Analysis of occurrence of torsion oscillations in wheelset drives used in modern railway vehicles

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Abstract

This text has been created in the context of the occurrence of the press-fitted joints failure in some running railway vehicles. This work deals with an idea of occurrence of the torsional oscillations in the vehicles' drives that can lead to the problem as previously mentioned. The aim of this work is to describe the ways of the oscillations' creation and duration according to the vehicles' external conditions.

The solution of previously mentioned has been made via MATLAB Simulink and Simpack software simulations. There was created a dynamic model of the vehicle, which is respecting the mechanical and the electrical part of the vehicle.

The results of the model are the time dependent oscillations' courses of the wheelset in the situation when the adhesion is lost. The results describe creation, duration and disappearance of the oscillations according to variable friction coefficients and other parameters. The results show that variable friction coefficient values lead to the different amplitudes of the torsional oscillations. Another influence are the values of the torque values and vehicle passing through a curve

Key words: STČ; Railway vehicles, transportation, speed, wheelset, dynamics, torsional oscillations, rolliers moment, mechatronics, slip, wheel rail contact, drives, asynchronous motors, tractive effort, traction characteristic, simulation, SIMPACK, Simulink

1. Introduction

The intense development of electro-technic used in railway vehicles during last decades allowed us to install a high power into relatively small vehicles. Asynchronous electric motors being controlled via semiconductor converters offer a considerably simple way how to run those machines with respect to costs, power and weight.

But high performances and high tractive efforts reveal new problems of dynamics events which can occur in drive that aren‘t well known nowadays. A great problem of recent days is a phenomenon called „Torsional Oscillation“ which can lead to defect occurrence in wheelset axles and decrease their durability.

This article is about the current research and ways of its solutions. This article is a sequel to the article of the author which has been presented on the STC conference in year 2015 (Optimization of Construction of Wheelset Drives Used in Modern Railway Vehicles) [1] and shows newly discovered findings.

1.1. History

Torsion oscillations have become well-known in September 2009. The beginning of this issue was discovery of a press fitted wheel disc which slightly revolved towards the axle shaft on one of the DB145 locomotive (TRAXX family, see Fig. 1.).

Fig. 1. *DB145 TRAXX locomotive [2]*

During maintenance checks and further investigations on DB145 there were discovered about ten another cases of relative rotation. Although there are currently lots of DB145 locomotives in service, amount of ten problems discovered is significant according to its seriousness.

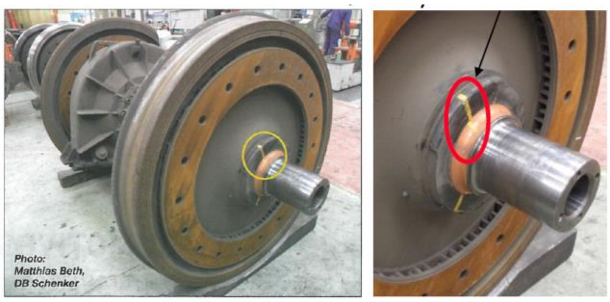

Fig. 2. *Wheel disc relative rotation detail [3]*

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Relative rotation between wheel and axle means losing of friction in press fitting. It means that a wheel can move in this moment almost freely along the axle in transversal direction and make vehicle derailed.

Although there have been no manufacturing problems or failures found, attention has been given to torsion oscillations and its possible consequences.

1.2. Phenomenon description

Torsional oscillation is a situation when both of the wheels start to oscillate one against another. This event leads to slightly twisting of the axle (see Fig. 3.). This can happen because of two wheels representing mass with high inertia are connected together via relatively slim axle representing torsional spring. Thanks to this it is possible to understand the wheelset as a dynamical system with a specific number of degrees of freedom and natural frequencies.

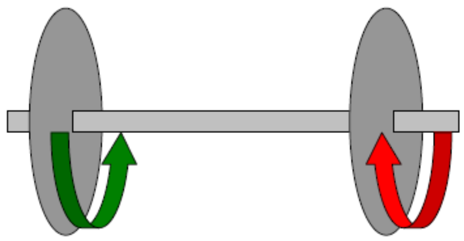

Fig. 3. *Schematic of torsion oscillations [4]*

There are more reasons why this happens.
Well known is a situation when railway vehicle passes through a small radius curvature. During this the outer wheel tends to spin slower than it should whereas the inner wheel revolves faster than it should. The same situation occurs for example in automotive where this is solved via differential gearbox. Railway vehicles usually have no differential gearbox so this is compensated through railway wheel conicity. But this works only in limited range of curvature radius – the smaller the radius is the harder is to compensate different wheel perimeter speeds. Thanks to this the most lightened wheel loses its adhesion and slips and the wheelset starts to oscillate. Example of this is a tram passing through a small curvature radius and emitting some high frequency sounds.

Another reason is overcoming the limit of adhesion thanks to high torque transmitted through the rail-wheel contact. When adhesion is lost on one of the wheel, this wheel loses its possibility to transfer tangential forces. After that the wheel slightly rotates forward. Thanks to this the preload in the axle decreases as well as the tangential transferred force decreases so the wheel renews its adhesion contact. During this the other wheel must transfer the whole wheelset torque. But there is no possibility of transfer and this wheel slips too. It results in a situation when the first and the second wheel alternately slips. [3]

The running wheelsets are not the only objects that may occur torsional oscillations. This phenomenon may occur in the whole drive chain that contains clutches, cardan shafts, gearboxes, motors etc. The reason is that every part of the drive has its specific mass properties and stiffness which depend on dimensions and used materials. The analysis of the problem requires detailed information about actions that may occur in the drive. These information may be obtained from measuring (which is expensive, requires a lot of time) or through numerical simulations (simple design, variability of parameters).

This is the reason why two kinds of numerical models have been made. The first one – simple model in the Matlab Simulink – contains the fundamental model of the drive chain and torque regulation structure. The second one – advanced model created in Simpack cooperating with Matlab Simulink – contains the whole vehicle running on the real track. The aim of the model design was to make the model of a modern electric locomotive (Taurus type). The locomotive is a four-axle railway vehicle propelled with asynchronous engines. The maximum power output is between 6÷7 MW. The maximum tractive effort is up to 300 kN. The maximum speed is up to 230 kph.

2. Mathematical model

The mathematical model is based on the scheme on (Fig 1). There are shown only the basic components of the drive chain. The scheme contains a wheelset, a cardan shaft with two clutches, a gearbox, and a rotor of the traction motor. The scheme takes into account all the stiffnesses that may occur in the real vehicle.

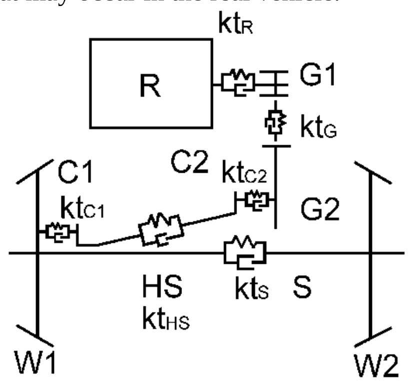

Fig. 4. *Schematic of the drive chain. W1 and W2 – wheels, S – shaft/axle, C1 and C2 – clutches, HS – hollow shaft, G1 and G2 – gear wheels, R – rotor of traction motor; coefficients k_{ti} represent stiffness of each shaft, clutch or gear pair.*

This scheme contains eight bodies and stiffnesses among them so the created model would be very complex. Considering this the model has been simplified. The main components are a wheelset, a rotor and two clutches.
The model was linearized and then described with following matrix equation.

$$M.\ddot{X} + T.\dot{X} + K.X = f(t) \tag{1}$$

Matrix M is the inertia matrix, matrix T is the damping matrix and K is the stiffness matrix. Vector f represents outer torque inputs. This equation was used for the basic analysis – obtaining natural frequencies of the system.
This set of equations was then converted into the State space description according to following equations.

$$\dot{x} = A \cdot x + B \cdot u \qquad (2)$$

$$y = C \cdot x + D \cdot u \qquad (3)$$

A is the system matrix, B is the control matrix, C is the output matrix, D is the feedthrough matrix, x is the state vector, y is the output vector and u is the control vector. The state vector represents the angular deformations of the components. The model has been created in the Matlab Simulink software.

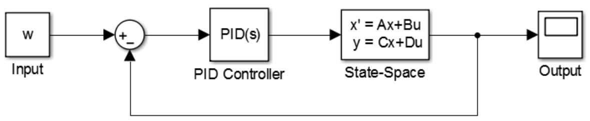

Fig. 5. *Schematic of the control system*

1.2. Results of the simulation

The idea of making the model was to find out, what is the reaction of the system when the adhesion on one of the wheels is rapidly decreased and the stick slip protection makes an intervention with short delay time. This is shown on Fig. 6.

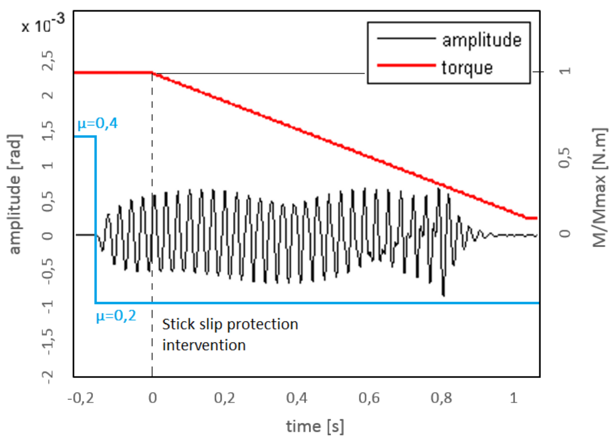

Fig. 6. *Time courses of the motor torque and torsional oscillations of the wheelset*

The figure shows a reaction of the wheelset when the adhesion between the wheel and the rail is decreased from 0,4 to 0,2 (blue line). In this moment the wheelset starts to oscillate (black line) and slightly increases its angular velocity. The oscillations are amplified thanks to the torque which is delivered from the traction motor. When the angular velocity is high enough the stick slip protection makes an intervention and decreases the torque (red line). When the torque is small enough, the adhesion renews and the oscillations disappear.

This simulation is showing a situation when the adhesion is decreased very fast and the motors torque is on its maximum value. Results of the simple mathematical model showed that the oscillations are highly dependent on the following factors:

- the torque must be at least 60÷70 % of its maximum value

- the adhesion needs to decrease very fast (step change)

- the time of stick slip protection delay influences the duration of the oscillations

2. Advanced MBS model

The main problem of the simple model is a fact that it is hard to include advanced influences like curvature passing, track irregularities etc. Consequently, an advanced MBS (multi body system) model has been created in the Simpack software.

The goal was to make a 3D geometry containing the drive used in a simplified model and the rest of the vehicle, see Fig 7, 8 and 9.

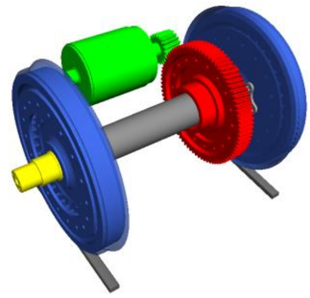

Fig. 7. *Complete drive of the vehicle*

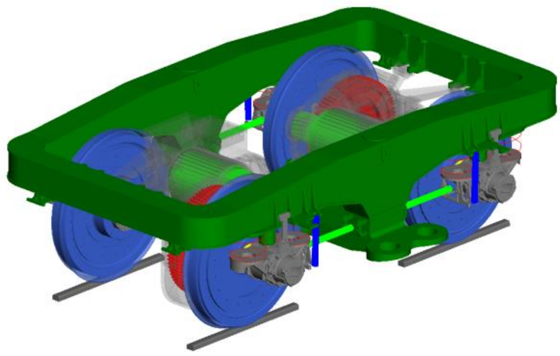

Fig. 8. *Locomotive drive bogie*

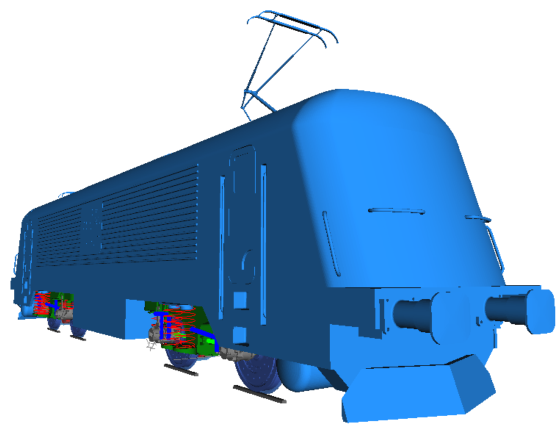

Fig. 9. *Complete locomotive model*

The model considers mechanical system and its superior electronic control system. This allows to include anti slip protection influence which could lead to additional torsional oscillations appearance.

Electronical part is solved via SIMULINK software working in cooperation on used MBS software. Basic scheme is presented on Fig. 10.

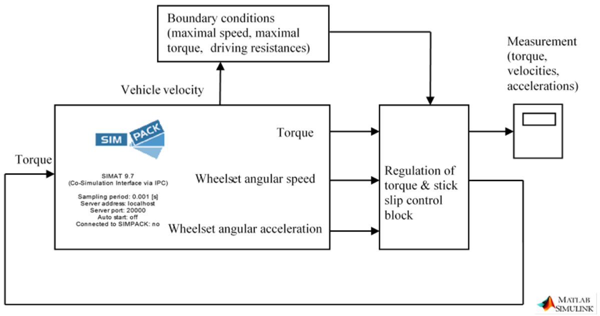

Fig. 10. *Locomotive drive regulation scheme*

The basic part of the structure is a feedback control circuit. The SIMAT block solves mechanical values of the system for example revolves, accelerations e.g. The SIMAT block output then continues into the regulation block. According to the boundary conditions of the model there is a resolution made if the wheelset is in state of rolling or slipping and if there is a need to increase or decrease the torque value.

3.1. Parameters of the simulation

The simulations have been made on two basic track types. The first one was a straight line, the other one was a curve with radius R=250 m. The adhesion limit was between $\mu = 0{,}1 \div 0{,}4$ in both cases. The change of the adhesion was made as a sharp decrease of the initial value on one of the wheels. Gradual decrease of the adhesion led only to oscillations with small amplitude and short duration. The initial velocity was in the range between 36 and 72 kph ($10 \div 20$ m.s^{-1}). It is a speed range where the vehicle may run with high traction efforts and where the adhesion limit slightly decreases according to Curtius & Kniffler measurements [5]. The adhesion parameters were set with respect to values measured on real vehicles. The track irregularities were set according to ERRI B176 (low quality).

3.2. Results of the simulation

The following figures are showing some results of simulations. Fig. 11 describes the situation when the vehicle has velocity 15 m.s^{-1} and the adhesion is decreased from its maximum value to μ=0,1 or μ=0,2 and the wheelset starts to oscillate until the torque is not sufficiently decreased. It is possible to see that the decrease of adhesion to μ=0,2 produces slightly higher amplitudes. The reason is that the change to μ=0,1 makes instant loss of adhesion on both wheels so the stick slip protection makes an intervention faster. When the adhesion loss is smaller, one of the wheels slips and the wheelset starts to oscillate. But the angular velocity does not rise fast enough and the stick slip protection reacts a bit later.

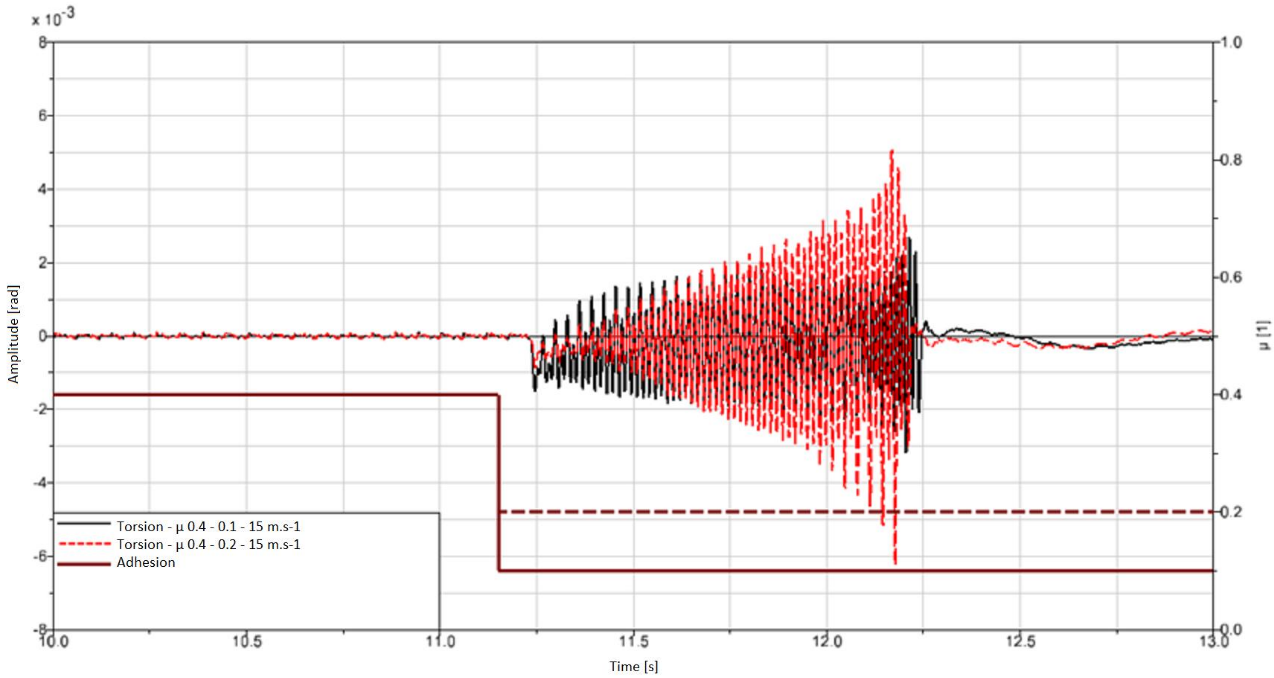

Fig. 11. *Time courses of torsion oscillations in absolute values. The black line represents change of the adhesion from 0,4 to 0,1. The red line represents change of the adhesion 0,4 to 0,2. Velocity of the vehicle is 15 m.s-1.*

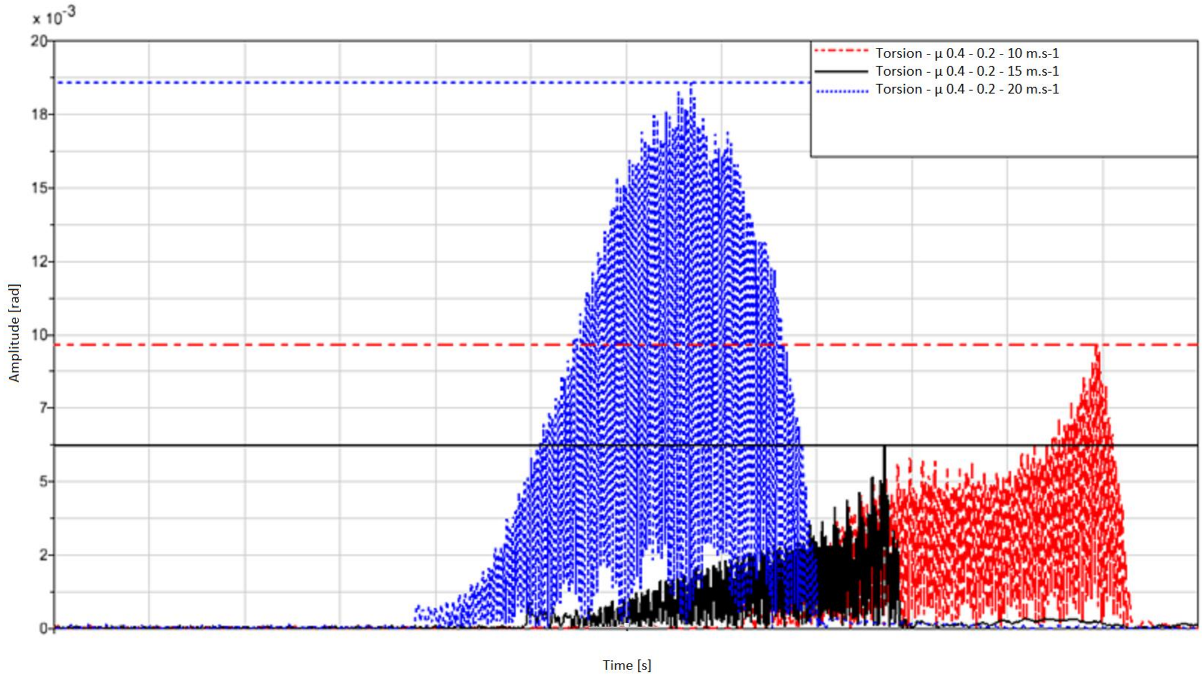

Fig. 12. *Maximum oscillations for each velocity in absolute values. The blue line points on very high amplitudes that may be harmful for the axle.*

Fig. 12 shows the highest amplitudes of the wheelset that have been measured for each velocity. The most interesting is the oscillation measured for the velocity 20 m.s-1. The wheelset had the highest amplitudes in this situation.

Very high amplitudes are problematic. The torque in the axle increases when the axle is twisting and it can exceed the nominal value. So does the stress in the axle that may rise into very high values and can produce fatigue cracks. Another problem is very high amplitudes of angular acceleration which may produce very high inertia moments that may lead to a defect of the press fitted joint, as mentioned in the introduction.

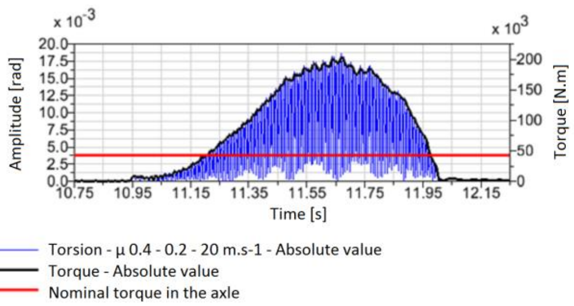

Fig. 13. *Time course of the oscillation amplitude. The black curve show an actual torque in the axle. The red line show nominal value of the torque in the axle. The problem is that the actual torque may be circa 4 times higher than it should be.*

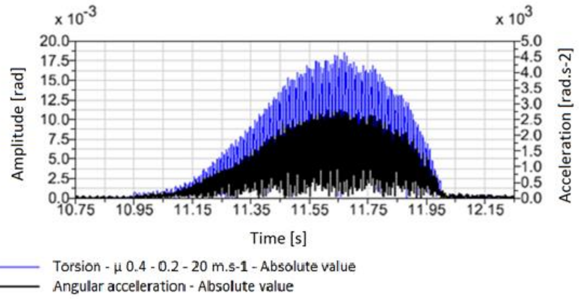

Fig. 14. *Time course of the oscillation amplitude. The black curve show an actual torque in the axle. The red line show nominal value of the torque in the axle. The problem is that the actual torque may be circa 4 times higher than it should be.*

Calculated data show a problem that may appear in relative high velocities when the torque is still very high but the friction slightly decreases according to Curtius & Kniffler measurements, see Fig. 15.

There is an area in the traction characteristics where the work point may locate. The most dangerous seem to be the range of velocities v=0÷100 kph. In this area of interest the maximal locomotive force exceeds the theoretical adhesion limit so there is a higher chance that the wheelset will slip against the rail. Unfortunately, this is the area where lots of locomotives operate very often (especially freight locomotives).

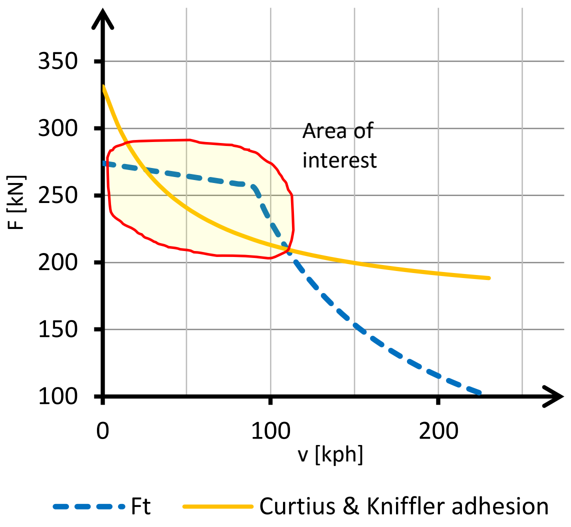

Fig. 15. *Traction characteristics showing maximum tractive effort of the locomotive (blue curve) and a theoretically maximum adhesion force that can locomotive use (yellow curve).*

4. Summary

Within the second year of grad study the simulation model was created with the help of SIMPACK and SIMULINK software.

Results of the simulations show that in some velocities the oscillations amplitudes may rise into very high up to very high values, which can be dangerous for the axle or for the whole wheelset. Oscillations are highly dependent on the value of the torque and the reaction time of the stick slip protection when the adhesion is rapidly decreased.

Acknowledgments

The paper was created with the financial support SGS grant No. SGS14/184/OHK2/3T/12 and of the Technology Agency of the Czech Republic, project No TE01020038 "Competence Centre of Railway Vehicles".

List of used symbols

A system matrix
B control matrix
C output matrix
D feedthrough matrix
$\vec{f}_{(t)}$ force vector
F force (kN)
k_{ti} torsional stiffness (kNm·rad-1)
K stiffness matrix
M inertia matrix, motor torque (kN·m)
R curvature radius (m)
t time (s)
T dumping matrix
$\vec{u}$ control vector
v velocity (kph)
w requested value
$\vec{x}$ state vector
$\vec{y}$ output vector
μ friction coefficient (1)

List of literature used

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