information about phases.

Implementations obtained using expressions (2) are periodic with a period of $T_p = 1/\Delta f$, therefore, they do not have the property of ergodicity.

The developed method was used in the simulation of the motion of studied cars on the track with random irregularities.

3.5. Calculated data

Values those are necessary for evaluation of both bolster beams loadings, and compliance of dynamic characteristics of the tested rolling stocks with conditions of the safe operation are used as the input data. The set of initial values of the car model has two main blocks. The first block is horizontal and vertical accelerations of the car body, bogie frames and wheel sets, and indexes of stability against derailment. The second block composed of displacements of points of the body in guide (pivot) cross section and displacements of points of the current collecting device.

To calculate the initial values the car model has certain point - "sensors", the total number of which is 44. These sensors are placed on the elements of the mechanical system in the following way: 5 points on the current collecting device in two positions which correspond to extreme heights of the catenary; 12 points on the car body; 5 points on each bogie frame; 3 points on each wheel set. “Sensors” arrangement layout is shown in Fig. 4 and Fig. 5.

To evaluate the dynamic characteristics of cars, namely, running characteristics and performances of the safe operation, the system of indicators is used. It includes: horizontal, lateral and vertical acceleration of the car body (C1, C0, C2 points in Fig. 4); horizontal lateral accelerations of the bogie frame (Ri1 and Ri2 points, where i is the number of the wheel set, Fig. 5); horizontal, lateral and vertical accelerations of axle boxes.

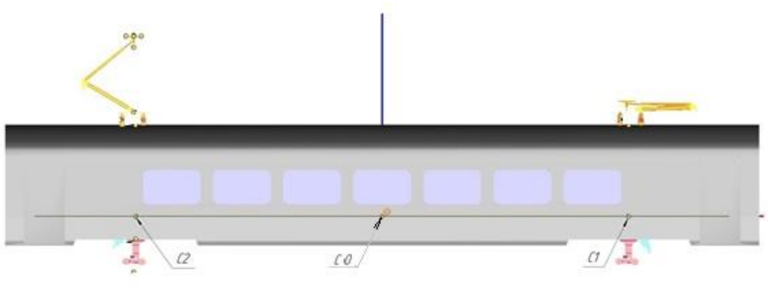

Fig. 4. Placing of “sensors” on the car body

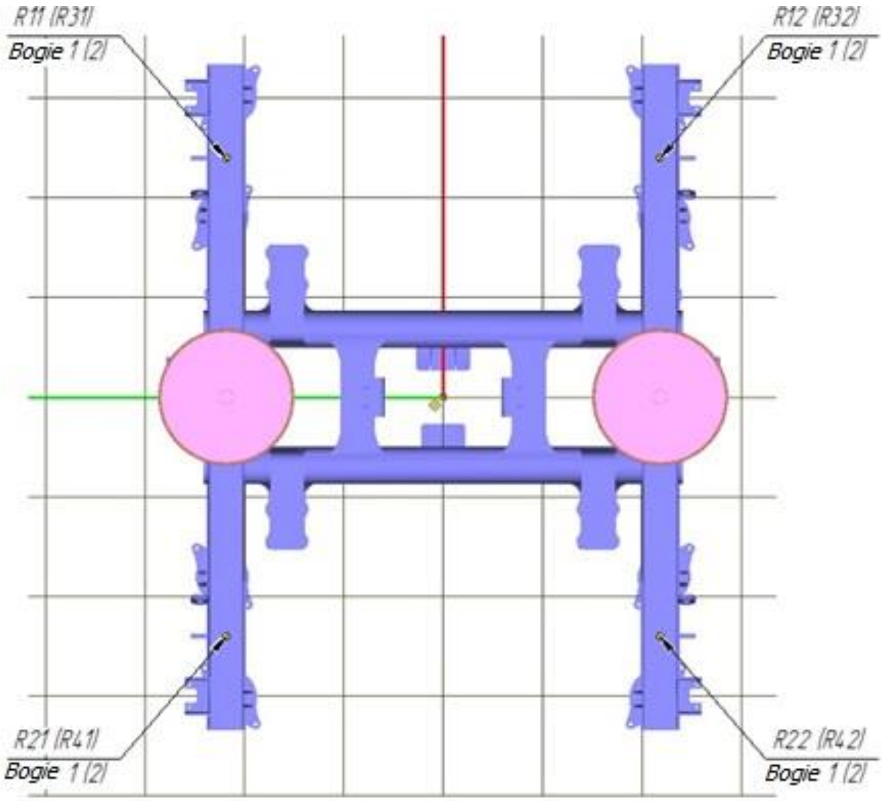

Fig. 5. Placing of "sensors" on the bogie frame

To define the critical value of the ratio of lateral and vertical forces of the interaction of wheels and rails Y/Q, by means of which the strict limitations to the gap between the wheel and top of the rail is defined, the M.J. Nadal formula is used:

$$\frac{Y}{Q} \le \frac{tg\beta - \mu}{1 + \mu \cdot tg\beta}, \tag{6}$$

where:

β is the angle of inclination of conical generatrix of the wheel flange to the contour line;

μ is the friction factor for sliding surfaces of wheels and rails that interact.

The analysis of dynamic performances of the safe operation of HRCS2 electric trains cars was performed on the basis of the numerical experiment according to the design conditions that most accurately represent operational conditions. To investigate the influence of characteristics of anti-yaw dampers on the safe operation, three design variants were considered. They correspond with the following calculation cases: 1 – initial power characteristic of anti-yaw dampers; 2 – twofold decrease of damping parameters of the anti-yaw damper; 3 – there are no anti-yaw dampers.

Fig. 6 and 7 show dependences of the maximum values of the index of wheel sets stability against derailment on the running speed according to the Nadal criterion for considered design variations regarding trailing and motor cars respectively (dash-and-dot cure – 1 variant, dashed line curve – 2 variant, solid base curve – 3 variant). The limit value of the Y/Q ratio is taken to be equal to 0,8 (EN 14363:2005; UIC, 2015).

As can be seen from the graphs presented in Fig. 6, the variants considered show that maximum values of the Y/Q ratio do not exceed the acceptable value of 0.8. The level of Y/Q values in the range of running speeds from 100 to 160 km/h in 1st variant (initial power characteristic of anti-yaw damper) is higher than the similar values obtained for variant with the decreased power characteristic of anti-yaw dampers (2nd variant) and variant with no anti-yaw dampers (3rd variant).

Therefore, decrease in the power characteristic of the anti-yaw damper or its removal from the car design leads to the improvement of conditions of the safe operation of the trailing car.

As can be seen from the graphs presented in Fig. 7, at different characteristics of anti-yaw dampers the maximum values of the Y/Q ratio do not exceed the limit value. In case of rated characteristics of anti-yaw damper (1st variant) the level of Y/Q values in the range of running speeds from 100 to 160 km/h is higher than the similar values obtained at reduced power characteristics of anti-yaw dampers (2nd variant) and values with no of anti-yaw dampers (3rd). It should be noted that in case of initial characteristics for the baseline design of anti-yaw dampers the stability margin of the motor car at the speed of 160 km/h is exhausted.

Therefore, the evaluation of the safe operation by the Nadal criterion shows that the decrease in power characteristics parameters of anti-yaw damper or removal of the latter leads to the improvement of the safe operation of the motor car.

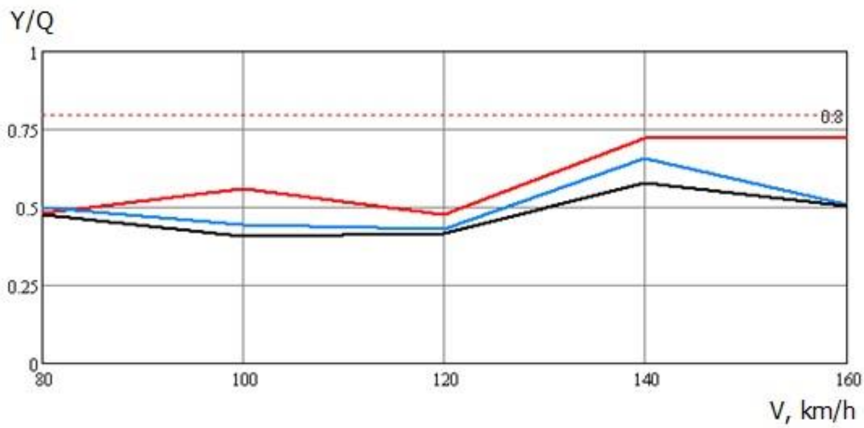

Fig. 6. Dependences of Y/Q ratio on the running speed of the trailing car

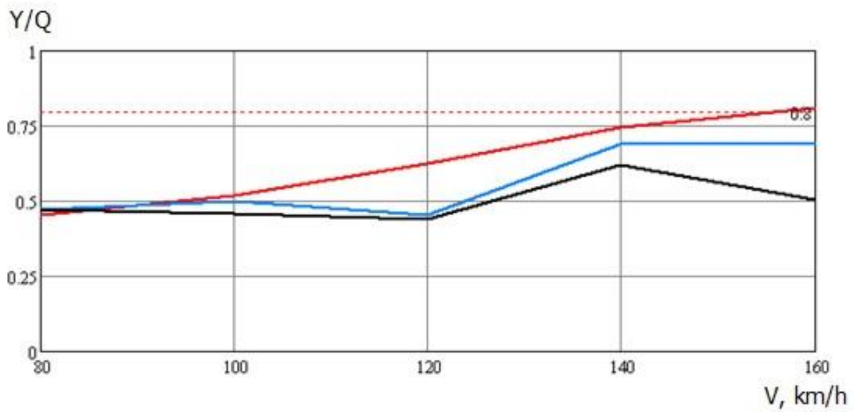

Fig. 7. Dependences of Y/Q ratio on the running speed of motor car

4. Conclusions

1) The experience in operation of HRCS2 high-speed electric trains threw the light on shortcomings of the existing system of admission of rolling stocks of a new generation to the operation on 1520 mm tracks. Due to shortcomings in this system and omissions that occurred during testing and examination of technical documentation, within a short period of time starting from the beginning of operation of HRCS2 electric trains the number of failures of mechanical parts of cars was observed. This has led to the threat to the safe operation and unexpected losses. In particular, technical failures involve the destruction of bolster beams of car body frames in the areas of mounting of anti-yaw dampers attachments.

2) Values of dynamic performances of the safe operation obtained as a result of computer simulation of dynamics of motion of HRCS2 electric trains cars demonstrate the sufficient margin of stability against derailment. However, the stability margin of motor car at the speed of 160km/h is exhausted in case of initial characteristics for the baseline design of anti-yaw dampers. Reducing the resistance characteristics of anti-yaw dampers or removal of the latter from underframes leads to the improvement of parameters of the safe operation of both trailing, and motor cars. The above mentioned indicates the inadequate rationale for the decision made by the company-manufacturer regarding the choice of characteristics of anti-yaw dampers and design concept of their attachment points on bolster beams of the bogie frames.

3) The results of initial operation of HRCS2 electric trains and results of calculated estimation of dynamic performances of their safe operation clearly demonstrate the importance of underframes design development considering characteristics of infrastructure at specified routes of operation. Thus, scientifically based approaches to the assessment of compliance of the rolling stock with conditions of the safe operation in terms of dynamic performances will promote further successful implementation of high-speed passenger traffic on domestic railways. At the same time, methods and means of computer simulation of the dynamics of the rolling stock should be of paramount importance.

References

[1] ALYAMOVSKII, A., 2007. *SolidWorks / COSMOSWorks 2006/2007. Engineering analysis by the finite elements method.* Moscow: DMK, 784 p.

[2] BENDAT, J.S., PIERSOL, A.C., 1971. Random data: analysis and measurement procedures. New York: Wiley, 407 p.

[3] CARTER, F.W., 1928. On the Stability of Running of Locomotives. *Proceedings of the Royal Society*, London, 121, pp. 585-611.

[4] CHERNIAK, A., 2003. Simulation of random disturbances in the system “railway rolling stock –track”. Reporter of Volodymyr Dahl East Ukrainian National University. Academic periodical. Engineering sciences. Series “Vehicles 1” 9 (67), pp.173-177.

[5] DIOMIN, YU., DIOMIN, R., 2013. Procedural issues acceptance of rolling stock gauge 1435/1520 mm, *Prace naukowe Politechniki Warszawskiej. Transport*, 98, pp. 109-116.

[6] DIOMIN, YU., KOVTUN, E., MARKOVA, O., 1994. Self-excited vibrations of railway vehicle with dry friction units, Vehicle System Dynamics: *International Journal of Vehicle Mechanics and Mobility*, 23(1), pp. 71-83.

[7] DOMIN, R., DOMIN, IU., CHERNIAK, G., et al., 2016. Investigation of some problems of running safety of rolling stock on the Ukrainian railways. *Archives of Transport*, 40 (4), pp. 15-27.

[8] DOMIN, R., GORBUNOV, M., KRAVCHENKO, K., 2015. The analysis of causes of damages to bolster beams of car body frames of high-speed trains. *Railway Transport of Ukraine*, 1, pp. 31-35.

[9] DOMIN, R., KONSTANTIDI, V., GRYNDEI, P., et al., 2014. The investigation of fatigue damages to the body frame of the high-speed train car. *Railway Transport of Ukraine*, 4, pp. 9-11.

[10] EN 14363:2005, 2005. *Railway applications – Testing for the acceptance of running characteristics of railway vehicles – Testing of running behaviour and stationary tests.*

[11] GARG, V.K., DUKKIPATI, R.V., 1984. Dynamics of railway vehicle systems. Academic Press, 407 p.

[12] IWNICKI, S., 2006. Handbook of Railway Vehicle Dynamics. CRC Press, 535 p.
[13] LOZIA, Z., KARDAS-CINAL, E., 2016. The use of a linear half-vehicle model for the optimization of damping in the passive suspension system of a railway car. *Archives of Transport*, 39 (3), pp. 31-49.
[14] UIC, 2003. *Motive power units – Bogies and running gear – Bogie frame structure strength tests.* UIC Code 615-4, International Union of Railways, Paris 2003.
[15] UIC, 2009. *Testing and approval of railway vehicles from the point of view of their dynamic behaviour – Safety – Track fatigue – Ride quality*. UIC Code 518, International Union of Railways, Paris, 2009.
[16] BOLOTIN, V.V. (Eds.), 1978. *Vibration in machinery: Reference book.* V. 1. Fluctuations of linear systems. Mashinostroenie, 352 p.