18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012

pp. 879–887
Paper **#193**

DYNAMIC BEHAVIOUR OF LOCOMOTIVE WITH AXLE-MOUNTED TRACTION MOTORS

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Abstract: *Especially in case of locomotives for freight operation, nose-suspended traction motors are usually used nowadays. This solution of traction drive is simple and relatively cheap; however, because of bearing of the traction motors directly on the axles, this solution contributes to increase the unsprung masses with all negative influences on dynamic interaction between the rail vehicle and the track, as well. Therefore, this paper deals with influence of nose-suspended traction drive of a locomotive on the dynamic interaction between the vehicle and the track. By means of simulations, dynamic behaviour of the locomotive with axle-mounted traction motors is compared with dynamic behaviour of a locomotive equipped with fully suspended traction drive.*

Keywords: ***Nose-suspended traction motor, dynamic interaction vehicle–track, simulations.***

1. Introduction

In framework of solving of R&D project "TIP" of the Ministry of Industry and Trade of the Czech Republic in years 2010–2012, Jan Perner Transport Faculty of the University of Pardubice co-operates with company CZ LOKO, a.s. at research and development of a new modular four-axled diesel-electric locomotive Class 744.0. Among others, computer simulations of running and guiding behaviour of the new locomotive are realized at Detached Branch of the Jan Perner Transport Faculty in Česká Třebová. Nowadays, the computer simulations create an integral part of development of new railway vehicles and allow assessing of dynamic behaviour of these vehicles in design stage and possibly optimizing of some parameters, as well. This work deals with dynamic interaction between the locomotive, which is equipped with axle-mounted nose-suspended traction motors, and the track. By means of simulations, dynamic effects of run of the locomotive equipped with nose-suspended traction motors are compared with a locomotive with fully suspended traction drive.

2. Locomotive Class 744.0

The locomotive Class 744.0 is a four-axled diesel-electric locomotive for shunting as well as track service which is equipped with new CZ LOKO bogies. These bogies are two-axled with wheel base of 2400 mm; each wheelset is driven by axle-mounted nose-suspended asynchronous traction motor TAM 1084 C6. Wheelset guiding is performed by means of connecting rods; primary as well as secondary suspension is realized by means of flexi-coil springs. Traction and breaking forces between the bogie frame and the vehicle body are transmitted by means of a central pivot. The wheelsets are equipped with a disc brake; the brake discs are mounted into the wheels. Detailed description of the new bogie is given for example in the paper (Kopal, 2009).

The locomotive Class 744.0 can be produced in various versions with a power of 800 up to 1500 kW and maximum speed up to 120 km/h. Total weight of a standard-gauged version of the locomotive can range from 64 up to 90 t. Besides the standard-gauged version, a broad-gauged version of the locomotive, which is designed according to the GOST standards, is being prepared for the track gauge 1520 mm, as well. Nowadays, a prototype of the standard-gauged version of the locomotive 744.001 is tested in framework of its authorisation process.

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3. Dynamic model of the locomotive

For purposes of computer simulations of dynamic behaviour of the locomotive, an original program system "SJKV" for multi-body simulations was used. This program system is being developed at the Detached Branch of the Jan Perner Transport Faculty in Česká Třebová and allows creating of various modifications for concrete rail vehicles. Detailed description of the program system "SJKV" is given in the paper (Zelenka, 2009). In framework of solving the R&D project "TIP", a new version of the program system named "SJKV-Lok744" was created. This modification of the program system allows investigation of dynamic behaviour of the standard-gauged as well as broad-gauged version of the locomotive Class 744.0 CZ LOKO; see also papers (Zelenka & Michálek, 2011; Kohout et al., 2011).

Because of time requirements and numerical stability of computations it is useful to consider only the important bodies (i.e. the bodies with a big weight) in the multi-body simulations. Therefore, dynamic model of the locomotive consists of seven rigid bodies: four wheelsets, two bogie frames and vehicle body. The other components are reduced to these "basic" bodies. Each rigid body of the dynamic model has 6 degrees of freedom and is defined by means of its mass, inertia moments as well as position of the centre of mass. Constituent bodies of the dynamic model are coupled by means elastic and damping joints which represent springs, dampers, elements of the wheelset guiding, bump stops etc. A schema of the dynamic model of the locomotive is shown in fig. 1.

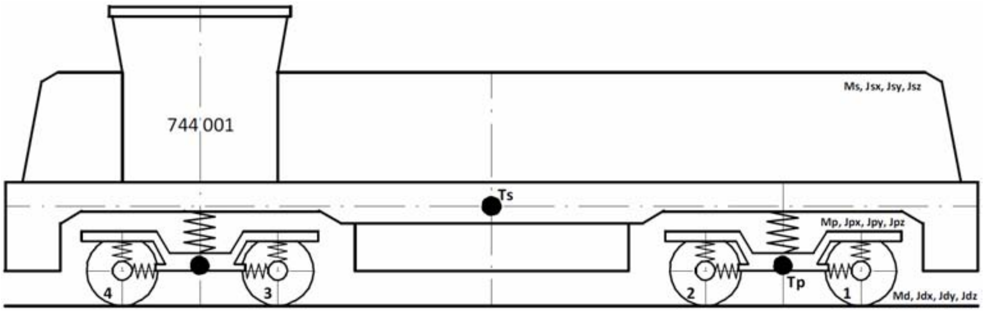

Fig. 1 Schema of dynamic model of the locomotive Class 744.0 CZ LOKO.

Besides to that, dynamic model of the track is created with reduced masses of rails which belong to each of wheels; these rails are coupled with the base by means of elastic and damping joints. For purposes of the simulations, wheel/rail contact is described by means of characteristics of wheel/rail contact geometry and it is considered as a one-point contact. Numerical solution of the model (i.e. solution of equations of motion) is based on finite differences method; see also the paper (Michálek & Zelenka, 2011), for example.

As it was stated above, the dynamic model of the locomotive is created only with seven "basic" rigid bodies and all the other elements have to be reduced to these bodies. Reduction of springs, dampers, elements of wheelset guiding etc. is relatively simple because of their mass which is very small in comparison with the "basic" bodies – i.e. vehicle body, bogie frames and wheelsets. However, reduction of components of the traction drive can be more problematic. In case of a fully suspended traction drive (for example drive with a hollow shaft), the traction motor including gearbox is fastened on the bogie frame and therefore we can suppose that the motor and bogie frame make a whole, i.e. one rigid body. However, the locomotive Class 744.0 is equipped with axle-mounted nose-suspended traction motors. Construction of the nose-suspended traction motor is very simple; the motor is mounted directly on the wheelset (by means of so-called nose bearings) and on the opposite side it is suspended on the bogie frame (by means of a flexible joint). A schema of the nose-suspended traction drive with rolling nose bearings is shown in fig. 2. The greatest advantage of the axle-mounted nose-suspended traction drive is just the simplicity and related lower price; therefore, this solution is often used on locomotives for freight operation. The greatest disadvantage of the nose-suspended traction motors is the fact that approximately 60 up to 80 % of the mass of the traction motor (including the gear transmission) creates unsprung masses; it is related with the three-point bearing of the traction motor on the wheelset and bogie frame. However, because of requirement on invariable position of the gearwheels (and the constructional solution – see fig. 2), the whole mass of the traction motor creates the unsprung mass in lateral direction. And it is generally known that a share of the unsprung masses has a significant influence on the dynamic interaction between the vehicle and the track.

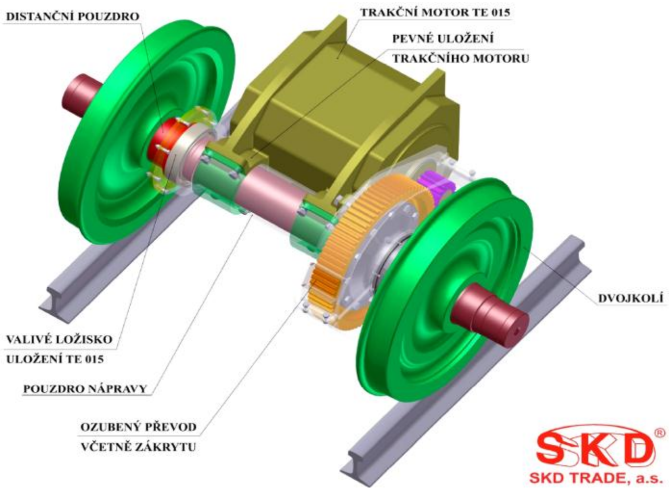

Fig. 2 Nose-suspended traction motor (Šlitr, 2007).

In framework of this work, two different alternatives of dynamic model of the locomotive were created. The first variant represents the locomotive Class 744.0 CZ LOKO with a total weight of 80 t equipped with the axle-mounted nose-suspended traction motors. The second one represents an imaginary locomotive which has the same parameters (total weight, masses and inertia moments of the bodies, characteristics of joints etc.) as the Class 744.0, but it is equipped with some kind of fully suspended traction drive. Therefore, mass of the traction motors does not increase the share of unsprung masses in this case. Relevant modifications of the dynamic model were performed in following way – in case of the locomotive equipped with nose-suspended traction drive, mass of the traction motors was "divided" between the wheelset and the bogie frame in the equations of motion of these bodies in vertical direction; it means:

$$\ddot{z}_d = g + \left(M_d + \frac{2}{3} \cdot M_{TM} \right)^{-1} \cdot \sum_{(i)} F_{dz,i}, \tag{1}$$

$$\ddot{z}_p = g + \left(M_p + 2 \cdot \frac{1}{3} \cdot M_{TM} \right)^{-1} \cdot \sum_{(i)} F_{pz,i}, \tag{2}$$

where $\ddot{z}_d$ is acceleration of wheelset in vertical direction, $\ddot{z}_p$ is acceleration of bogie frame in vertical direction, g is acceleration of gravity, M_d is mass of wheelset, M_p is mass of bogie frame, M_{TM} is mass of traction motor, $\Sigma F_{dz,i}$ represents forces, which act on the wheelset in vertical direction, and $\Sigma F_{pz,i}$ represents forces, which act on the bogie frame in vertical direction. In case of all other degrees of freedom (except rotational motion of the wheelset around its lateral axis), the whole nose-suspended traction motor is considered as a part of the wheelset in this dynamic model. Inertia moments of wheelset were modified on basis of CAD model of the bogie so that their values represent the whole rigid body "wheelset + traction motor". Thus, this modification takes into account the fact that approximately 70 % of the nose-suspended traction motor creates the unsprung mass in vertical direction and 100 % of mass of the motor creates the unsprung mass in lateral direction.

In case of the imaginary locomotive, which would be equipped with a fully suspended traction drive, relevant modification of dynamic model of this locomotive is based on the assumption that traction motors are fastened to the bogie frame. Therefore, mass of the traction motors is added to the mass of the bogie frame and inertia moments of the bogie frame are modified in relevant way. This condition is valid for all translational degrees of freedom in this case; for example the equations of motion of the wheelset and the bogie frame in vertical direction have following form now:

$$\ddot{z}_d = g + \frac{1}{M_d} \cdot \sum_{(i)} F_{dz,i}, \tag{3}$$

$$\ddot{z}_p = g + \left(M_p + 2 \cdot M_{TM} \right)^{-1} \cdot \sum_{(i)} F_{pz,i}. \tag{4}$$

4. Simulations of dynamic behaviour of the locomotives

The aim of this work is to compare the dynamic behaviour of a locomotive, which is equipped with an axle-mounted nose-suspended traction drive, with a locomotive with a fully suspended traction drive. This comparison was made by means of computer simulations of run of the locomotive Class 744.0 CZ LOKO with a total weight of 80 t and an imaginary locomotive with the same parameters, but with the fully suspended traction drive. Dynamic models of these locomotives, which were used for multi-body simulations in the program system “SJKV”, are described in previous chapter.

It is generally known that the share of unsprung masses in running gear of a rail vehicle influences above all dynamics of wheel forces (i.e. the vertical forces acting in wheel/rail contact); the dynamic effects of the vehicle run on the track increase with increasing vehicle speed and decreasing quality of a track geometry. Therefore, the assessment of dynamic behaviour of the locomotives (Class 744.0 with nose-suspended traction drive and the imaginary locomotive with fully suspended traction drive) was performed for various speeds and under conditions of three various tracks (with various track geometry). In all cases, conditions of wheel/rail contact geometry and the friction coefficient in wheel/rail contact were identical – the wheel/rail contact with a value of equivalent conicity 0.207 and the friction coefficient 0.40 were used.

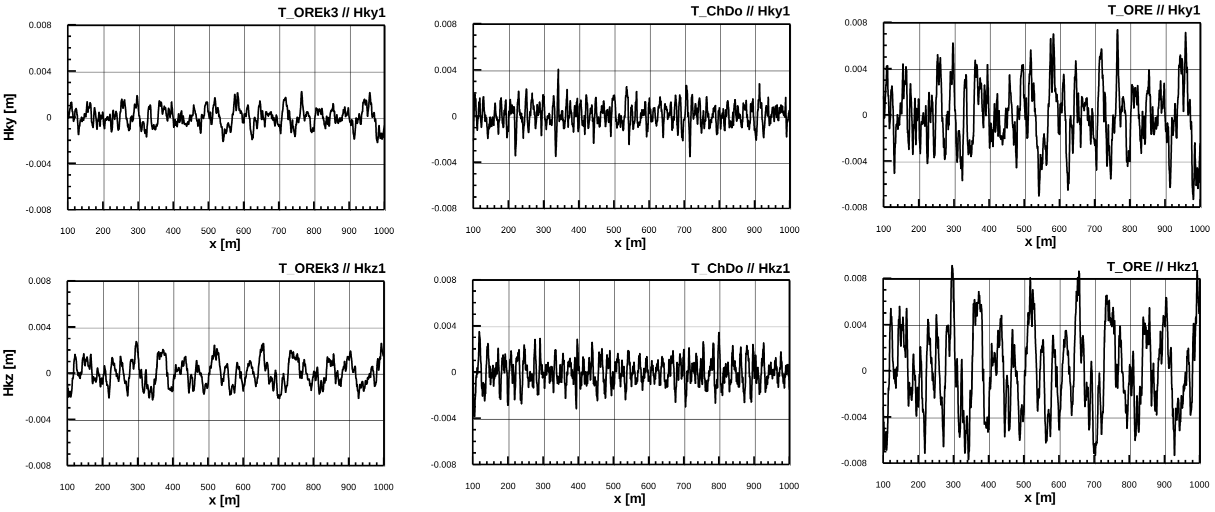

Fig. 3 Deviations of left rail position from the ideal position in horizontal (top) and vertical (bottom) direction for considered tracks – “T_OREk3” (left), “T_ChDo” (in the middle) and “T_ORE” (right).

Three various tracks were used at the simulations; these tracks are designated as “T_OREk3”, “T_ChDo” and “T_ORE”, and each of these tracks shows different level of quality of the track geometry. These simulation input data describing the track geometry were obtained from a superstructure measurement car or on the basis of so-called “ORE-track” which is given by means of a power spectral density of deviations of European tracks. All the simulations were performed in a straight track with a length of 900 m. According to the Appendix C of the European standard EN 14363, the quality of the track geometry is assessed by means of maximum values Δy_{max} and Δz_{max} and standard deviations s_y and s_z of deviations of the real rail position from the ideal position which is given by means of a track alignment. Values of these characteristics for considered tracks are given in tab. 1; records of deviation of the left rail from the ideal position in vertical and horizontal direction are shown in fig. 3. The track “T_OREk3” has the best quality; “T_ORE” has the worst quality.

Tab. 1 Maximum values and standard deviations of deviation of rail position from the ideal position.

Track	Δy_{max} [mm]	s_y [mm]	Δz_{max} [mm]	s_z [mm]
“T_OREk3”	2.21	0.80	2.74	1.08
“T_ChDo”	4.03	0.97	3.85	1.14
“T_ORE”	7.36	2.68	9.11	3.59

5. Simulation results

As it was mentioned, the share of unsprung masses influences above all the dynamics of wheel forces. Therefore, especially the wheel forces were observed at the simulations. In case of considered locomotives with a total weight of 80 t, the static wheel force (static load) has a value of 98.1 kN. During the run of the vehicle, the wheel forces oscillate around this static load value; level of these oscillations depends on vehicle speed as well as on quality of the track geometry.

At the simulations post-processing, time histories of the wheel forces were statistically processed. At first, the time histories were filtrated by means of upper limiting filter 20 Hz. Consequently, standard deviations of wheel force of the left wheel of the 1st wheelset were calculated from the filtered time histories. In fig. 4 there are compared obtained dependencies of these standard deviations on the vehicle speed from a range of 80 up to 160 km/h for all three considered cases given by the quality of the track geometry (see chapter 4).

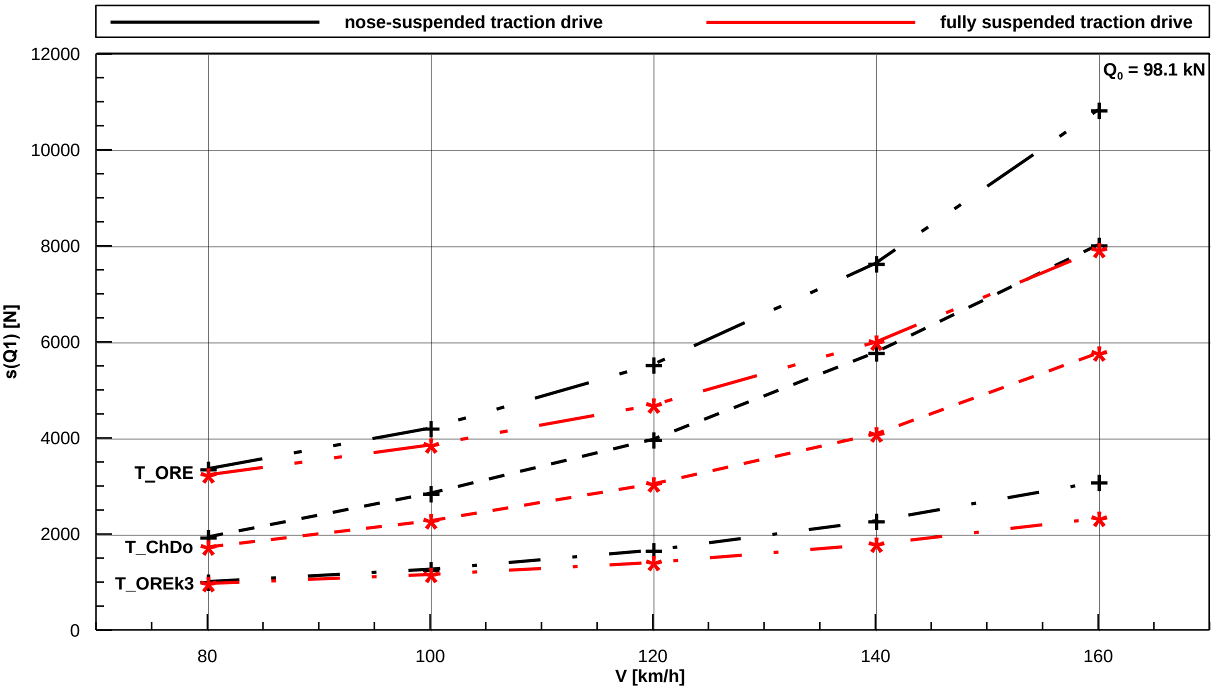

Fig. 4 Standard deviations of wheel force of the left wheel of the 1st wheelset in dependency on vehicle speed for all three considered cases of quality of the track geometry.

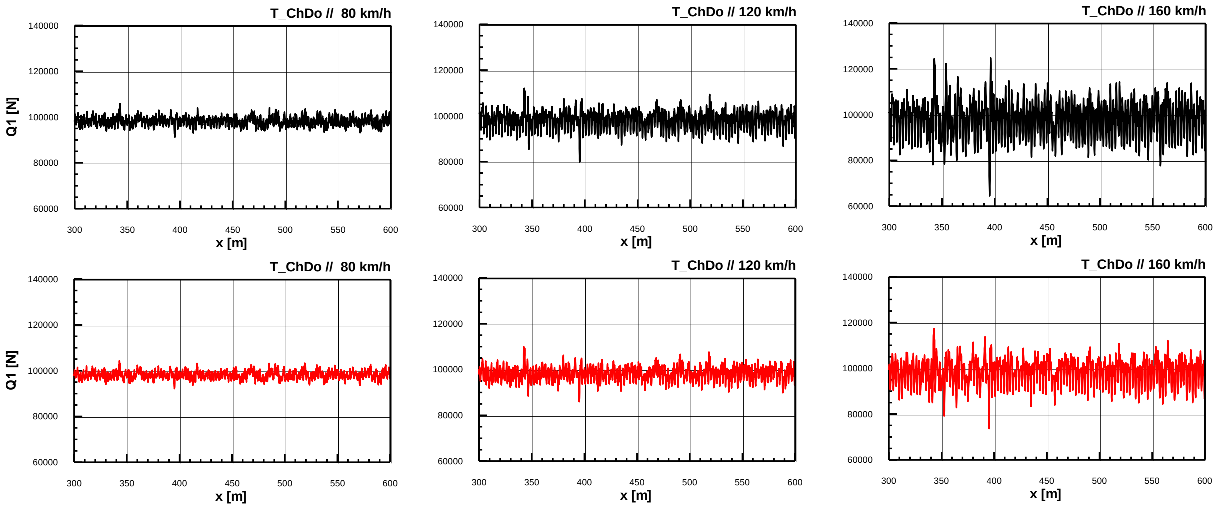

Fig. 5 Records of wheel force of the left wheel of the 1st wheelset on the track "T_ChDo" at speed of 80 km/h (left), 120 km/h (in the middle) and 160 km/h (right) for the locomotive equipped with nose-suspended traction drive (top) as well as with fully suspended traction drive (bottom).

From the graph in fig. 4 it is apparent that the dynamics of wheel forces depends strongly on the quality of the track geometry as well as on the vehicle speed. A difference between the locomotive equipped with axle-mounted nose-suspended traction drive and the locomotive with fully suspended traction drive is more significant with increasing speed, too. This statement is valid for all three tracks; in case of worse quality of the track geometry, the difference is certainly bigger. For example in case of the track "T_ChDo", relative value of the standard deviation of the wheel force (related to the static wheel load) reaches following values – in case of the locomotive with nose-suspended traction motors: 2.0 % (at speed 80 km/h), 4.1 % (120 km/h) and 8.2 % (160 km/h); in case of the locomotive with fully suspended traction drive: 1.8 % (80 km/h), 3.1 % (120 km/h) and 5.9 % (160 km/h). In fig. 5 there are shown records of wheel force of the left wheel of the 1st wheelset on the track "T_ChDo" for both alternatives of the locomotive at these speeds. Of course, maximum values of the relative standard deviation are reached on the worst track "T_ORE" – in case of locomotive with nose-suspended traction motors, the relative standard deviation has a value of 11.0 % at speed 160 km/h; in case of locomotive with fully suspended traction drive it is "only" 8.1 % at the same speed.

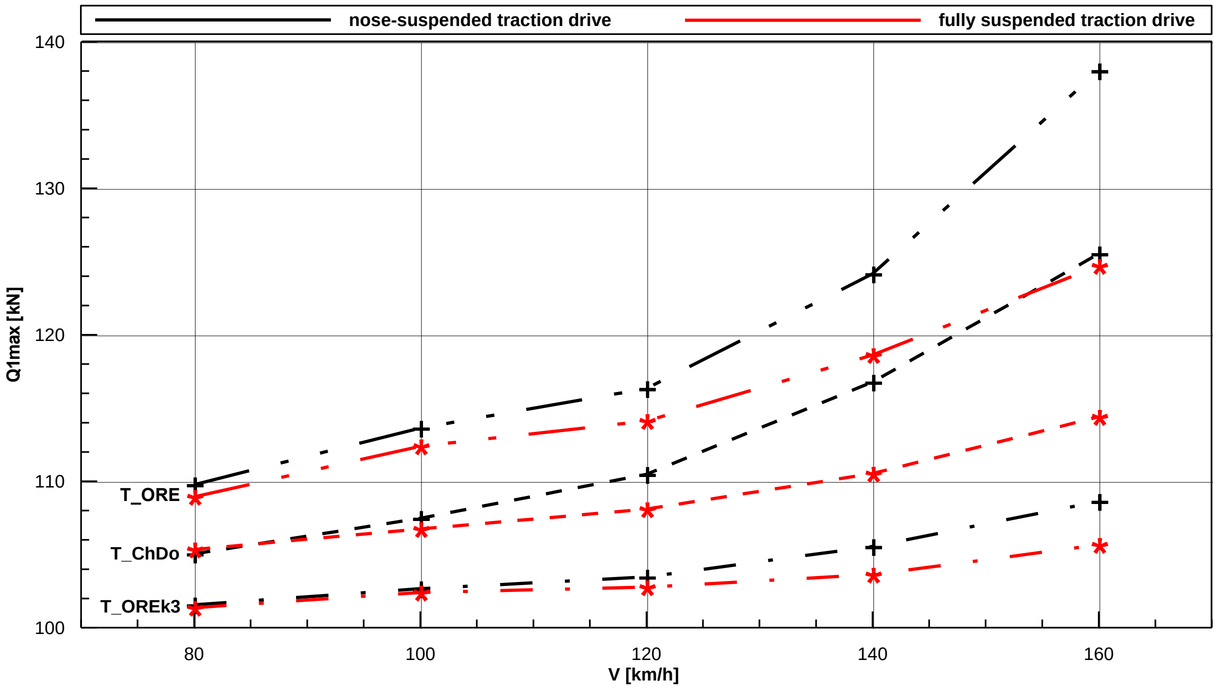

Fig. 6 Expected maximum values of wheel force for both alternatives of the locomotive with total weight of 80 t in dependency on vehicle speed according to the EN 14363.

The second method, which was used for the assessment of dynamic interaction between the vehicle and the track in vertical direction, was an evaluation of so-called expected values of maximum wheel forces according to the European standard EN 14363, which deals with testing of new or modernized railway vehicles in framework of their authorization process. This assessment was also used for both alternatives of the locomotive running at speeds from the range of 80 up to 160 km/h on the same three tracks. The filtered time histories (upper limiting filter 20 Hz) of wheel forces were also used at this method of evaluation. In this case, the time histories are divided into sections with a length of 250 m (± 10 %); then, it is necessary to determine for each assessed set of wheels in all these sections values of wheel forces, which correspond to a cumulative frequency of 99.85 %. After that, a mean value $M[Q_{max}]$ of these values and their standard deviation $S[Q_{max}]$ are calculated. The expected value of the maximum wheel force is given as:

$$Q_{\max} = M[Q_{\max}] + 2.2 \cdot S[Q_{\max}]. \tag{5}$$

In this concrete case, both wheels of the first wheelset were considered at computation of the expected values of maximum wheel force and the time histories of the wheel forces obtained from the simulations were divided into four sections with a length of 225 m. Results of this statistic assessment are presented in fig. 6. A limit value of the maximum wheel forces (according to the EN 14363) of both considered variants of the locomotive is 188.1 kN.

This method of assessment of the wheel forces confirms the above mentioned results obtained by means of the simplifier method using the standard deviations (see fig. 4). Although the limit value of the maximum wheel force is not exceeded in any case, it is evident that the difference between the locomotive with nose-suspended traction motors and the locomotive with fully suspended traction drive becomes to be more significant with increasing speed. Especially in case of worse quality of the track geometry, this difference is considerable at speeds higher than approximately 120 km/h. For example on the tracks “T_ChDo” and “T_ORE” – while the locomotive, which is equipped with nose-suspended traction drive, shows values of the maximum wheel force higher by approximately 2 % (than the locomotive with fully suspended traction drive) at speed 120 km/h, this difference has a value of approximately 10 % at speed 160 km/h.

Although the share of unsprung masses influences above all the dynamics of wheel forces, it certainly has an influence on interaction between the vehicle and the track in lateral direction, as well. As it was said, in case of the axle-mounted nose-suspended traction drive, approximately 60 up to 80 % of weight of the traction motor creates unsprung masses in vertical direction, but it is practically 100 % in lateral direction. However, an assessment of the lateral interaction between the vehicle and the track is more complicated. At first, the dynamic behaviour of rail vehicle in lateral direction is influenced by means of wheel/rail contact geometry very significantly. Especially at higher speeds, the stability of vehicle run can influence the results, as well. Then, it is also necessary to take into account that a simplified dynamic model of the locomotive was used at the simulations. From these reasons, an evaluation of the “lateral dynamics” was made only by means of standard deviations of lateral acceleration of the 1st wheelset in this stage – in a similar way as the assessment of wheel forces. Time histories of the lateral wheelset acceleration were also filtrated (upper limiting filter 20 Hz) before calculation of the standard deviations. In fig. 7 there are compared obtained dependencies of these standard deviations on the vehicle speed from a range of 80 up to 160 km/h for the tracks “T_ORE” (the worst quality of the track geometry) and “T_OREk3” (the best quality of the track geometry). In fig. 8 there are shown records of lateral acceleration of the 1st wheelset on the track “T_ORE” for both alternatives of the locomotive at various speeds; moving quadratic means are added there, as well.

The realized simulation results show following: from the point of view of the “lateral dynamics” during the run in a straight track, the difference between the locomotive with nose-suspended traction motors and the locomotive with fully suspended traction drive also exists. On the basis of fig. 7 it is possible to state that the “lateral dynamics” is related above all with the quality of track geometry and the difference between both variants of the locomotive are marked only at higher speeds.

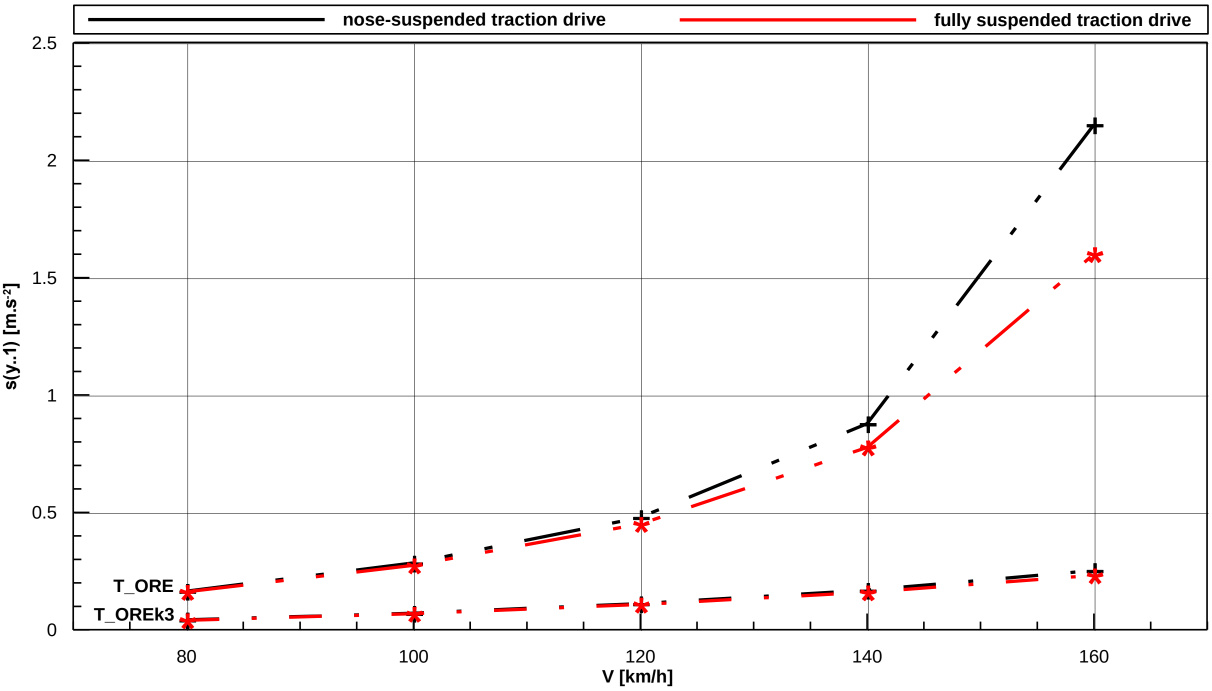

Fig. 7 Standard deviations of lateral acceleration of the 1st wheelset in dependency on vehicle speed on tracks “T_ORE” and “T_OREk3”.

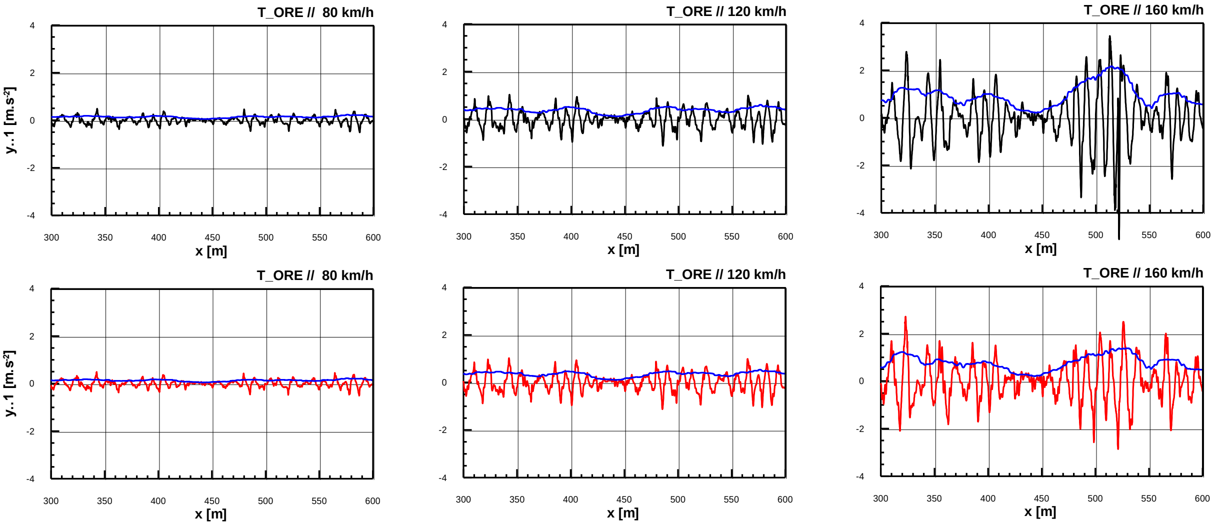

Fig. 8 Records of lateral acceleration of the 1st wheelset on the track "T_ORE" at speed of 80 km/h (left), 120 km/h (in the middle) and 160 km/h (right) for the locomotive equipped with nose-suspended traction drive (top) as well as with fully suspended traction drive (bottom); the blue lines in graphs present moving quadratic means with a window length of 25 m.

6. Conclusions

Nowadays, a traction drive using the axle-mounted nose-suspended traction motors is often used on locomotives for freight operation. This technical solution, which is conceptually very old, is very simple, robust and relatively cheap. However, the greatest disadvantage of the nose-suspended traction drive is a significant increase of unsprung masses in running gear of the vehicle in comparison with various types of fully suspended traction drives. Although relatively lightweight asynchronous traction motors are used today, their weight ranges in order of tons and approximately 60 up to 80 % of this weight is suspended directly on wheelset. The higher share of unsprung masses increases then the level of dynamic effects between the vehicle and the track with all negative impacts on stability of geometric position of the track, stress of the superstructure and the vehicle running gear etc.

In this paper, the new locomotive Class 744.0 CZ LOKO with a total weight of 80 t equipped with axle-mounted nose suspended traction drive is compared with an imaginary locomotive with fully suspended traction drive from the point of view of the dynamic interaction between the vehicle and the track. At various speeds from range of 80 up to 160 km/h, wheel forces as well as lateral wheelset accelerations were observed by means of computer simulations of vehicle run on straight tracks with various quality of the track geometry. The aim of this paper is to assess the differences between the dynamic behaviour of both mentioned conceptions of locomotive running gear.

From the point of view of "vertical dynamics" (i.e. the dynamics of wheel forces), the simulation results show that the predominant factor for the force interaction between the vehicle and the track is the quality of the track geometry. The dynamic effects of the vehicle run increase with increasing speed; in case of worse quality of the track geometry, this increase is more significant. However, the difference between the locomotive equipped with nose-suspended traction motors and the locomotive with fully suspended traction drive is also significant. In case of worse quality of the track geometry, these differences are substantial at speeds higher than approximately 120 km/h, although for example the limit value of the maximum wheel force according to the EN 14363 was not exceeded in any case.

From the point of view of "lateral dynamics", the assessment is more complicated, because for example the stability of run of the vehicle at higher speeds could also have a certain influence. Performed assessment using the lateral acceleration of wheelset shows that the dominant influence on the dynamic behaviour has the quality of the track geometry, again. However, a certain difference between both considered conceptions of the locomotive also exists. From the mentioned reasons, a more detailed investigation of an influence of conception of the locomotive running gear on the stability of run will be performed in the next stage of research of the dynamic behaviour of the new locomotive Class 744.0. Besides that, a special attention will be also paid to the influence of unsprung masses in locomotive running gear on dynamic effects of the vehicle run through the switches.

Nowadays, a prototype of the new locomotive 744.001 is tested on tracks in the Czech Republic. Results of these tests will be used for validation and possible improvement of the dynamic model of this locomotive which is being developed in framework of co-operation of the company CZ LOKO, a.s. and the Jan Perner Transport Faculty of the University of Pardubice.

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 and by internal grant project No. 51030/20/SG520001 of the University of Pardubice.

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