APPLICATION OF SENSITIVITY ANALYSIS IN DESIGN OF CHARACTERISTICS OF DAMPING JOINTS IN LOCOMOTIVE RUNNING GEAR

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Operation of railway vehicles at higher speeds is conditioned by assurance of a stable run of the vehicle in straight track with a high level of geometric parameters. This property is usually reached by retrofitting of a joint between the vehicle body and the bogies with an efficient damping with suitable characteristics. As the relative motion between the vehicle body and the bogies in the straight track shows low amplitudes and high velocities, special longitudinal dampers – so-called yaw dampers – are used for these purposes. The aim of this paper is a theoretical analysis of influence of yaw dampers characteristics on the stability limit of a locomotive performed by means of sensitivity analysis.

Keywords : *sensitivity analysis, stability of vehicle run, critical speed, yaw dampers, simulations*

1. Introduction

Nowadays, computer simulations of running and guiding behaviour create an integral part of development of new or modernized rail vehicles. The simulations are practically the only possible way how to verify the dynamic properties of the vehicle in its design stage. It is possible to use them for optimization of suspension and damping parameters, as well. The parameters of suspension and damping elements (stiffness of the primary and secondary springs and the wheelset guiding, characteristics of the hydraulic dampers) influence the dynamic behaviour of the rail vehicles very significantly. Therefore, the computer simulations are often used especially for assessment of the influence of these parameters on lateral force interaction between the rail vehicle and the track in curves and on the stability of run at higher speeds in a straight track. Requirements on these properties of railway vehicles (lateral force interaction in curves and stability of run in straight track) are defined in relevant standards (see [1]) and the vehicles must fulfill them. In case of damping joints, the yaw dampers have probably the most important effect on the running behaviour of the vehicle. The computer simulations allow assessment of suitability of suggested characteristics of these dampers and possibly their optimization.

In years 2010 to 2012, the Jan Perner Transport Faculty of the University of Pardubice co-operated with the company CZ LOKO, a.s. on solving of R&D project 'TIP' of the Ministry of Industry and Trade of the Czech Republic; the aims of this project were manufacturing a prototype of a locomotive Class 744.0 as well as preparation of a broad-gauged

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version of this locomotive according to the GOST standards. The computer simulations of dynamic behaviour of the new locomotive created one of the main parts of the project. This paper deals with theoretical methods of stability assessment of the railway vehicles and the computational model of the locomotive Class 744.0 is used for demonstration of application of one of these methods, as well.

2. Locomotive Class 744.0 CZ LOKO

The locomotive Class 744.0 CZ LOKO (see fig. 1) is a four-axle diesel-electric locomotive with an electric – AC/AC or AC/DC – power transmission which is intended for track as well as shunting service. A modular conception of the locomotive allows manufacturing various versions with a maximum power of a Caterpillar combustion engine from 800 up to 1500 kW. The traction drive is assured by means of four asynchronous or serial direct-current axle-mounted nose-suspended traction motors with roller bearing. Each of these motors belongs to one wheelset and has the maximum power of 360 kW. The maximum speed of the locomotive can be up to 120 km/h.

The main frame of the locomotive is mounted on two-axle bogies (see fig. 2) by means of four flexi-coil springs per bogie. The longitudinal force transmission between the bogie and the locomotive body is performed by the central pivot. The wheelset guiding in the bogie frame is performed by means of the connection rods and primary suspension is created by two flexi-coil springs at each axle box. The vertical (primary as well as secondary) suspension is supplemented with hydraulic dampers; damping of lateral oscillations between the vehicle body and the bogies is performed by two lateral hydraulic dampers per bogie. An example of more detailed description of the new CZ LOKO bogie is given in [2].

Besides the locomotive for European track gauge 1435 mm, a broad-gauged version of the locomotive for the Eastern market is developed parallelly. This locomotive, which comes out from the standard-gauged locomotive to a maximum degree, is intended for the 'Russian' track gauge 1520 mm and is designed according to the GOST standards. Besides indispensable modifications of the bogie frames and usage of new wheelsets, it is necessary to modify parameters of the suspension (because of the intended total weight of the locomotive from the range of 80 up to 90 t) and to verify the influence of these modifications on dynamic behaviour of the locomotive.

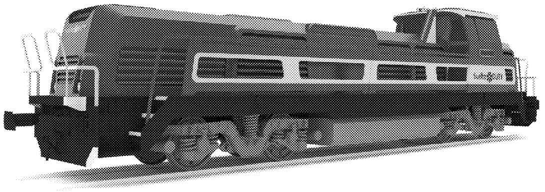

Fig.1: Visualization of the Class 744.0 CZ LOKO

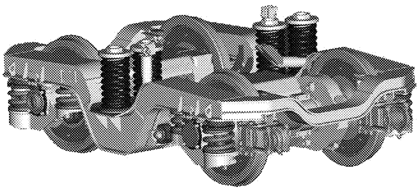

Fig.2: The new CZ LOKO bogie

3. Simulations of dynamic behaviour of the locomotive

Computer simulations of dynamic behaviour of the new locomotive are performed by means of a multi-body simulation software 'SJKV', which is being developed at the Detached Branch of the Jan Perner Transport Faculty of the University of Pardubice in Česká Třebová. A brief description of the simulation software 'SJKV' is given in [5] or [7], for example.

Many simulations of various versions of the new locomotive Class 744.0 CZ LOKO have been already performed. The first simulation results of the broad-gauged version of the locomotive were presented in paper [9]. The simulation input data were specified on the basis of current documentation and measurements of real parameters of the locomotive suspension (see paper [10]). An investigation of the influence of relevant parameters change, which is related to the modification of the locomotive for the broad track gauge was also performed, and its results were presented in paper [3]. In paper [4], an influence of unsprung masses in the locomotive running gear on the dynamic interaction between the vehicle and the track was investigated, as well.

The main input parameters of the dynamic model of the locomotive (i.e. mass and geometric parameters, characteristics of elastic and damping joints etc.) were determined with the project documentation, and they are being specified gradually during the development and subsequent manufacturing of the locomotive. However, not only the constructional parameters of the locomotive but also the characteristics of the wheel/rail contact geometry have a substantial influence on the dynamic behaviour – i.e. so-called running behaviour in a straight track and guiding behaviour during the run through a curve. The characteristics of the wheel/rail contact geometry, which are determined by shapes of wheel and rail profiles, rail inclination, track gauge and wheel back-to-back distance, characterize a geometric joint between the wheelset and the track. In this stage, the simulations of run of the locomotive Class 744.0 CZ LOKO were performed for two different sets of characteristics of the wheel/rail contact geometry which are characterized with values of so-called equivalent conicity of $\lambda_{\text{eq}} = 0.207$ (theoretical wheel profiles and rail profiles 60E1/1:40) and $\lambda_{\text{eq}} = 0.403$ (operationally worn wheel and rail profiles). In fig. 3, curves of the delta-r function and function of the equivalent conicity for three different sets of the wheel/rail contact geometry are shown as an example. The delta-r function describes a dependency of the roll radius difference of a wheelset on its lateral displacement in the gauge clearance and the equivalent conicity function defines a dependency of the wave length of the wave motion of a free wheelset on the amplitude of this motion. The curves depicted in fig. 3 demonstrate that a different measure of wear of the wheel profiles as well as the rail inclination can influence these characteristics very significantly. Next, the relevant wheel/rail contact geometry will be always (in a simplified way) named by means of value of the equivalent conicity for the wheelset amplitude $y_0 = 3\,\text{mm}$, as it is usual in the railway branch.

From the point of view of the vehicle dynamics, the locomotive is a complicated non-linear dynamic system. Therefore, a sensitivity analysis can be used for purposes of determination

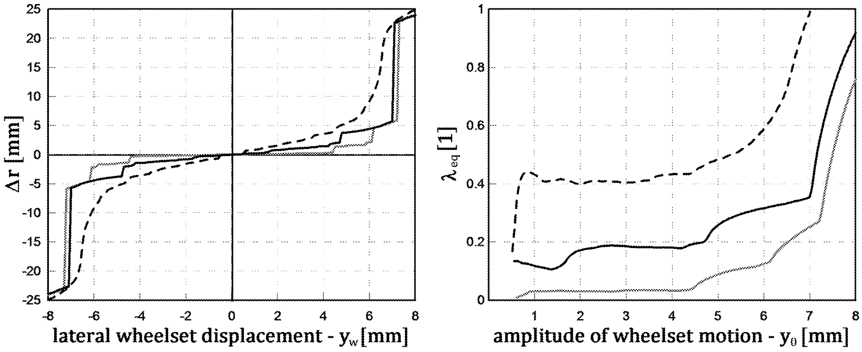

Fig.3: Characteristics of the wheel/rail contact geometry

of influence of different input parameters on dynamic behaviour of the locomotive. The sensitivity analysis allows gaining an image which describes a qualitative behaviour of such complicated system (locomotive) with respect to variable input parameters. One of the most important parameters of a rail vehicle from the point of view of its running behaviour in a straight track (especially at higher speeds) is the critical speed. The critical speed represents the maximum speed at which the rail vehicle shows so-called stable run, i.e. running behaviour without lateral oscillations of wheelsets, bogies and the vehicle body. The value of the critical speed is influenced by many parameters, and exceeding this speed can lead to exceeding safety limits of the vehicle run (see standard [1]) as well as the degradation of the ride comfort. For the purpose of the sensitivity analysis of the locomotive Class 744.0 various weight variants were considered. Besides that, the influence of some other parameters was observed, above all, the equivalent conicity (i.e. the wheel/rail contact geometry), the friction coefficient in the wheel/rail contact, and the influence of yaw dampers.

4. Assessment of stability of run of the locomotive

For the purpose of the assessment of the stability of vehicle run (i.e. determination of the critical speed of the vehicle), several methods are usually used. The aim of the stability assessment is to determine a bifurcation diagram which usually shows the dependency of the amplitude of lateral oscillations of a wheelset on the vehicle speed. In dependency on input parameters of the dynamic model (especially on characteristics of the wheel/rail contact geometry and characteristics of elastic and damping joints), two basic types of the Hopf bifurcation [6] – subcritical Hopf bifurcation and supercritical Hopf bifurcation – can occur. The general shapes of relevant bifurcation diagrams are shown in fig. 4. At the subcritical Hopf bifurcation, the oscillations disappear suddenly at the decreasing vehicle speed; at the supercritical Hopf bifurcation, there is a speed range, in which the wheelset amplitude gradually decreases with decreasing speed. In case of supercritical Hopf bifurcation, a speed range, where the wheelset oscillations show unstable limit cycle does not exist. Problems of the stability assessment are discussed in detail in the work by Prof. Polách – see [6].

In the next, the stability analysis of a rail vehicle is demonstrated using the following three various methods:

- simulation of the vehicle run on an ideal track at a decreasing speed,
- simulation of the vehicle run on an ideal track at a constant speed,
- simulation of the vehicle run on a real track with irregularities.

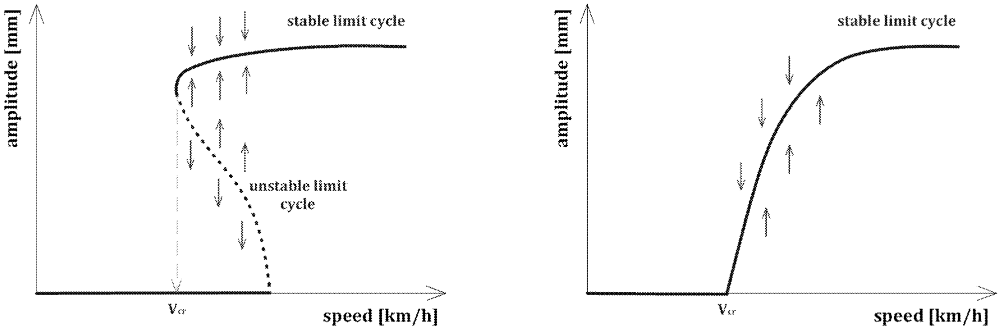

Fig.4: Bifurcation diagrams for subcritical (left) and supercritical (right) Hopf bifurcation [6]

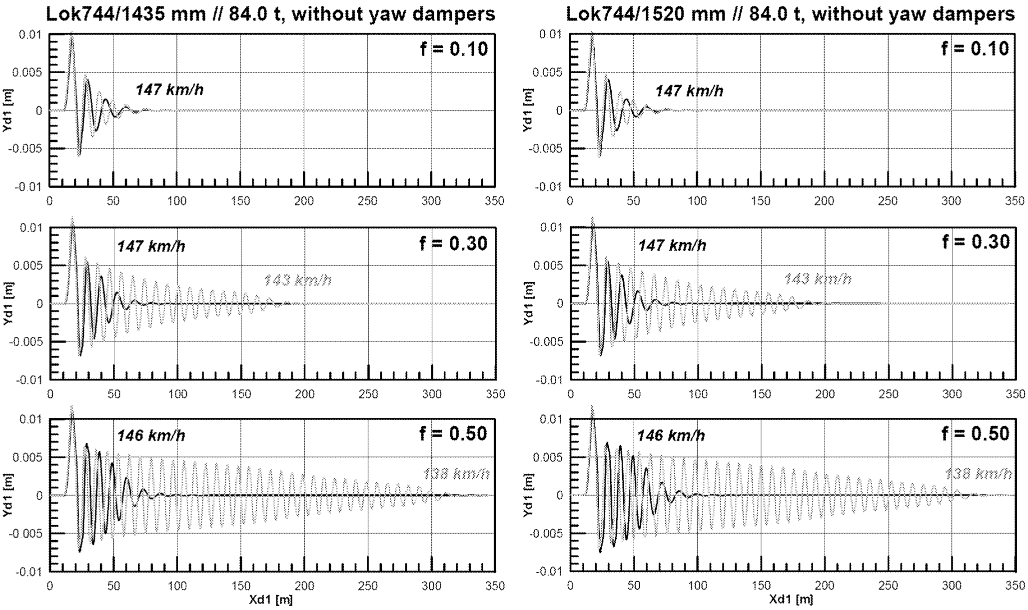

Fig.5: Lateral motion of the first wheelset after excitation on the ideal straight track for the standard- (left) as well as broad-gauged (right) version of the locomotive with the total weight of 84 t, without yaw dampers, for various friction coefficient and various contact conditions (decreasing speed; grey – $\lambda_{\mathrm{eq}} = 0.403$*, black –* $\lambda_{\mathrm{eq}} = 0.207$*) [3]*

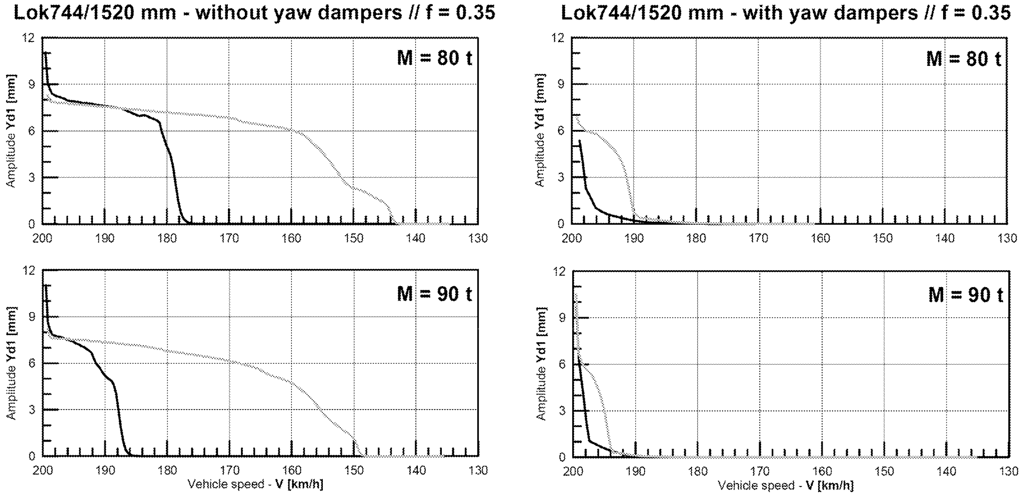

Fig.6: Amplitude of the lateral motion of the first wheelset after the excitation on the ideal straight track for various total weight of locomotive and various contact conditions (decreasing speed; value of a friction coefficient in the wheel/rail contact: 0.35; grey – $\lambda_{\mathrm{eq}} = 0.403$*, black –* $\lambda_{\mathrm{eq}} = 0.207$*) [3]*

If the first method (i.e. the simulation of the vehicle run on an ideal track at a decreasing speed) is used, the dynamic model of the locomotive is excited by means of an isolated lateral track unevenness at a high speed at first. Then the vehicle runs on an ideal straight track and it decelerates in the consequence of acting of a longitudinal force, which is applied on the vehicle body. During the simulation, lateral oscillation of the wheelsets is observed. This method was used in case of the stability analysis of the locomotive Class 744.0; in fig. 5, the behaviour (lateral motion) of the first wheelset of the standard-gauged as well as the broad-gauged locomotive with a total weight of 84 t under the conditions of various friction coefficients and the wheel/rail contact geometry is shown. In this case, the excitation of the vehicle was performed at the speed of 150 km/h. The envelope curve of the lateral wheelset motion (see fig. 5) can be used as the bifurcation diagram; it is only necessary to transform it into a dependency on the vehicle speed. Bifurcation diagrams for the broad-gauged version of the locomotive with total weight of 80 t and 90 t, which were obtained in this way, are shown in fig. 6; the simulations were performed for the locomotive both without yaw dampers and with them, and the initial speed, at which the vehicle was excited, was higher – 200 km/h.

The second way, how to investigate the stability of the run of a rail vehicle, is the usage of simulations of the run on the ideal straight track at a constant speed. After excitation of the vehicle by means of isolated lateral track unevenness, the lateral wheelset motion stabilizes in a steady state which is characterized with its amplitude. The qualitative change of the dynamic behaviour at some parameter change can be presented by means of bifurcation diagrams again. In comparison with the first method, the bifurcation diagrams, which were obtained in this way, are more exact – especially in the neighbourhood of the critical speed, i.e. on the stability limit. If the first method (simulation on an ideal track at the decreasing speed) is used, the unstable solution cannot be found in the case of the subcritical Hopf bifurcation. For better clearness the second method is demonstrated on the example of an electric locomotive – see also paper [8]. In fig. 7, the simulation results (i.e. lateral motion of the first and third wheelset of the locomotive) at different speeds for concrete conditions, which are given by the wheel/rail contact geometry ($\lambda_{\text{eq}} = 0.033$) and characteristics of yaw dampers (signed as 'Os4', in this case) are shown. In fig. 8, the relevant bifurcation diagrams (i.e. dependencies of amplitudes of the lateral motion of the first and third wheelset on the vehicle speed) for the concrete wheel/rail contact geometry

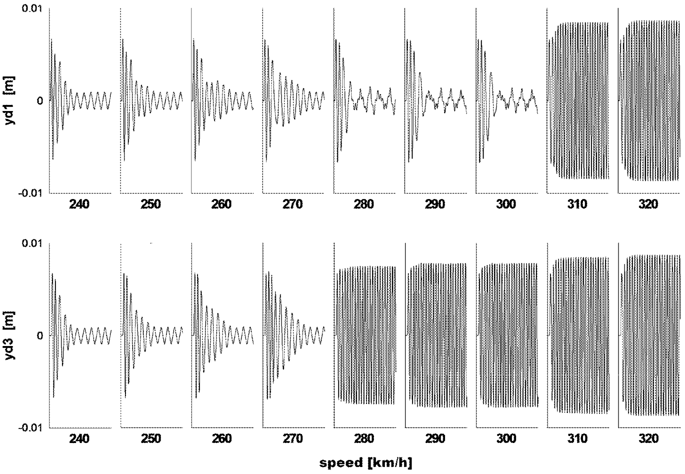

Fig.7: Lateral motion of the first (top) and third (bottom) wheelset of investigated electric locomotive for concrete conditions given by the wheel/rail contact geometry and characteristics of yaw dampers at various speeds [8]

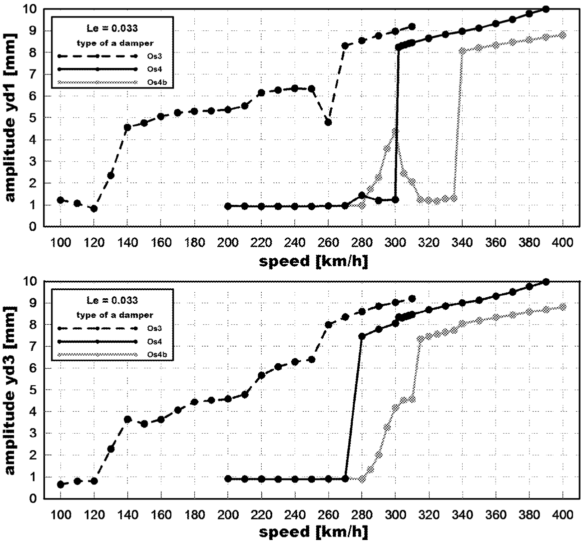

Fig.8: Bifurcation diagrams – amplitudes of the first (top) and third (bottom) wheelset of the investigated electric locomotive for the concrete wheel/rail contact geometry and various characteristics of yaw dampers [8]

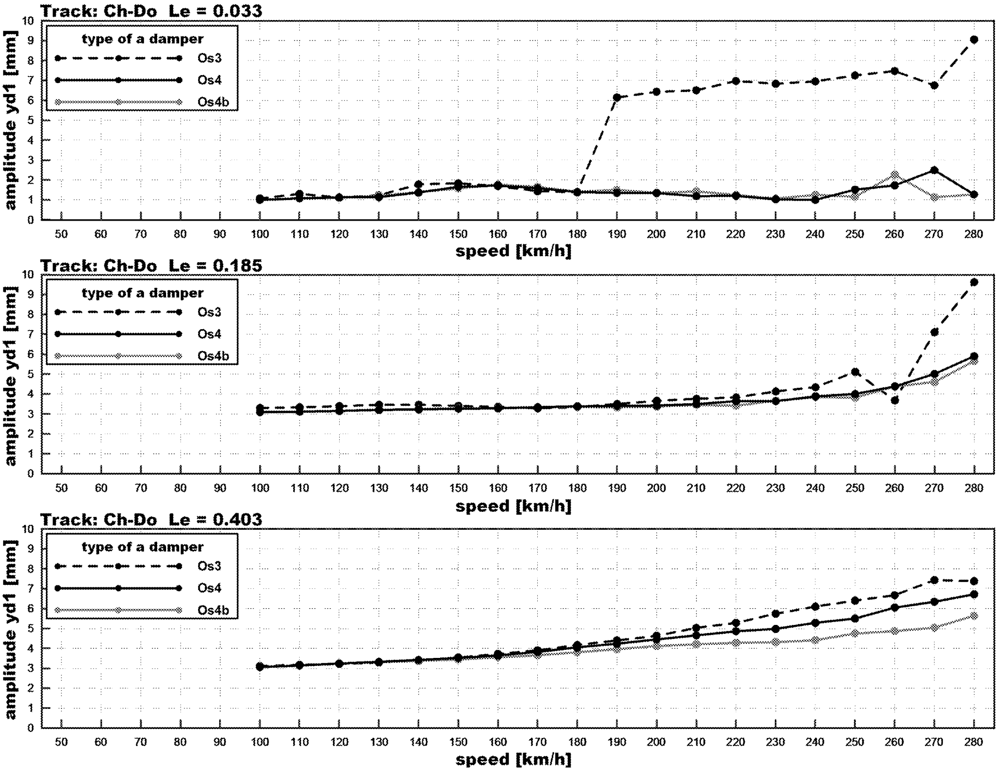

Fig.9: Stability assessment performed by means of simulations on a real track – 99.85 % quantiles of amplitudes of lateral motion of the first wheelset for various characteristics of yaw dampers and various conditions of the wheel/rail contact geometry [8]

($\lambda_{\mathrm{eq}} = 0.033$) and for various characteristics of yaw dampers are presented. It is evident that the characteristics of the yaw dampers can influence the dynamic behaviour of the whole locomotive very significantly; it can even change the type of the Hopf bifurcation. Besides the yaw dampers, the characteristics of the wheel/rail contact geometry can influence the stability of the run (the critical speed) very significantly as well – this is also evident from the previous example of the locomotive Class 744.0 CZ LOKO; see fig. 6.

The third mentioned method uses simulations of the vehicle run on a real straight track (i.e. track with irregularities) for the stability assessment. Similarly to the previous method, the investigated rail vehicle runs at a constant speed and the lateral motion of wheelsets is observed again. However, a statistical assessment has to be used in this case, because the motion of the wheelsets (and the whole vehicle) is influenced by means of the track irregularities. In fig. 9, an example of such stability assessment of an electric locomotive (see also paper [8]) is shown; values of the amplitudes, which are presented is the graphs, were calculated as a 99.85 % quantile of the lateral motion amplitude of the first wheelset. All the calculations were performed on the track with measured irregularities (signed as 'Ch-Do'); influences of various characteristics of the yaw dampers (signed as 'Os3', 'Os4' and 'Os4b'), and various characteristics of the wheel/rail contact geometry on running behaviour of the vehicle were investigated in this case.

5. Conclusions

This paper deals with the application of sensitivity analysis at the assessment of the dynamic behaviour of railway vehicles by means of computer simulations. By means of the sensitivity analysis, many different parameters, and above all an influence of their changes on the dynamic behaviour of the vehicles can be observed in the design stage of these vehicles. In this way, the computer simulations of running and guiding behaviour allow the optimization of design and properties of some important constructional parts of newly developed vehicles.

An application of bifurcation diagrams at stability analysis is presented, and three possible methods of stability assessment are described and shown on concrete examples. The method of simulation of the vehicle run on an ideal straight track with isolated lateral unevenness at the decreasing speed is presented on an example of the new diesel-electric locomotive Class 744.0 CZ LOKO, which is being developed in co-operation of the Jan Perner Transport Faculty and the company CZ LOKO. By means of the sensitivity analysis, the influence of the total weight of locomotive, application of the yaw dampers into the running gear, various conditions of the wheel/rail contact geometry as well as various values of the friction coefficient in the wheel/rail contact at the critical speed were observed. In all cases, the critical speed seems to be higher than the intended maximum speed of this locomotive. Besides that, two other methods of the stability analysis were presented on example of an electric locomotive in chapter 4 as well. Both methods use simulations of vehicle run on a straight track at constant speed. However, one of them uses an ideal track without irregularities and the other one uses a real track. These methods are used for purposes of assessment of influence of the yaw dampers characteristics and the wheel/rail contact geometry on dynamic behaviour of the investigated locomotive at the stability limit.

In the next stage, authors will deal with an analysis of the influence of other simulation input parameters on dynamic behaviour of rail vehicles. Areas of sudden increase of amplitudes of lateral oscillations of the wheelsets in bifurcation diagrams – i.e. the dynamic behaviour of the vehicle at the stability limit – will be observed for purposes of acquisition of a more detailed image of the dynamic properties of the whole non-linear dynamic system of the rail vehicle. The knowledge, which will be obtained in this way, will be used for verification of the dynamic behaviour of several types of rail vehicles, subsequently.

Acknowledgement

This work was supported by R&D project No. FR-TI2/562 'Research and Development of a Modular Four-axled Locomotive' of the Ministry of Industry and Trade of the Czech Republic.

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Received in editor's office: October 1, 2012
Approved for publishing: October 10, 2013