Investigation of the Longitudinal Track Profile Influence on the Forces Acting in the Train Inter-car Connections Using the MSC.ADAMS Software

Alexandr Shimanovsky[1][0000-0001-8550-1725], Pavel Sakharau[2][0000-0003-0356-7750],

[1]Belarusian State University of Transport, 34 Kirova St., Gomel, 246653, Belarus
tm.belsut@gmail.com
[2]Belarusian State University of Transport, 34 Kirova St., Gomel, 246653, Belarus
sahpa@mail.ru

Abstract. The simulation of a freight train movement in the MSC.ADAMS software package is considered. There are presented the investigation results for longitudinal forces in the inter-car connections of homogeneous and heterogeneous trains while moving through parts of the track longitudinal profile. It was established the effect of the train length and mass as well as the loaded and empty cars location along the train on the values of the coupling devices inner longitudinal forces.

Keywords: freight train, modeling of the solid body, longitudinal forces, track profile grade change.

1 Introduction

The electric traction introduction is one of the most important measures to reduce the costs of train traction. The efficiency of modern electric locomotives operation depends on the full usage of their power. Such locomotives show real energy savings compared to electric locomotives of previous generation only at high-mass trains transporting. The maintenance of long-compounded trains is associated with difficulties in the train controlling on way profile sections with grade changes. The insufficient knowledge of the heterogeneous train dynamics at locomotive electric braking has led to the need of its limited usage on the Belarusian railway. This fact caused the additional wear of the brake pads and wheel sets of cars due to the need of wagon brakes operation. Also it is missed the possibility of electrical energy returning to the contact network at regenerative braking. Therefore, it became necessary to analyze the longitudinal forces arising in the train moving along the grade changes of the longitudinal track profile in the locomotive electrodynamic braking mode.

2 Literature review

A detailed description of train motion mathematical models as a mechanical system is described in [1]. The main calculation schemes of the train cars are considered: cars with rigidly attached cargoes and cars with goods moving relatively to wagon body, including reservoirs with liquid. The presented train movement calculation schemes and equations are given for a solid rod or chain of solid bodies. Particular attention is paid to the analysis of the inhomogeneous train movement through the longitudinal profile grade changes with and without gaps in the harness devices. On the base of the research, it was concluded that the longitudinal forces in the train at impacts cause intense vertical oscillations of the car body, but their influence is insignificant on the longitudinal forces value. Therefore, the vertical oscillations of the cars can be neglected at analyzing the longitudinal forces in the train.

The study of a heterogeneous train motion along a complex track profile was considered in the work of Grebenyuk [2]. It is pointed that the heterogeneity of the train cars according to their types leads to an increase in longitudinal forces at braking by about 20 %, and their loading inhomogeneity – by 30-35 %. Placing one group of lighter cars into the train head increases the forces in the inter-car joints, and placing them in the train tail reduces the values compared to the forces arising in a uniform train of equal mass and length. It is noted that longitudinal forces arising in a train, moving along a complex profile, depend on a large number of factors. The most important of them are the magnitude and nature of changes in external forces (thrust, braking), the characteristics of inter-car connections and clearances in them, the position of automatic couplers at the beginning of the control actions realization.

The nature of the train motion, its velocity and acceleration substantially depend on the track profile. In the work of Vershinsky [3], there are presented the analytical calculations of longitudinal forces in harness devices of various train sections for the case of moving along a fixed track profile and along a broken profile. The calculation results show that if the profile does not change within the train length, the efforts in the inter-carriage connections are determined by the tractive forces, the distribution of masses and braking forces along its length. At the same time, when the train moves along the grade change of the track longitudinal profile, the magnitude of the greatest gradient has a great influence. The increase in the number of grade changes within the train length leads to a decrease in longitudinal forces. It was concluded that, the case of the electric braking by a locomotive moving in a recess, from descent to ascent is particularly difficult from the cars stability against squeezing point of view.

The dissertation work of Masleeva [4] considers the investigation of transient processes caused by the long train movement control on the longitudinal track profile grade changes. It has been established that the values of longitudinal forces having impact and quasistatic nature do not practically depend on the angle characterizing the asymmetry of the grade changes relative to the vertical, and they are determined only by the difference of the conjugating slopes and the radius of the connecting curve.

The study of longitudinal forces in non-stationary modes of train motion based on computer simulation was considered in [5, 6]. It is noted that the heterogeneity of the train composition according to the wagons and cargo types leads to significant changes in the transition process nature and in the distribution of maximum efforts along the train. There is an increase in the values of maximal forces in the inter-car connections by 10–12 % compared with the intensity of forces in a homogeneous train.

Simulation of train movement across longitudinal profile grade changes was performed with the help of the Universal Mechanism software package and it was considered in [7-10]. There was investigated the possibility of using the increased longitudinal profile grade changes at the railway construction and repair to reduce financial costs. Thus, in [10], on the basis of studies of wagon vertical accelerations and forces in the inter-car connections, the necessity of using biclothoid vertical curves is proved for pairing elements of a longitudinal profile. It is shown that in this case the values of the train longitudinal forces decrease to 14 % and the vertical forces – to 45 %, compared with movement along vertical circular curves.

In work [11] the process of pneumatic braking is considered. The effect of the delay in the braking forces application along the train and the inter-car joints parameters on the longitudinal forces arising in coupling devices was investigated theoretically and experimentally. There was made the conclusion that the three waves of longitudinal elastic oscillations occur along the train. These forces cause the increase in the inter-car joints forces, they reach maximum values at the peak of the third wave in the first half of the train.

A comparison between various methods of braking calculations used in the EU and Russia is analyzed by Bureika [12]. It revealed that the differences between the values of the braked mass of Russian freight cars estimated by TSI (Europe Union) method and calculated by MPS (Russian) method for four-axle freight cars with cast-iron brake shoes are (0–2.2) %.

There can be found a great amount of articles dedicated to researches on electrodynamic braking. Thus, Pugi [13] presents a modular tool for prediction of train braking performance, with particular attention to accurate prediction of stopping distances. A comparison between braking forces in the cases of air and electrical braking is conducted in it. In article [14], there are investigated the main factors that lead to the empty wagons derailment in the long-compound trains. It is concluded that the main reasons for the cars stability loss are large longitudinal forces, deviation of automatic couplings, as well as the condition of the rolling surface and wheel flanges. There is a need to reduce the friction coefficient between the rail and the wheel flange to prevent the wheel from raking it on the rail and further derailment.

The problem of reducing of longitudinal forces between cars is considered in [15]. There are presented the main factors affecting the longitudinal forces in the automatic couplers: characteristics of amortizing devices, longitudinal vibrations of wagons, uneven height position of automatic couplers due to different loading of each car, misalignment of automatic couplers in the transverse direction. It is noted that the introduction of electropneumatic brake is most effective method to reduce the forces arising in freight trains.

To increase computational accuracy and to reduce time of computations it was proposed in [16] to use the global and local coordinate systems. This is especially important at train movements simulation on long track sections. The global coordinate system is used to describe the locomotive motion, the local one takes into account the deviations in the inter-car connections. It is stated that the use of such an approach allows to reduce the computation time by 8.6 % and to maintain the accuracy of the calculations.

There are also developed the approaches related to the kinematic parameters determination for the several train sections in a real-time mode and their transfer of incoming data to the locomotive [17]. Analysis of the incoming information allows to make a decision about changing the control action (thrust or braking) in order to reduce the longitudinal forces in the train.

The results of the reviewed investigations confirm the scientific relevance of studies on the train dynamics at transient driving conditions. The purpose of the presented work is to analyze the longitudinal forces in the inter-car joints arising at movement along a track with variable inclination.

3 Mathematical model of train

For the mathematical description of the train movement it was taken into consideration the calculation scheme of the train considered as a chain of solid bodies with elastic-viscous inter-car connections. The pattern of the train movement over a complex profile section is shown in Figure 1. There, cars are considered to be absolutely rigid bodies with masses concentrated in their centers of mass. Vertical oscillations of wagons on springs, their angular displacements, and also gaps in the inter-car connections are not taken into account.

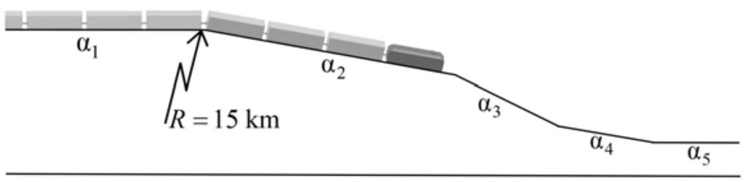

Fig. 1. Scheme of the train movement along a complex profile section

The train motion in the presented scheme is described by differential equations system [18, 19]:

$$\left.\begin{aligned} & m_l \ddot{x}_l - T_1 - m_l g \sin\alpha_l + S_l + R = 0; \\ & m_k \ddot{x}_k + T_k - T_{k+1} + S_k - m_k g \sin\alpha_k = 0;\ k = 1, 2, \ldots, n-1; \\ & m_n \ddot{x}_n + T_n + S_n - m_n g \sin\alpha_n = 0. \end{aligned}\right\}, \tag{1}$$

where n – number of the train cars; m_l, m_k – mass of the locomotive and the k-th car, respectively (k = 1, 2, …, n); $\ddot{x}_l, \ddot{x}_k$ – longitudinal acceleration of the locomotive and the k-th car; T_k – forces acting from the inter-car connections; g – acceleration of gravity; α_l, α_k – slope of the track under the moving locomotive and the k-th car; S_l, S_k – resistance forces to locomotive and the k-th car movement; R – external force acting the locomotive (thrust or electrodynamic braking).

Forces in the inter-car coupling with elastic-viscous connections are determined in accordance with the expression

$$T_k = c(x_k - x_{k-1}) + K(\dot{x}_k - \dot{x}_{k-1}), \tag{2}$$

where c – stiffness coefficient of elastic elements in the inter-car connections; in the calculations the value is $c = 1{,}1\cdot10^7$ N/m; x_k, $\dot{x}_k$ – the movement and speed of the k-th car respectively; K – damping factor; the accepted value $K = 10^6$ N·s/m.

The resistant to movement forces depend on the type of the track and, in the case of a continuous railway are determined in accordance with the Rules [20] by the formulas:

– for the locomotive driving in traction mode

$$S_l = m_l g\left(1.9 + 0.008\cdot 3.6\dot{x}_l + 0.00025\cdot(3.6\dot{x}_l)^2\right)/1000\,; \tag{3}$$

– for the locomotive driving in the idle mode

$$S_l = m_l g\left(1.9 + 0.008\cdot 3.6\dot{x}_l + 0.00025\cdot(3.6\dot{x}_l)^2\right)/1000\,; \tag{4}$$

– for the empty cars ($q \le 6$ ton/axis)

$$S_k = m_k g\left(1.0 + 0.042\cdot 3.6\dot{x}_k + 0.00016\cdot(3.6\dot{x}_k)^2\right)/1000\,; \tag{5}$$

– for the loaded ones ($q > 6$ ton/axis)

$$S_k = m_k g\left(0.7 + (3 + 0.09\cdot 3.6\dot{x}_k + 0.002\cdot(3.6\dot{x}_k)^2)/q\right)/1000\,; \tag{6}$$

where q – weight per one pair of wheels, ton.

4 A computer model of the train

To implement the presented mathematical description in the MSC.ADAMS software package, $n + 1$ parallelepipeds were created for the locomotive and the cars (in Figure 2 one of the model cars is shown). Their dimensions correspond to the dimensions of the existing rolling stock. They are located at a distance of the car length between the axles of automatic couplings (13.92 m) from each other. Through the curve "GCURVE_1" passes the cars centers of gravity (for the second car - "VAGON_2.cm"). It sets the parameters of the longitudinal profile of the track for the train displacement. The car is connected to the curve in two points “PTCV_5” and “PTCV_6” by the “Point-Curve Constraint” connection (the connections “PTCV_4” and “PTCV_7” belong to 1 and 3 cars, respectively). A resistant to the movement force “SFORSE_2” is applied to the car center of gravity. The force is determined by the formula (5) or (6) depending on the load of the car. The cars are interconnected by springs "SPRING_2" and "SPRING_3", the forces in them are determined by the formula (2). The point of connection of the spring-car corresponds to the location of the coupler wedge drawbar.

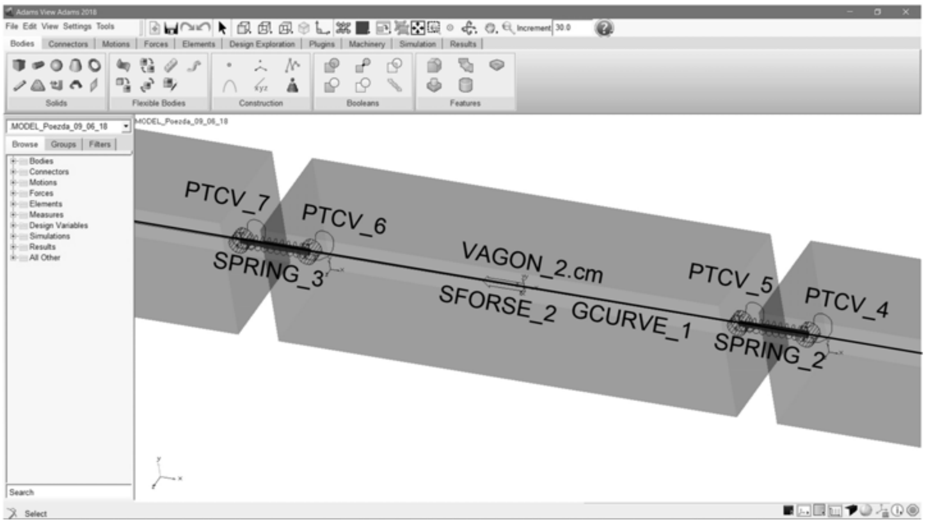

Fig. 2. The train model in MSC.ADAMS/View

The final model allows to change the initial speed and the mass of each wagon, the parameters of elastic connections, the railway profile, as well as to change the number of cars in the train by their activating or deactivating.

For the convenient analysis of the motion simulation computational results, they are presented in the form of graphs. An example of the traveled distance, the velocity and acceleration of the locomotive movement graph is presented in Figure 3.

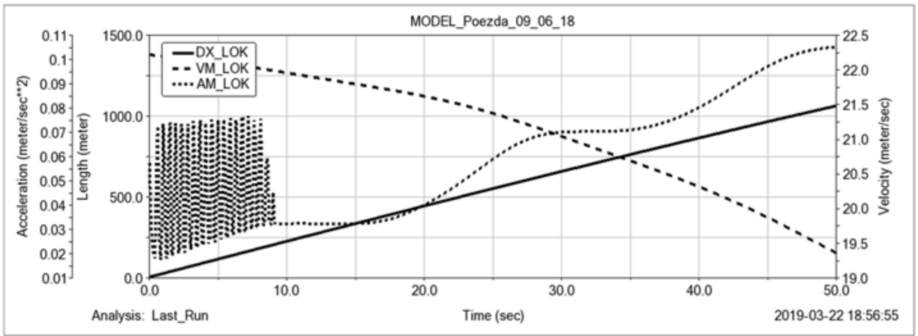

Fig. 3. Kinematical parameters of the locomotive movement in MSC.ADAMS

The earlier studies carried out by the presented model [21] made it possible to analyze the degree of the track profile grade changes influence on the magnitude of the maximal forces in the homogeneous train inter-car connections. Analysis of the train movement from plane to ascent and from site to descent in the idle mode showed that an increase in the conjugation radius of elements in the vertical plane leads to a decrease in maximal forces in automatic couplers. The change of forces in the homogeneous train inter-car joints is almost the same at moving one slope up and down and it is determined only by the difference in slopes of adjacent elements and the radius of their conjugation.

Since it was established that the dependence of the maximal forces in the inter-car connections on the difference between the adjacent elements slopes is close to linear, the current investigation considers the movement only along the grade change of the constant steepness and conjugation radius. The presented below results were obtained for the case of the train moving from the horizontal way to a 13 ‰ grade steep rise

5 Computational results

Trains of the same mass can have different length and number of cars. With the help of the model, the influence of these factors on the longitudinal forces in the train was studied. Figure 4 shows the change in forces in the most heavily loaded inter-car connections of trains of the same mass (2500 tons) and different numbers of cars over time for case of motion through a profile break in the idle mode. The initial velocity was 80 km/h. In each train, the mass is distributed uniformly over the car. If there were more cars their mass was taken less.

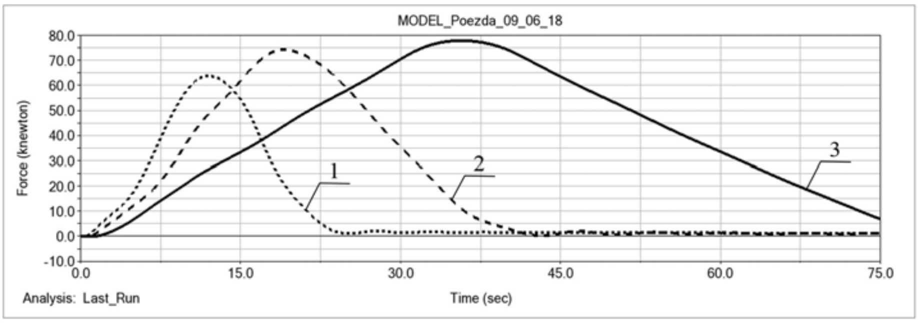

Fig. 4. Change in longitudinal forces in the most loaded automatic couplings of a homogeneous trains with the equal mass: 1 – 25 cars, 13 inter-car joint; 2 – 50 cars, 24 inter-car joint; 3 – 100 cars, 48 inter-car joint

With a decrease in the number of cars from 100 to 25, the maximal longitudinal forces decreased from 78 to 64 kN, and there could be observed a significant reduction in time of compressive forces action. The time of the compressed position of the inter-car connections is proportional to the train length and for the considered cases it reduced by 4 times. Consequently, a decrease in the homogeneous trains length due to a decrease in the cars number leads to a slight decrease in the maximum longitudinal forces and to a reduction in their action time, proportional to the number of cars. At the same time, the mass of the train remains unchanged.

For a detailed study of the maximum forces distribution along the train length, similar calculations were carried out for a train of 5000 tons mass. The results are presented in Figures 5 and 6.

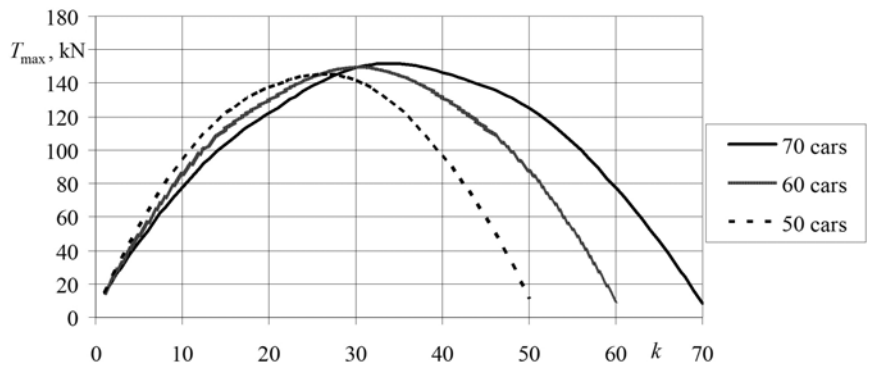

Fig. 5. The distribution of maximal forces T_{max} along the length of a train of equal mass, formed from 50, 60 and 70 cars (k – car number)

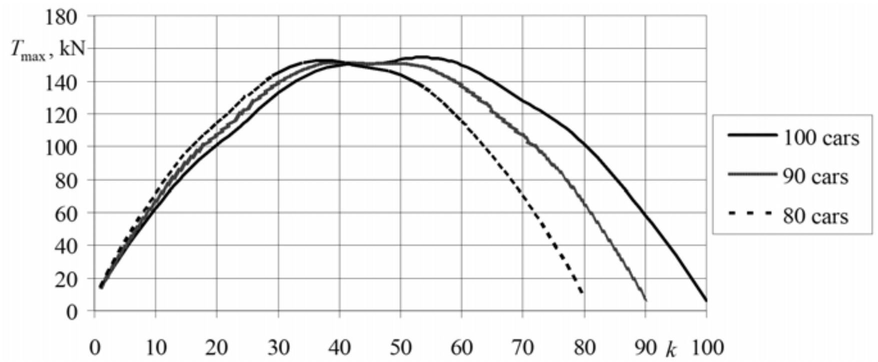

Fig. 6. The distribution of maximal forces T_{max} along the length of a train of equal mass, formed from 80, 90 and 100 cars (k – car number)

According to the presented figures, the maximal forces in the inter-car couplings appear in the central part of the train and change relative to it almost symmetrically. This is typical for homogeneous trains. There is a non-significant increase in forces from 145 to 155 kN when the number of cars changes from 50 to 100 and the train mass decreases from 100 to 50 tons correspondingly. The maximal forces increase for case of reducing car mass can be explained by an increase in specific resistant to movement forces (forces per unit mass) of less loaded cars compared to more loaded ones due to a decrease in q in formula (6).

There was investigated the effect of a homogeneous train mass on the longitudinal forces in automatic couplers. The train was formed from 100 cars and its initial velocity was equal to 80 km/h. There were considered four variants of common train mass: 2500, 5000, 7500, 10000 tons. There was simulated the movement of each train through a broken profile. Curves of forces changes over time in the most loaded inter-car connections of these trains are shown in Figure 7, and the maximal forces distribution along the train is shown in Figure 8.

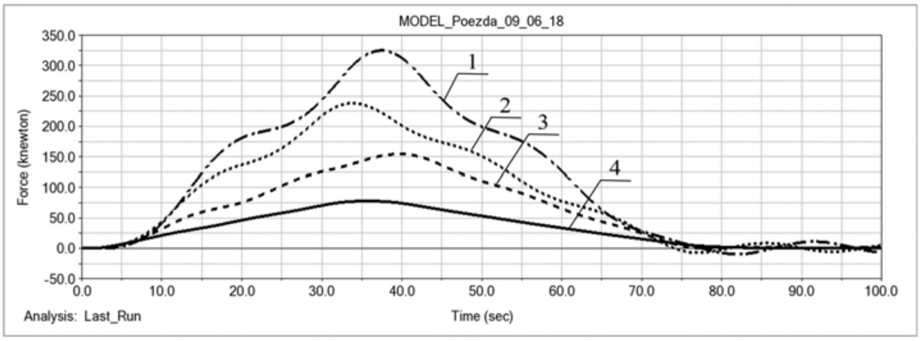

Fig. 7. Change of longitudinal forces in the most loaded inter-car connections of a homogeneous train formed from 100 cars: 1 – car weight 100 t, 52 inter-car joint; 2 – car weight 75 t, 47 inter-car joint; 3 – car weight 50 t, 54 inter-car joint; 4 – car weight 25 t, 48 inter-car joint

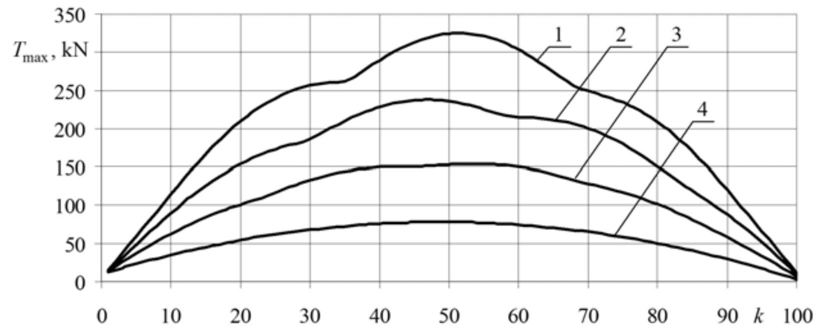

Fig. 8. The maximal forces T_{max} distribution along the length of a homogeneous train formed from 100 cars for gross car weights: 1 – 100 t; 2 – 75 t; 3 – 50 t; 4 – 25 t

The maximal forces in a homogeneous train with an unchanged number of cars are proportional to the train mass. The maximal longitudinal force appears in the central part of the train and, according to the Figure 7, it can be located in the inter-car connection of both the first half (connections 47 and 48; cars masses are 75 and 25 tons, respectively), and in the second half (connections 52 and 54' cars masses are 100 and 50 tons, respectively) of the train.

The curves of the maximal forces distribution along the length of the train of different mass (Figure 8) are similar to the dependences obtained for the train of constant mass passing the profile grade changes of different steepness. Analysis of the simulation results showed that the dependence of the maximal forces in the train on its mass is practically linear. This relationship is shown in Figure 9.

It should be noted that the above mention dependence is valid for the case of movement through a profile grade change with 13 ‰ slopes difference and 15 km radius of adjacent elements conjugation. For other slopes and conjugation radii, the maximal force values change proportionally. A slope angle increase leads to a shift of the presented graph above up, and a decrease – to a downward shift. An increase in the conjugation radius of adjacent elements in the vertical plane leads to a decrease in the angle of inclination of the line, and radius decrease - to an increase in this angle.

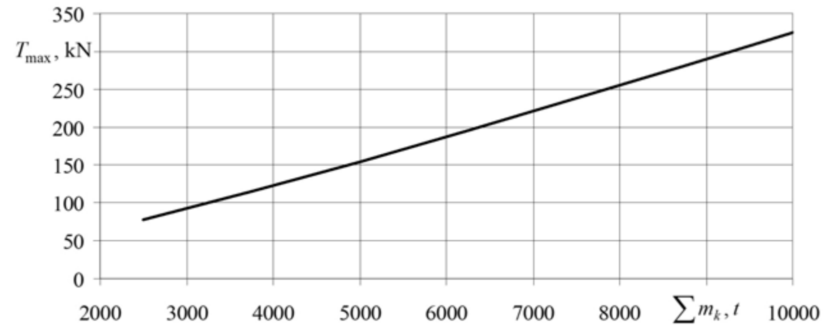

Fig. 9. The dependence of the maximal forces T_{max} in the train inter-car joints on its mass for the case of movement along the profile grade change

Figure 10 presents the simulation results demonstrating the possibility of using the dependence shown in Figure 9 for an approximate estimate of the maximal forces arising in the train of various mass and number of cars.

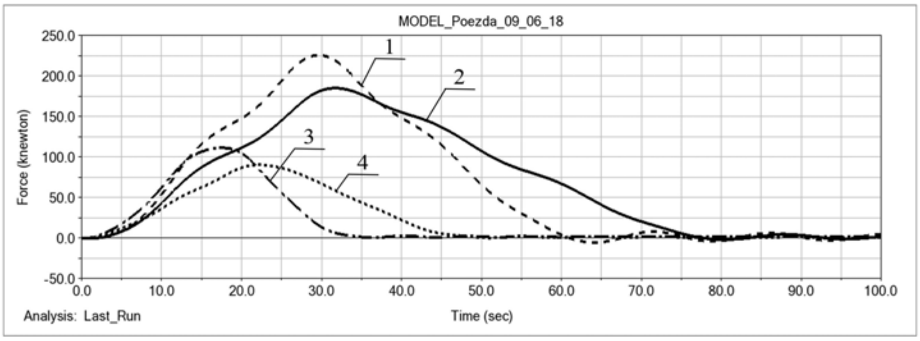

Fig. 10. Change of longitudinal forces in the most loaded inter-car connections of a homogeneous train of different masses and number of cars: 1 – 80 cars with mass 90 t; 2 – 100 cars with mass 60 t; 3 – 40 cars with mass 100 t; 4 – 60 cars with mass 50 t

In the presented graphs the maximal forces are 225, 185, 111, 90 kN. The forces appeared in the trains of 7200, 6000, 4000, 3000 t correspondingly. These results are in good agreement with the graph shown in Figure 9.

With the help of the model, there were performed the computations and their results allow us to determine the time moment and the location of the profile point where there I observed the maximal force in the inter-car connection at the train movement through the profile grade change in the idle mode.

The movement of a homogeneous train formed from 50 loaded cars weighing 100 tons is considered. The maximal forces in all automatic inter-car couplings and their position on the track profile section are determined. The results of the simulations are presented in Figure 11. Their analysis showed that the maximal forces in all inter-car connections appear directly at moving along a transition curve connecting adjacent elements of different steepness. The greatest forces values, corresponding to the automatic couplings of the train central part, arise in the center of this transition curve and they smoothly decrease at a distance. In this case, the interconnection between the coupler position along the train and the location of the profile point at which the maximum force occurs is observed: when the coupling is removed from the train tail, this point moves away from the beginning of the transition curve to its end.

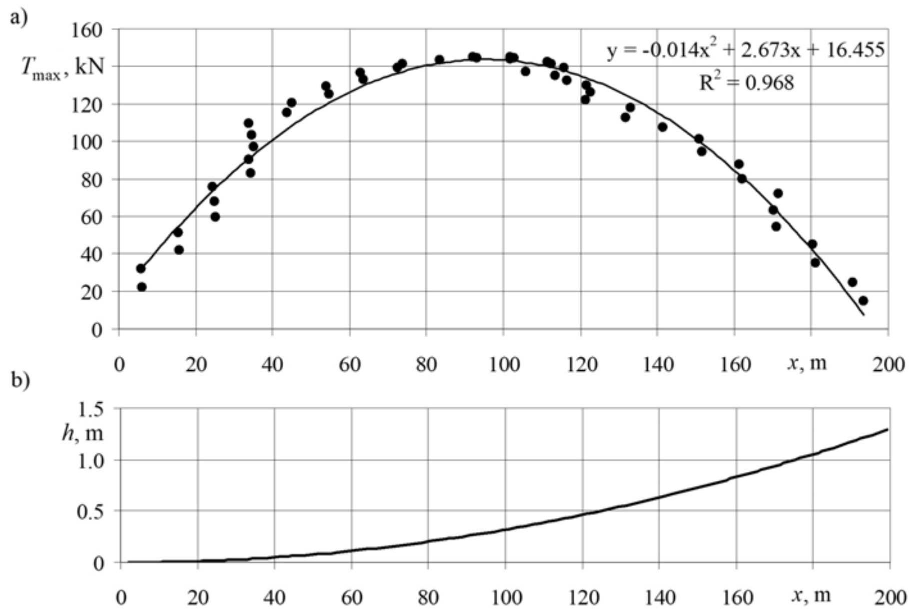

Fig. 11. The location of the inter-car joints at the moment when the maximal longitudinal forces appear in them in section (a) and the profile section level change (b)

There was performed the movement analysis of the heterogeneous by mass trains. At simulation there was taken the same number of cars – 90 and the train mass – 6300 t. The empty cars were arranged in groups of 30 in the head, center and tail of the train, and they were also distributed in groups of 10 cars located in different parts of the train. The mass of empty car is 24 t, and of the loaded one – 93 t. A homogeneous train formed of cars of 70 t each is considered for comparison. Figure 12 shows the dependence of the longitudinal forces change on time in the most loaded inter-car connections of homogeneous and heterogeneous trains.

Graphs of the maximal forces distribution for the inter-car connections with different empty cars locations are shown in Figures 13–15.

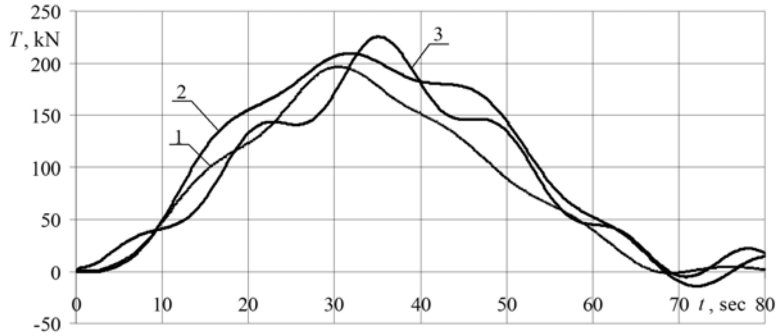

Fig. 12. The dependence between the forces in the most loaded inter-car connections of homogeneous and heterogeneous trains and the time of movement along the profile grade change: 1 – without empty cars; 2 – empty cars location from 31 to 60; 3 – empty cars are groups from 1 to 10, 21 to 30, 41 to 50

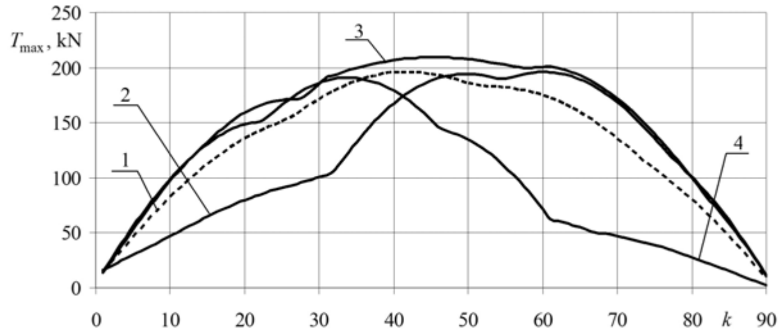

Fig. 13. Comparative characteristics of the maximal longitudinal forces distribution for couplings of homogeneous and inhomogeneous trains of the same mass: 1 – without empty cars; 2 – empty cars location from 1 to 30; 3 – empty cars location from 31 to 60; 4 – empty cars location from 61 to 90

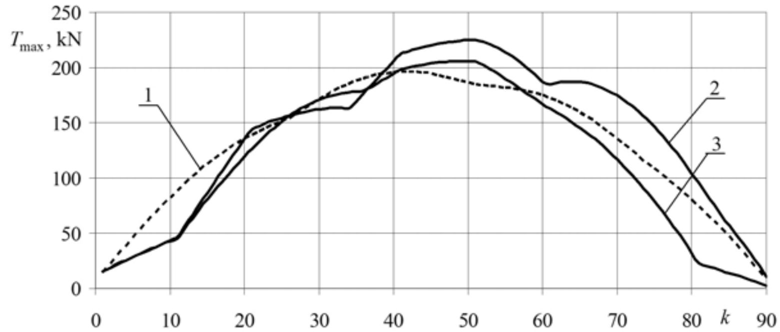

Fig. 14. Comparative characteristics of the maximal longitudinal forces distribution for couplings of homogeneous and inhomogeneous trains of the same mass: 1 – without empty cars; 2 – empty cars are groups from 1 to 10, 21 to 30, 41 to 50; 3 – empty cars are groups from 1 to 10, 41 to 50, 81 to 90

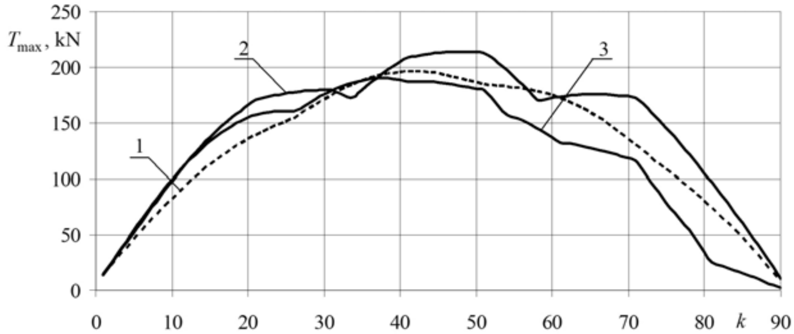

Fig. 15. Comparative characteristics of the maximal longitudinal forces distribution for couplings of homogeneous and inhomogeneous trains of the same mass: 1 – without empty cars; 2 – empty cars are groups from 21 to 30, 41 to 50, 61 to 70; 3 – empty cars are groups from 41 to 50, 61 to 70, 81 to 90

The graphs presented in Figures 12–15 show that when driving an otherwise heterogeneous train through a grade change of a longitudinal track profile in the idle mode, the arrangement of empty cars in the middle part of the train leads to an increase in the maximal longitudinal forces. The alternating arrangement of empty and loaded wagons in the head and central part of the train leads to an even greater increase in strength. So the location of 30 empty cars in groups of 10, located after the locomotive, 20th and 40th cars is the most unfavorable variant. In this case, the maximal force increases by 15 % compared with a homogeneous train of the same mass.

There was analyzed the movement of an inhomogeneous train with 6000 t mass. The train was composed of 100 cars, the number of empty cars varied from 10 to 50. At the same time, empty cars were grouped in the head, in the center or in the tail of the train. The simulation results are presented in Figure 16.

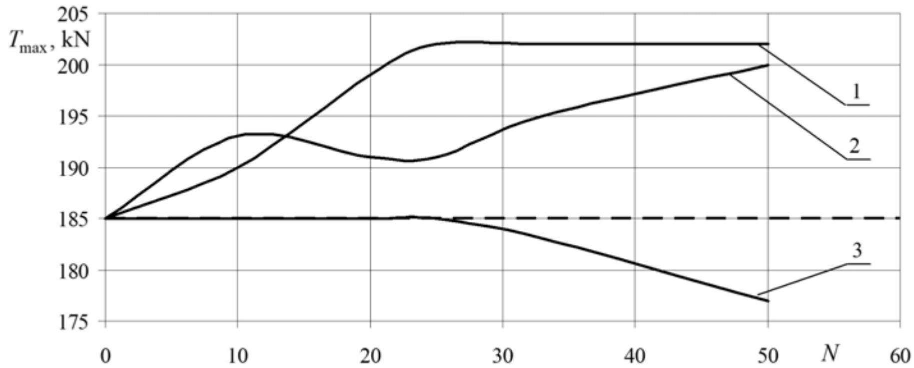

Fig. 16. Maximal forces in a heterogeneous train of the same mass with different numbers and location of empty cars: 1 – in the middle; 2 – in the head; 3 – in the tail

6 Conclusion

Simulation modeling made it possible to evaluate the effect of train track profile grade change on the forces between cars at train movement. It was determined that when the train moves in the idle mode through the profile grade change with 13 ‰ slope difference, the maximal forces change from 90 kN (train mass is 3000 t) to 320 kN (train mass is 10000 t).

The dependence of the maximal forces in a uniform train on its mass was obtained. It was established that the maximal forces in all inter-car connections are at the moment when the cars pass along a transition curve connecting the elements of different inclines, and the greatest of them is located in the central part of the train at the curve middle passing.

There was taken into consideration the effect of train mass heterogeneity on the maximal forces in the automatic inter-car couplers at train movement along the track profile grade change. The simulation results showed that the greatest increase in longitudinal forces is observed when the empty cars are located in the central part or they alternate with loaded in the head and central part of the train. At the same time, the maximal forces increase by 15 % or more compared to a uniform train of the same mass.

The obtained simulation results can be used for the development of recommendations for the forming and maintenance of trains.

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