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І Н Ф О Р М А Ц І Й Н О – К Е Р У Ю Ч І С И С Т Е М И Н А З А Л І З Н И Ч Н О М У Т Р А Н С П О Р Т І

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Assoc. Prof. J. Dižo,
Ing. M. Bučko,
Assoc. Prof. M. Blatnický,
Ing. P. Slušňák

DYNAMIC ANALYSIS OF A SUBURBAN RAILWAY VEHICLE

Simulation modelling and analyses are widely used in a railway vehicle design. They allow to find the most favourable parameters of wagons in order to achieve high level of ride comfort and running safety. The presented research is focused creation of an suburban rail vehicle, i.e. a passenger wagon. The simulation model was used for analysis of dynamic properties for two running cases, namely to find a critical running speed and the derailment quotient in a curve. The derailment quotient is a factor of running safety of the solved vehicle.

Keywords: *rail vehicle, suspension system, multibody simulations, dynamics.*

Introduction

Dynamic analyses play a key role in the development and optimization of railway vehicle. There are various ways to perform the analysis. Currently used programs for computer simulations of railway vehicle operation provide a significant advantage in terms of time and financial complexity for optimization purposes compared to testing vehicles in real conditions on measuring equipment [1, 2].

One of such commercial multibody programs is Simpack, which is used at the research authors' workplace. The basic simulation calculations performed in these programs include eigenvalue analysis, simulation of driving on a straight line with investigation of vehicle running stability, passenger comfort when driving on worn track, and especially simulation of driving in a curve and investigation of safety against derailment and loading of the track and vehicle, etc.

The aim of the research is to perform dynamic analyses of a suburban railway vehicle with electric traction. The prescribed minor structural changes to the vehicle and their impact on the simulation results are investigated. The research contains theoretical knowledge about simulation calculations. The next part discusses the objectives of the research. The work is focused on the study of dynamic behaviour of vehicles using the Simpack multibody program and the influence of vehicle design on it, as well as for the summary of information and its adaptation.

The need for dynamic analyses of the behaviour of railway vehicle is influenced by their mechanical structure. Railway vehicle represents large dynamic systems with a large number of degrees of freedom, i.e. in principle, each mechanical body has six degrees of freedom (3 in the translational sense and 3 in the rotational sense). Furthermore, there are complex force elements and also a complex problem of wheel-rail contact. The number of degrees of freedom is limited only by mechanical connections. The behaviour of such systems is therefore complicated and unclear. Thus, such complex systems cannot be solved analytically with a meaningful expenditure of effort, time and financial costs [3, 4].

The basic areas of practical use of dynamic calculations in the field of railway vehicle include the conceptual development of new railway vehicle, calculations for the purpose of dimensioning, verification calculations, analysis of dynamic forces and movements, which are used as inputs for other analyses, e.g. strength analyses of structures, support for driving tests, comparison of measurement and calculation results, thereby verifying the correctness and authenticity of the model, solving problems with vehicles in operation, as well as measurement, evaluation and design of new wheel and rail profiles.

The reasons for the use and application of simulation programs in practice could be briefly summarized as follows. Simulation calculations allow to shorten the time and reduce the costs required for the development of new railway vehicle, to reduce the number of tests runs of railway vehicle when experimental measurements are performed, to expand the possibilities for optimizing railway vehicle parameters, and also to provide information on the loading of individual railway vehicles components.

Analysis of recent studies and publications.

Recently, scientists and scholars took their effort to analyse running properties of rail vehicles by means of simulation computations at many universities and institutions. A brief overview of the latest available studies and publications are provided in this section.

The study performed by Sugathapala et al. [5] is focused on comprehensively investigation of the influence of wheel and rail wear on both derailment coefficients and critical derailment limits when a railway vehicle is running on a curved track. The authors team revealed that existing assessment methods have certain deficiencies.
They either fail to account for the critical derailment limits of rely on conservative criteria known as the Nadal and Weinstock criterion.

They conducted multibody dynamics simulations to numerically determine the greatest derailment quotients for various combinations of a set of nominal and worn S1002 wheel and UIC60E1 rail profiles.

Another interesting research about the multibody numerical simulations of post-derailments dynamics of a trainset the aim at a comparison between guard rails and derailment containment wall is given by the team of the authors Santelia et al. [6]. They presented the results of the research are focused on supporting the design of effective derailment containment measures through numerical simulation techniques, employing a multibody model to simulate the post-derailment behaviour of a railway trainset. The presented simulation model was combined with a finite element model of a track-based derailment containment device and it was used to predict the forces on the structure resulting from the impact with the derailed train. The key innovations of the presented study consisted in a fact, that it considers the modelling the entire trainset instead of a single vehicle instead of the effect of inter-vehicle interaction forces due to the traction gear and buffers, and the modelling of guard rails as an alternative to derailment containment walls which were previously investigated.

Alizhan et al. examined the modernization of the 61-4179 TVZ passenger coach for transporting light automobiles up to 3 tons, addressing the efficiency of multifunctional rail use in the work [7]. The main goal of the work was to assess the influence of the additional mass–dimensional loading to the strength, load distribution, and the dynamic stability of the vehicle–track system. Two approaches of numerical modelling were applied for the research, namely the finite element methods for determination of a stress distribution, deformations, and safety margins and the multibody dynamics modelling, where the wheel/rail contact forces, wagon body accelerations, and stability coefficients were assessed.

As it is stated in the research [8], the geometry of the wheel/rail contact is a key factor in resolving the dynamics of a rail vehicle. It is generally recognized that the shape used to create both the wheel profile in the rolling region and the railhead has a significant impact on the vehicle's reaction in terms of stability, vibration absorption, and curve-negotiating ability. Analysis of the effects of wheel/rail profile and lateral suspension characteristics on the dynamic hunting stability of rail vehicles moving on tangent tracks is one of the main areas of the presented research. Further, the main goal of the research is reducing vibration in railway wheel/rail profiles by an application of a novel design for enhancing speed.

The authors team Shi et al. [9] devoted their effort to study the proposal of the use of active lateral secondary suspension system to address low-frequency swaying railway vehicle body motion under low wheel-rail conicity conditions. This research was also focused on evaluation of railway vehicle dynamics, and it was focused on assessment of the Sperling index for the wagon body swaying motion. Krason et al. [10] performed numerical tests of the influence of railway bogie suspension on the wagon motion parameters. The research was subjected on dynamic tests of a prototype wagon, which is intended to transport semi-trailers. It means, that in the contrast with the goal of the presented research, it is focused on freight wagons. However, the presented methodology of numerical tests of the dynamics of a freight wagon and the problems of selecting suspension parameters in used bogies of railway wagons moving at chosen speeds on straight and curved tracks can be also applied for a suburban railway vehicle. A phenomenon of high-frequency vibration transmission through primary suspension system is examined in the study [11]. The authors created the multibody vehicle model, which was extended by considering the structural dynamics of the wheelsets, axle boxes and bogie frames, and by employing more detailed models, which describe the dynamic stiffness of the primary suspension components such as roller bearings, hydraulic dampers, rubber bushings and coil springs. The created model served to describe the dynamic behaviour of the bogie in this frequency range. The achieved results of the research showed that the vibrations are mainly transmitted by the rubber bushings. These findings provided a better understanding of the dynamic behaviour of the bogie.

Statement of the purpose and objectives of the study.

Dynamic simulation of the designed railway vehicle represents the main part of the presented research. The process of performing dynamic analysis of the designed railway vehicle includes studying the vehicle parameters, subsequent compilation of its computational model and performing the necessary simulations. The main activities and goals of the presented research are following tasks:

1. To create of a sufficiently accurate computational model of the suburban railway vehicle under consideration, which considers all requirements for performing the relevant simulations.
2. To perform the necessary simulation calculations, which are primarily intended to clarify the impact of changes in suspension parameters on the driving characteristics and dynamic behaviour of the suburban railway vehicle under consideration.
3. To identify critical speed of the solved suburban railway vehicle for the defined parameters.
4. To identify the derailment quotient of the solved suburban railway vehicle during running in a curve for original suspension parameters and for softer suspension system.

A simulation model of the solved suburban railway vehicle. The created the model of the solved suburban passenger wagon in the Simpack software using the following procedure. The vehicle body, which represents the most significant part of the vehicle mass, was created by importing a computer aided model that contained defined geometric parameters of the 3D model display and inertia parameters of the body mass. Both bogies were subsequently created as so-called substructures. In principle, they have the same properties, therefore, thy are input twice to the model. The three-dimensional model of the bogie frame helped to define mass and inertia properties, including all parts of smaller dimensions, which were included as a fixed part of the frame for rationalization and acceleration of calculations. Separate components included in the bogie substructure were the axle boxes and wheelsets guiding, also imported as three-dimensional models, and the axle bodies. The guide body, i.e. a swinging arms, also included the bearing body itself. The model of the second, as a copy of the original model of the bogie. The UIC 60 rail profile a rail cant of 1:40 was chosen.

Overall, the created multibody model consisted of the following rigid bodies, i.e. a body of the wagon, the bogie frames, the axle boxes guiding, wheelsets. Fig. 2 shows the real vehicle and the multibody model created in the Simpack software

a b

Fig. 1. The solved passenger wagon: a - an illustration in reality; b - the model created in the Simpack software

These elements were assigned the appropriate mass and inertia parameters and their mutual position, and the appropriate degrees of freedom were defined. Subsequently, it was necessary to define the mutual connections between the rigid bodies through the so-called connecting elements. These consisted of the following elements, such as a primary suspension consisting of vertical rubber conical springs, rubber conical springs forming the axle bearing guide bushings and further, a secondary suspension consists of pneumatic springs, vertical dampers, lateral dampers, lateral bumpers for the centre pivots.

The primary suspension elements were defined as spring-damper modelling type with an ideal flexible massless element with defined stiffness and damping in a parallel way. The spring stiffness was defined as linear for x, y and z direction. The above method is also applied for creation of the suspension system of the second level, which includes spring elements, rubber emergency springs and the stiffness of the longitudinal guide of centre pivots. It was used also for a model of the element of lateral buffers for centre pivots, which is characterized by a nonlinear stiffness curve and zero damping in the lateral direction, in other directions both parameters will also be zero. The stiffness is constant zero within the limits given by the buffer, and sharply increases to an excessively high value when the clearance defined by the buffer is exhausted.

Results of the research and discussion. The first task was to determine the critical speed of the solved passenger wagon. It was observed the behaviour of the wagon at different running speeds after applying the excitation of the oscillations at the beginning of the movement. Then, it was established the oscillations, at which, the wheelsets are damped during the movement, i.e. it is a stable state, remain the same, i.e. it is the critical speed, or these oscillations increase to high amplitudes, i.e. it is an unstable state. Therefore, it is determined the critical speed the one at which the oscillations only minimally decay. For this calculation, the wagon running was simulated on a straight track with a standard model of the wheel-rail contact of a length of 500 m. The wagon was excited by an initial excitation in order to occur the oscillations of the wagon. Calculations for individual speeds must be set and started separately and manually. The number of speed variations was set to 15, so that the critical speed area of the vehicle in the range of 1 to 2 km/h at most was found in the most suitable way in 15 steps.

The results of the analysis of the critical running speed for the constant values of the wheelset guidance bushing are depicted in Fig. 2 and Fig. 3. It shows the course of the deflection of the lateral oscillations of the wheelset. It is possible to identify the decreasing amplitude of the vibrations in the case of stable running (Fig. 2), which stabilizes after overcoming the distance approx. 250 to 300 m from the start of the running of the wagon. On the contrary, it increases in the case of unstable running. It is depicted in Fig. 3. It is possible to identify, that with the overcoming distance, the amplitude of the lateral motion increases. It is obvious after 50 m of running. During the stable operation, its highest value was found to be approximately $\pm\ 0.525\times10^{-3}$ m. This can be seen in the distance of approx. 85 to 90 m.

The second task was focused on investigating quasi-static values escribing the behaviour of the solved passenger wagon while running in a curve with a specified radius of 350 m. The quasi-static values are determined by a quasi-static analysis. It means, that the model of the track does not include track irregularities, i.e. the wagon is not excited and only quasi-static values of the output quantities are observed. The model of the railway track consists of an 1200 m long section. The first 50 m are formed of a straight section. This is followed by a 50 m long section forming a transition to a curve with a radius of 350 m and then a 750 m long constant curve. In a constant curve, the outer rail is raised by 0.12 m compared to the inner one. A transition from the curve to the straight section is of 50 m and the last section of the track is of 300 m.

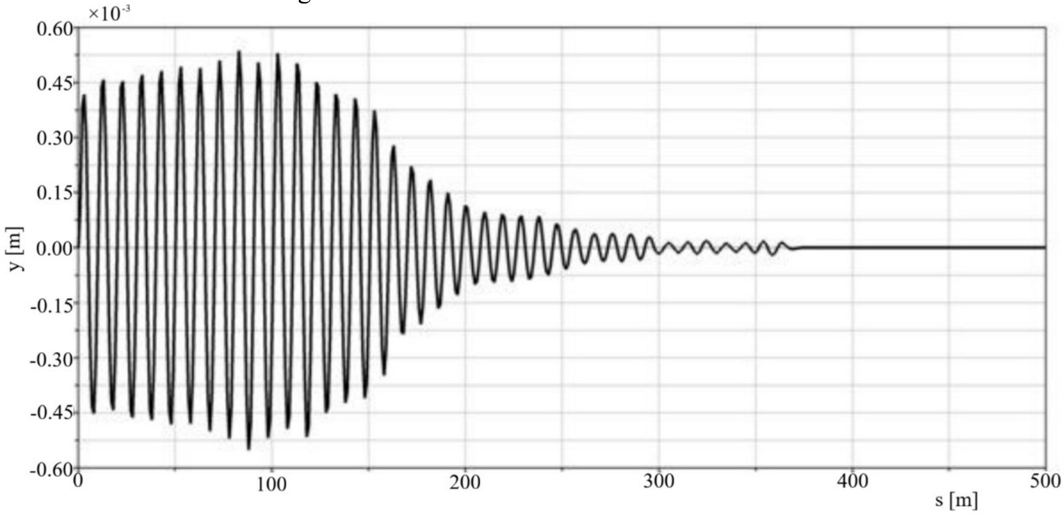

Fig. 2. An illustration of the lateral deflection of the wheelset during the stable movement

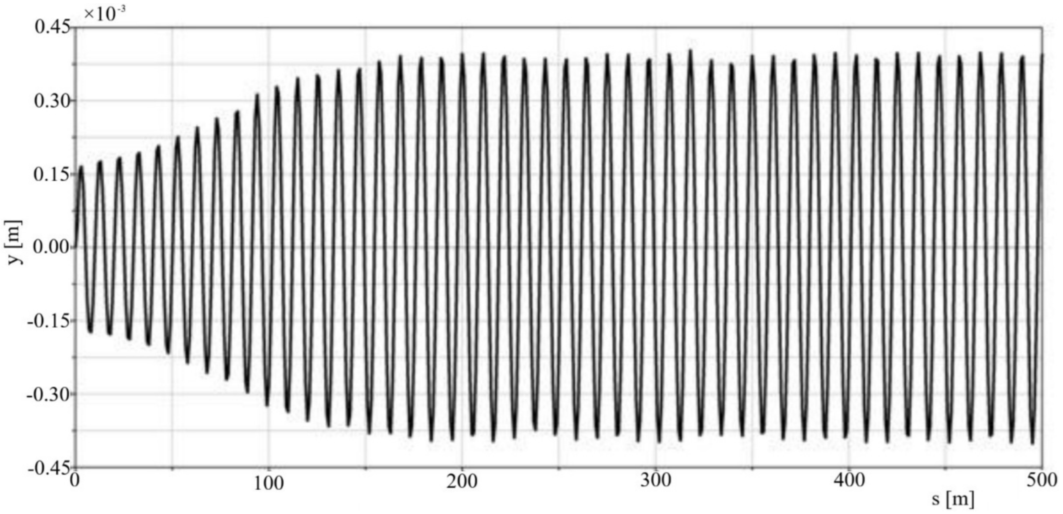

Fig. 3. Illustration of the lateral deflection of the wheelset during the unstable movement

Results of the derailment quotient for the stiffer suspension system are shown in Fig. 4. The evaluation of the derailment safety coefficient *Y*/*Q* shows relatively safe values, the maximum is reached by the approaching wheel of the first bogie at a value of 0.75 (a red curve, Fig. 4) when the wagon runs out of the curve. On the approaching wheel of the second wheelset, this value is of 0.22 (a green curve, Fig. 4). On the opposite side wheel of the same wheelset, the derailment quotient is more favourable, it is of 0.5 (a black curve, Fig. 4). The safety values for the 2nd wheelset on the opposite side are slightly more favourable, it is of 0.21 (a blue curve, Fig. 4). According to the standard, the limit value for the safety coefficient is 0.8 [12].

After changing the stiffness of the suspension parameters, values of the observed parameters are also changed. The results are depicted in Fig. 5. The values of the derailment quotient are obviously improved. This is proven by the achieved values of the derailment quotient. The highest value of the derailment quotient of the 1st wheelset in a curve is approx. of 0.58 (a red line, Fig. 5). The value of the derailment quotient of the opposite wheel of the same wheelset reached the value approx. of 0.42. Further, the values of the derailment quotient of the 2nd wheelset of the same bogie achieved much smaller values. Namely, the derailment quotient of the left wheel reached the value approx. 0.13 and the opposite wheel of the same wheelset, i.e. the right wheel achieved the value of 0.1. Also, these values of the derailment quotient are smaller than the maximal permissible value of 0.8 [12]. The smaller values of the derailment quotient of for the softer suspension system is caused by the fact, that softer suspension system allows to reduce the angle of attack of

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the wheelset in a curve. This results to more favourable distribution of the wheel forces, i.e. to safer running properties of the railway vehicle.

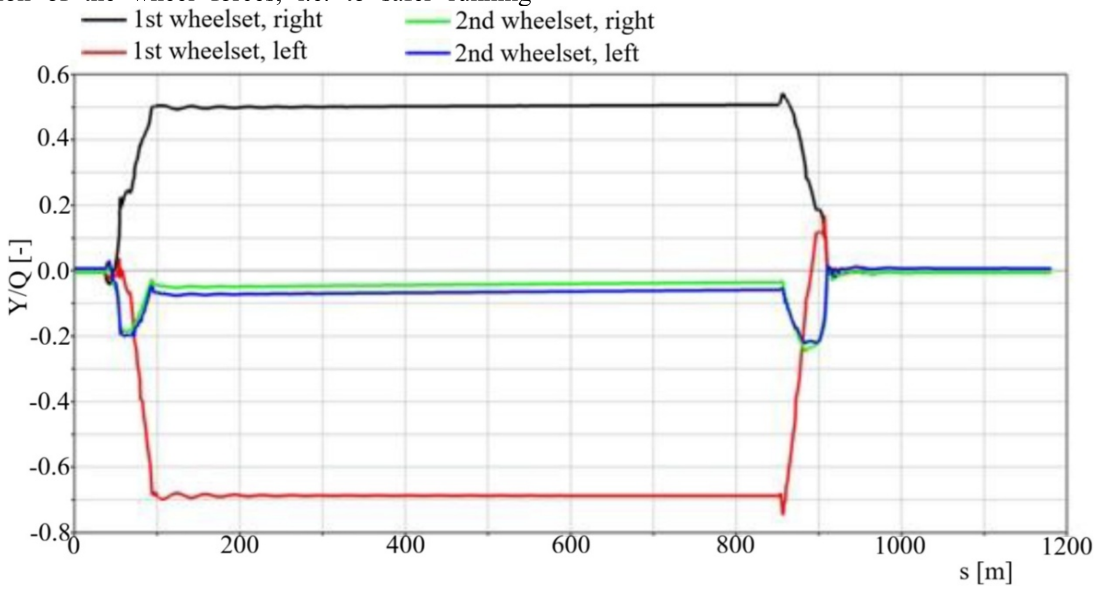

Fig. 4. Illustration of the lateral deflection of the wheelset during the unstable movement

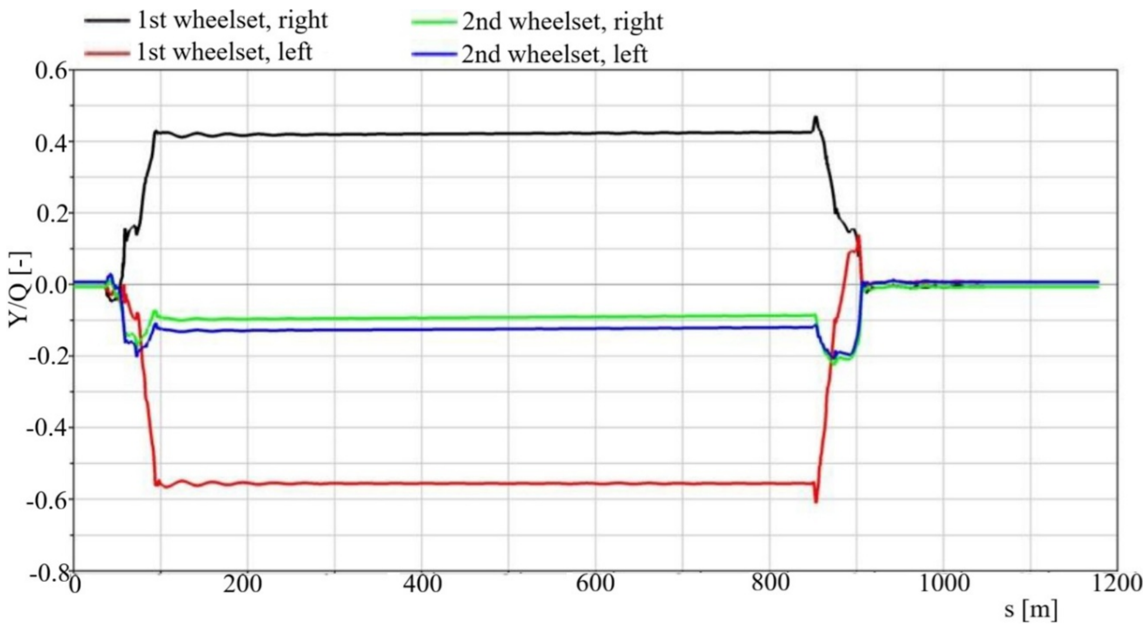

Fig. 5. Illustration of the lateral deflection of the wheelset during the unstable movement

It is considered to perform within the future research another simulation analysis of the solved suburban railway vehicle in order to optimize the parameters of the suspension system. Number of simulations will be performed to find the most suitable response of the vehicle to the excitations caused by the track unevenness. The suspension system will be tuned regarding to ride comfort for passengers and well as regarding to running safety.

Conclusions.

Urban and suburban railway transport represent very important element of the transportation system in the developed countries as well as in developed cities. Efforts of engineers to find suitable vehicles lead to apply advanced simulation tools to save time and financial costs for development of modern, reliable, comfortable and safe railway vehicles. The presented research was focused on creation of a suburban railway passenger wagon. A commercial simulation software was applied in the research. The main goal of the research was to analyse the critical running speed of the vehicle in a straight railway track as well as running safety in a curved track section. These observed output parameters were evaluated for two types of suspension system, for stiffer suspension parameters as well as for softer suspension parameters. It was found softer suspension parameters lead to slightly better running safety, because the wheelset has a more favourable position relative to the longitudinal track axis.

The maximal permissible value of the derailment quotient of 0.8 was not exceeded for any observed case.

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доц. Я. Діжо, інж. М. Бучко, доц. М. Блатницький, інж. П. Слушняк

ДИНАМІЧНИЙ АНАЛІЗ ПРИМІСЬКОГО ЗАЛІЗНИЧНОГО ТРАНСПОРТНОГО ЗАСОБУ

Залізничний транспорт вважають одним із найекологічніших і найефективніших видів транспорту. Ступінь розвитку інфраструктури залізничного транспорту часто відповідає рівню розвитку країни. Висока якість залізничного транспорту неминуча без високоякісних залізничних транспортних засобів, які працюють на залізничних коліях між пунктами призначення. Залізничний транспорт забезпечує перевезення пасажирів як на короткі, так і довші відстані. Моделювальні розрахунки є дуже важливими в процесі проєктування та аналізу ходових властивостей залізничних транспортних засобів.

Подане дослідження зосереджено на застосуванні симуляційних розрахунків для аналізу ходових властивостей приміського залізничного транспортного засобу. Це пасажирський вагон, призначений для експлуатації в певному місті. Проведені імітаційні розрахунки спрямовані на знаходження вибраних вихідних величин досліджуваного залізничного транспортного засобу. Ці параметри – критична швидкість і коефіцієнт сходу з рейок як критерій безпечної експлуатації транспортного засобу за розглянутих умов. Визначено критичну швидкість руху, за якої спостерігають бічні зміщення колісної пари. Коли амплітуди бічних коливань колісної пари стабільні, критичної швидкості не досягають. Момент стабільних і нестабільних бічних коливань колісної пари є визначальним для критичної швидкості руху. Іншим контрольованим параметром безпеки руху був коефіцієнт сходу з рейок. Коефіцієнт сходу з рейок спостерігали для першої і другої колісних пар у напрямку руху. Досліджено два рівні жорсткості системи підвіски. Виявлено, що м'якша система підвіски призводить до безпечнішого руху залізничного транспортного засобу в кривій. Допустиме значення коефіцієнта сходу з рейок не було досягнуто в жодному випадку.

Ключові слова: *залізничний транспортний засіб, система підвіски, багатотільне моделювання, динаміка транспортного засобу.*

Ján Dižo, Associate Professor, Philosophy Doctor, associate professor at the Department of Transport and Handling Machines, Faculty of Mechanical Engineering, University of Žilina. Tel.: +421 41 513 2650. E-mail: jan.dizo@fstroj.uniza.sk.

Martin Bučko, mechanical Engineer, PhD student at the Department of Transport and Handling Machines, Faculty of Mechanical Engineering, University of Žilina. E-mail: martin.bucko@fstroj.uniza.sk.

Miroslav Blatnický, Associate Professor, Philosophy Doctor, associate professor at the Department of Transport and Handling Machines, Faculty of Mechanical Engineering, University of Žilina. Tel.: +421 41 513 2659. E-mail: miroslav.blatnicky@fstroj.uniza.sk.

Partik Slušňák, mechanical Engineer, PhD student at the Department of Transport and Handling Machines, Faculty of Mechanical Engineering, University of Žilina. E-mail: patrik slusnak@fstroj.uniza.sk.

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