SIMULATION OF RAILWAY VEHICLE MOTION ON THE STRAIGHT TRACK

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Abstract

The article presents the methodologies based on multi-body systems used to analyze the dynamics of rail vehicle in motion in a straight line.

Study of the railway vehicles dynamics requires the creation of three mutually independent models: the model of the vehicle, the track model and a model of the wheel – rail contact.

A railway vehicle model developed in the multi-body systems convention was an electric locomotive of the EU07symbol.

The general software model of the wheel - rail contact was programmed and is presented, which allows one in the course of analysis to determine the coordinates of the contact point between wheel and rail and thus the designation of the wheels forces in contact with the rail.

The model of the contact forces includes normal force with damping hysteresis and tangential forces determined by the Polach method.

Developed models were implemented in Matlab program environment.

The numerical simulations were performed for the complete vehicle and a single bogie steady state conditions.

Keywords: *transport, motion simulation, railway vehicle*

1. Introduction

Recently, numerical methods of dynamic analysis of mechanical systems have become significantly more efficient and reliable, allowing making the description of dynamic phenomena occurring in them with increased complexity.

These models are a valuable tool in the design of vehicles, machinery or structures.

The usage of simulation models is applied both for a new transport solutions as well as previously operated vehicles.

Requirements associated with increased speed, improved comfort, carriage of cargo tonnage concern not only the newly designed but also existing vehicles.

Along with these requirements, one must verify the value of the forces resulting from the wheel - rail cooperation, which is related to maintaining vehicle stability in the new work conditions.

The simplified models of contact forces are not sufficient in calculations.

The complexity of physical phenomena accompanying the contact between the wheel - rail leads to the need of complex contact models, because the forces generated at the interface between these elements strongly influence the dynamic behaviour of the entire vehicle.

As well as the characteristics of the vehicle suspension, the masses of the elements, the track geometry and inequalities of the track play a key role in this case.

Consideration of all these phenomena requires the usage of advanced computer techniques in study focused on developing a realistic model of a rail vehicle and the exact characteristics of the wheel-rail contact phenomena.

2. Rail vehicle dynamic model

In the investigations of railway vehicles dynamics, processing of the whole vehicle movement and its basic elements is very important for the quality of the analysis.

This allows the designation of kinematic parameters of these elements and their interaction forces.

For the test of the dynamic interactions that occur at the interface between the track and the vehicle, for a rail vehicle analysis the electric locomotive with symbol EU07 (Fig. 1) was chosen.

Despite the awareness that it is „the aging” locomotive model, it was chosen because of easy access to technical documentation to allow replay in the virtual space of the essential features of the vehicle.

Thanks to that massive set of parameters, such as the masses and the moments of inertia and the distances between the individual elements of the vehicle which are useful in the construction of a physical model on the canvas of multiple body systems.

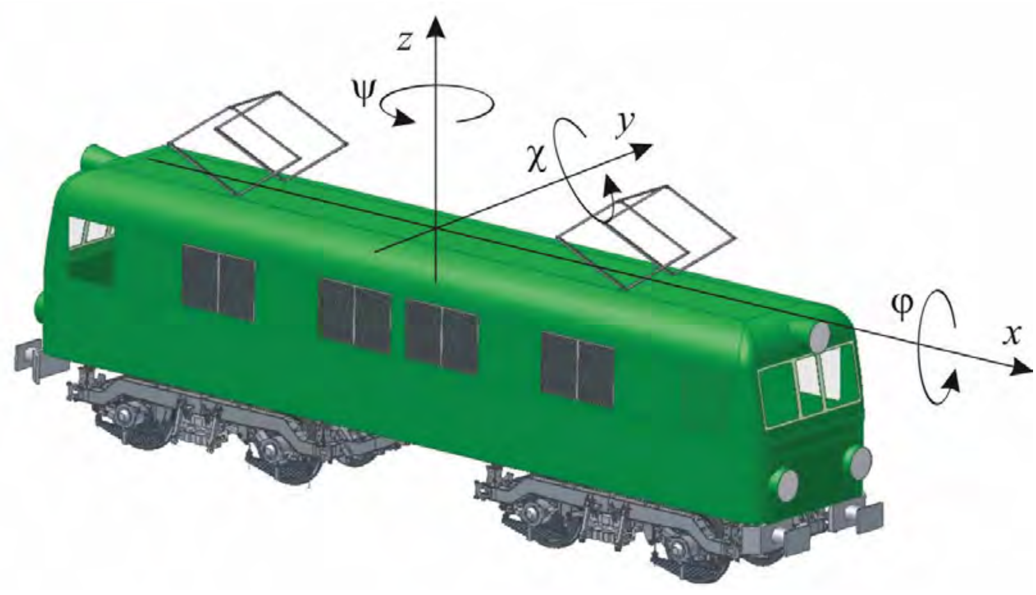

Fig. 1 Model of the vehicle created in Inventor program

The need for large precision of obtained solutions, user-friendly interface and powerful computational tools makes steady progress of advanced computing technologies.

Mechanical systems require a description of the elements motion, often realizing large movements, including complex interaction with the surrounding environment.

The use of formalism for multi-body systems understood as multiple-body systems interconnected by different types of kinematic pairs, and internal or external forces acting on it allows studying dynamic phenomena occurring in them.

To date a number of computer programs emerged to tackle these issues.

Most of them are programs that allow you to obtain and solve the dynamic equations of motion based on symbolic computation, or programs that perform numerical calculations on the basis of 3D-CAD models.

There are other programs of a more general application such as the programming environments based on block diagrams.

The last group includes Simulink / Simmechanics environment operating in MATLAB software system.

Simmechanics is a computer program that implements the theory of multi-body systems of rigid solids.

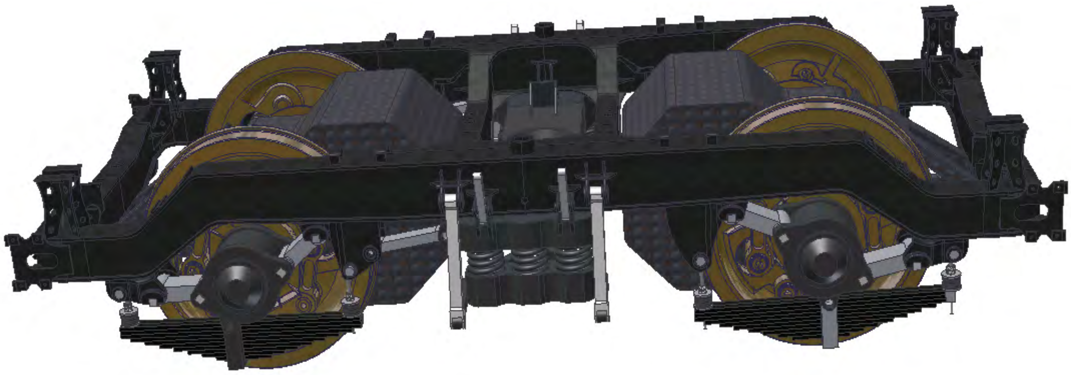

Fig. 2. CAD model of wheel bogie

Mechanical systems are represented in it by a combination of linked block diagrams.

These Simechanics blocks do not reflect mathematical functions directly but have specific physical meaning.

Models generated by this program consist of blocks of bodies, the connections between them in the form of kinematic pairs and elastic damping components, sensors, actuators.

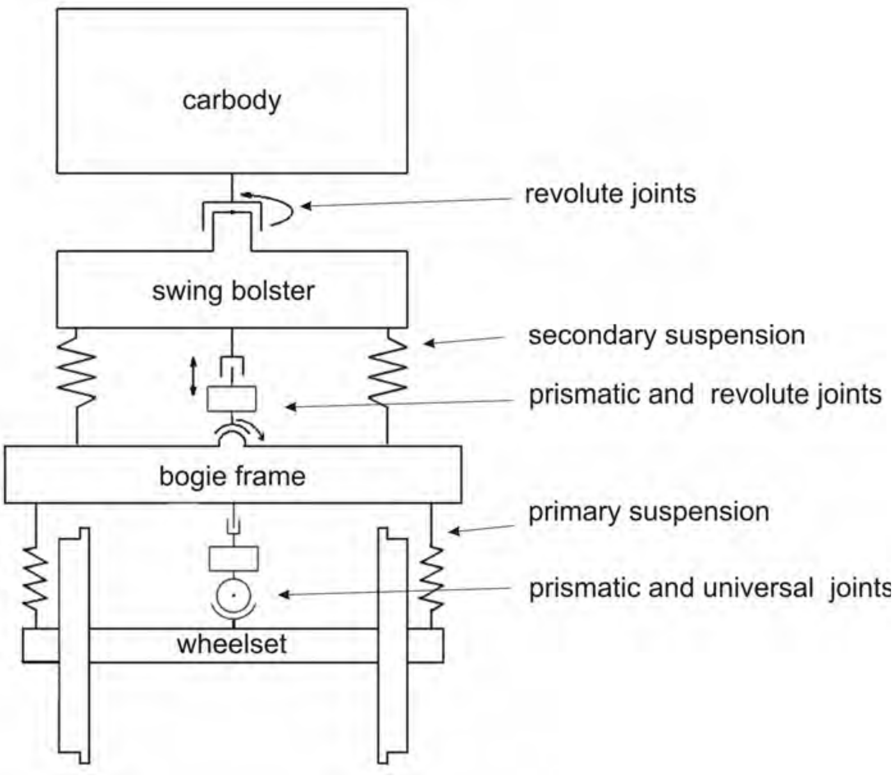

Fig. 3. Physical model of the vehicle under consideration

3D physical model based on analysis of the real system was developed to the necessary simplifications (Fig. 3) consisting of the vehicle body and two wheel bogie models, which reflects the basic features of the EU 07 rail vehicle.

The CAD model created in Autodesk Inventor was used to determine the mass parameters and the anchor points of elastic and linking elements (kinematic pairs), coupling individual elements of the vehicle.

Stiffness's of elastic components were obtained on the basis of the data contained in the technical documentation.

The physical model was implemented in Matlab/Simmechanics program receiving the model described in the multi-body system formalism, whereas the algorithm designating forces generated at the wheel – rail contact point was written in Matlab script [5].

This file in each integration step uses the solution coming from the vehicle model developed in Simmechanics (position, velocity, the transformation matrixes defining the location of local systems related to the individual model solids) to calculate the contact forces.

These forces are responsible for prop and proper traction of the vehicle and are, together with the other forces: gravity, centrifugal, inertia – the external forces acting on the model.

The computer program used to analyze the dynamics of a rail vehicle on the track implements the following algorithm:

a) Assumption of the initial conditions for the coordinates of the location $\mathbf{q}(t^0)$ and speed $\dot{\mathbf{q}}(t^0)$ and determination of the initial values of the surface parameters $s_r(t^0)$, $u_r(t^0)$, $s_w(t^0)$ and $u_w(t^0)$ associated with a particular wheel - rail pair.

The used contact model in formalism of the multi-body systems requires solving the wheel - rail interaction problem the definition in the parametric form of geometry surfaces in contact [1].

One requires satisfying the two demands for the applied surface equations.

First, the surfaces must be defined in a global reference coordinate system, since the equations of motion of multi-body system refer to the inertial coordinate system.

Secondly, the method of surface description is to be a general one, in the sense that its parametric equations must allow to submit unrestricted, spatial configuration of the wheel bogie and the rails for any profile of both wheel and rail.

The definition of contact surface geometry between the rigid wheel and rigid rail is based on four independent surface parameters [2].

For the description of rail surface geometry the parameters of this surface s_r and u_r were used while the s_w and u_w are parameters used to describe the surface of the wheel, as is shown in Fig. 1.

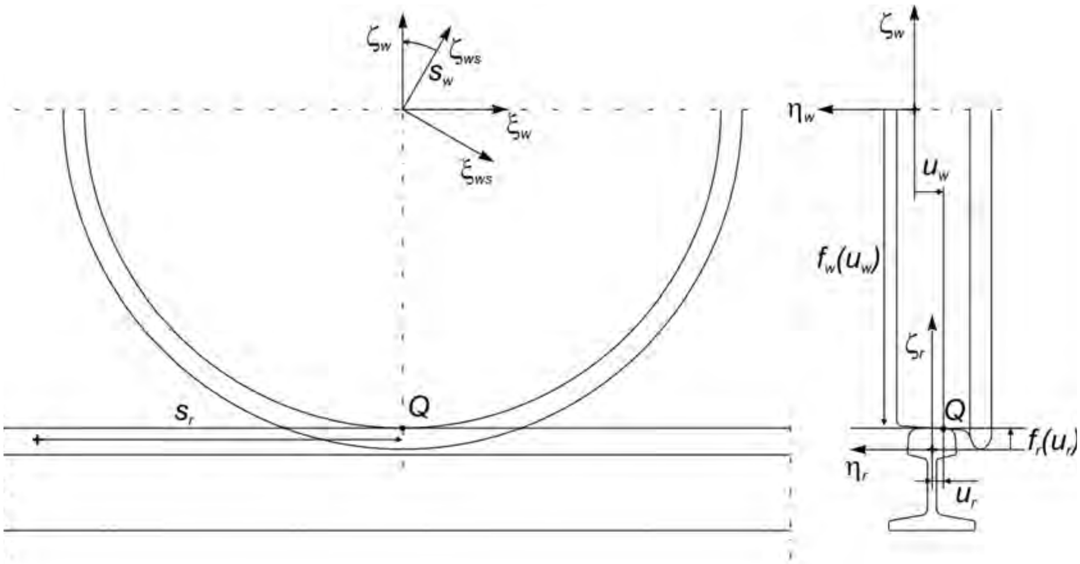

Fig. 4 The parameters used to describe the wheel and rail surfaces

Location of the vector radius at the point of contact Q in a coordinate system linked with the wheel or rail is a function of their surface characteristics only, defined as:

$$\mathbf{u}_l = \mathbf{u}_l(s_l, u_l) \quad ; \quad l = r, w, \tag{1}$$

b) The solution to the system of nonlinear equations to obtain the surface parameters that defines the coordinates of the points of contact of each wheel - rail pair.

c) Calculation of normal forces in contact, which are caused by the mutual wheel and rail interaction and the area of contact surface.

The most familiar model of the contact, which had been applied also in the railway industry is a model based on elasticity theory presented by Hertz.

In considering the situation in which contact between the two spheres (the wheel surface with the rail surface) is caused by a central collision, the spheres does not rebound with the same initial speed as the part of the initial kinetic energy is dissipated in the form of permanent deformation, heat, etc.

So, for obvious reasons Herzian model of contact forces cannot be used during both phases of contact, i.e. the compression and restitution, because that would imply lack of energy dissipation in the collision.

One of the approaches is based on the idea that the energy dissipation occurs in the form of internal damping of colliding solids.

This assumption is valid for small velocity collisions, i.e. collisions in which the collision velocity is neglected when you compare it to the speed of propagation of deformation waves travelling along the solid body.

Hertzian model of contact force is modified by introducing damping forces which leads to [3] to express it as:

$$N = K\delta^n + D\dot{\delta}, \tag{2}$$

where:

D - the damping coefficient,

$\dot{\delta}$ - is the indentation speed into the solid.

In this model, the total force is the sum of the forces expressed by the Hertzian component, which is a function of the indent, and the hysteresis damping component, which is proportional to the indentation speed.

d) The calculation of micro-slips and the calculation of micro-slips tangential forces and spin torques, which arise from the interaction between the wheel and the rail.

Hertz theory does not include shear interactions, however, in the investigations of wheel and rail contact phenomena they play an important role because they represent the shear stresses exerted by the wheel on the rail in the area of contact.

Polach's formula [4], is a model for designation of micro-slip force, which was implemented in a computer algorithm proposed in this work.

According to the Polach's method, longitudinal and lateral component of micro-slip force appearing in the wheel and rail contact area is determined as:

$$F_\xi = F\frac{\upsilon_\xi}{\upsilon_C} \quad ; \quad F_\eta = F\frac{\upsilon_\eta}{\upsilon_C} + F_{\eta S}\frac{\phi}{\upsilon_C}, \tag{3}$$

where F is the contact tangential force caused by longitudinal and transverse micro-slip, υ_C is modified translational micro-slip, which takes into account the effect of spin, and $F_{\eta S}$ is the lateral tangential force caused by spin.

Polach's algorithm requires as input the micro-slip values υ_ξ, υ_η and ϕ, the contact normal force N, a half axes of contact ellipse *a* and *b*, the combined transverse modulus of the wheel and the rail *G*, the coefficient of friction μ and micro-slip Kalker's and spin c_{ij} coefficients.

As a result, the algorithm calculates the value of the micro-slip force components F_ξ, F_η.

e) Addition of the contact forces and moments, associated with each wheel, to the vector of external forces acting in the system.

Application of multi-body system formalism to obtain the solution of the new system position and velocity for the next time step $t + \Delta t$.

f) Upgrade the system for the next moment of time by assuming the starting data from the previous step to determine the surface parameters associated with each wheel - rail pairs.

g) Continuing the whole process for a new time step to reach the final time of the performed analysis.

Detailed dependencies used for the calculation performed in points of a-g of the presented algorithm can be found in [1-4].

3. Numerical simulations

Simulations were carried out for a rail vehicle and for comparative purposes for a single wheel bogie of the EU07 locomotive.

The movement in a straight line at a constant speed of 10 m/s at initial excursion from the track centre line of 0.002 m was assumed.

The parameters and geometry of the wheel bogie and the rail were assumed for the new elements.

As a result of the performed simulation the waveforms were obtained for the change of the vehicle centre of gravity and a single wheel bogie as a function of travelled distance (Fig. 5-6) and the changes of lateral forces with a prominent place where the wheel flange contacted with the rail (Fig. 7).

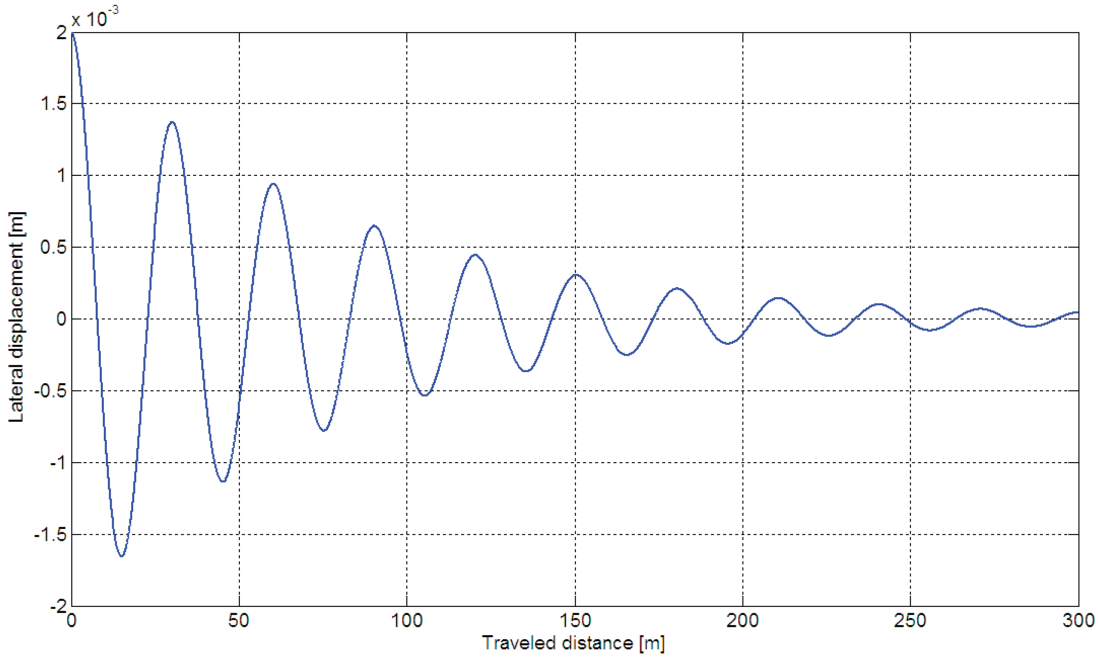

Fig. 5. Lateral displacement of the front wheelset for vehicle forward velocity of 10 m/s

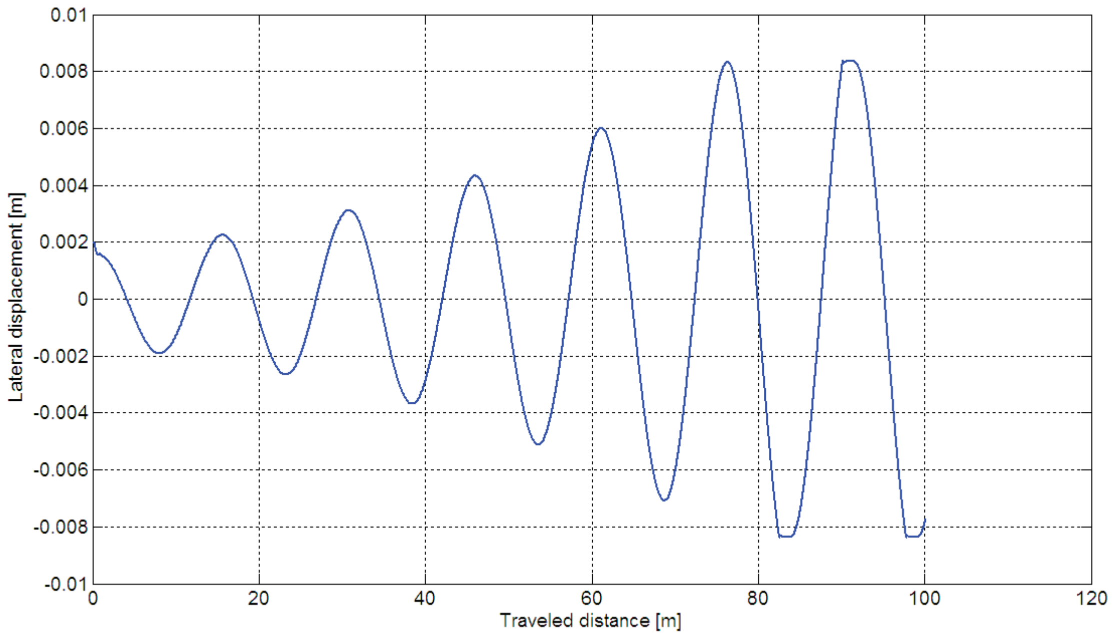

Fig. 6. Lateral displacement of the vehicle wheelsets for a forward velocity of 10 m/s

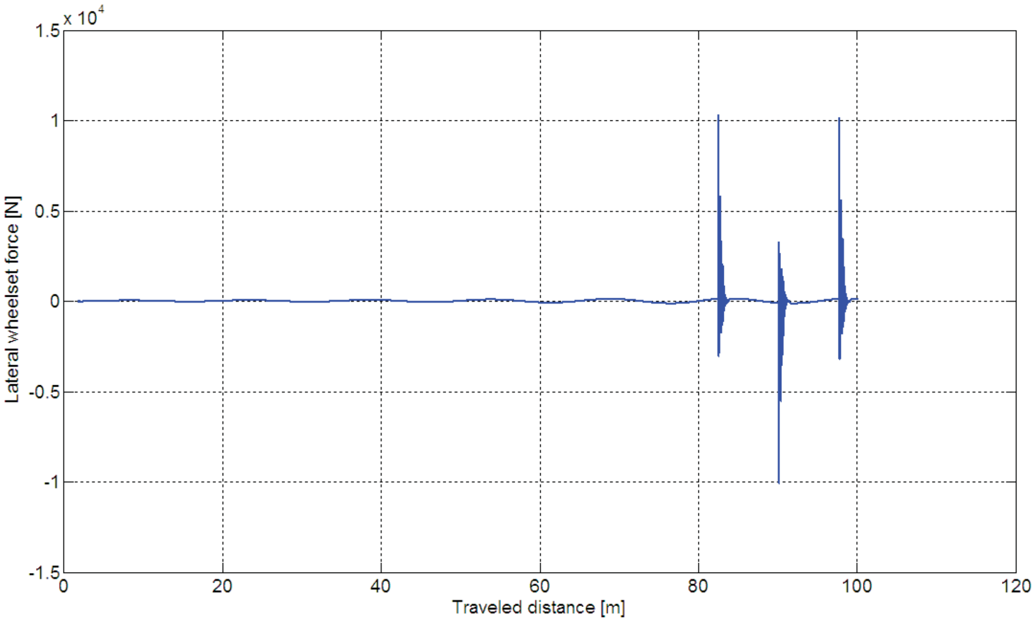

Fig. 7. Lateral contact force on wheelset for a forward velocity of 10 m/s

4. Conclusion

The paper presents a computer tool to study the dynamic behaviour of rail vehicles in movement on the track.

For this purpose the computer programs have been developed in Matlab / Simulink environment.

To take into account all the relevant characteristics of railway vehicles, a dedicated software package was also developed for the construction of the model of the nominal railway track including track irregularities.

Paper presents a programmed general model of the wheel - rail contact which helps to determine in the course of performed analysis the coordinates of the points of contact between wheel and rail.

The used model not only allows the identification of multi-point contact (Fig. 8) but also allows for efficient and accurate calculation of the mutual interaction forces between wheel and rail.

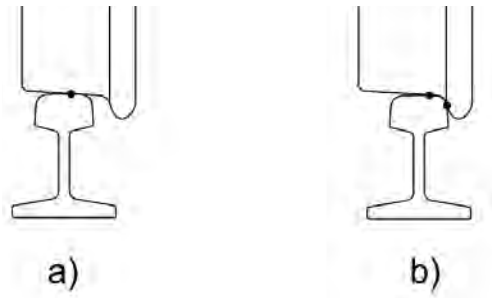

Fig. 8. Different types of contact between wheel and rail: a) tread contact – one point of contact; b) flange contact – two points of contact

According to the theory of stability of rail vehicles, a single wheel bogie is always unstable in its motion on the track.

When moving in a straight line with an initial transverse deflection with respect to the centre line of the track, its serpentine movement increases until the flange contacts, in terms of the analyzed example, about 8 mm (Fig. 6) and consequently for higher speed traffic can lead to derailment the wheel bogie due to the higher values of forces from micro-slips or spin

For the railway vehicle this phenomenon manifests itself at very high speed, so called critical velocity.

As shown in Fig. 6 as a result of the wheel flange contact with the rail, the lateral forces are increasing rapidly.

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