Dynamics of the Drives Used in Modern Railway Vehicles

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Abstract

This text deals with a research, which is focused on the torsional oscillations in drives of modern railway vehicles. The oscillations have become a subject of various researches and discussions in technical society over last years. Therefore the author of the text deals with this topic as well in the frame of his PhD studies. The aim of the research was a possible mutual influence between mechanical and electrical values in the drive. The research has been done via simulation methods with a help of Simpack and Simulink software. This text describes a methodology of the research, obtained results and its main outcomes. Some of the simulations results have been used for a proposal of a way how to reduce or suppress the oscillations.

Keywords: railway vehicles; drives; dynamics; torsional oscillations

1. Introduction

In 2009 a slight rotation of the wheel and the axle on the powered wheelset has been discovered during maintenance on one of the DB locomotive. The same problem has been found consequently on other vehicles of the same type. Although the occurrence was just a matter of a small number of the total count of the vehicles, this issue showed to be a serious safety risk [1].

Fig. 1. *Relative rotation of the wheel and the axle [1].*

The main problem is a fact that the relative rotation of the wheel and the axle means a short term loss of the friction between them. This means a failure of a press fitted joint that guarantees the right position of the wheels on the axle. This may be very problematic, especially in the situation when the vehicle passes through a curve and it is pulled on the outer rail due to the centrifugal force. Resulting transversal force may lead to a movement of the wheel along the axle and decrease of the wheelset gauge under a permissible value. This may lead to a derailment with critical consequences in the extreme situation.

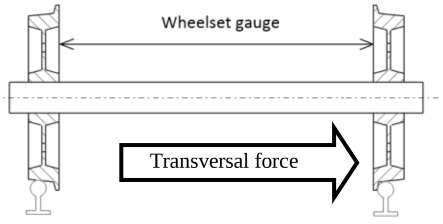

Fig. 2. *A standard wheelset composed from one axle and two wheels.*

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2. State of Art

This issue has been given a great attention in Germany and worldwide since its discovery. It is a generally known fact that the wheelset and whole drive may torsionaly oscillate. [2]. The axle is a torsional spring with given stiffness and both wheels may be considered as two masses. This makes mechanical oscillator.

Among the first, who described a wheelset as a mechanical oscillator, were Benker and Weber [3]. Except Germany there was other topic from authors Yao, Zhang and Luo [4]. These articles were focused mainly on analysis of the phenomena, others were focused on possibilities of detection and reduction.

A method of detection has been described in an article from Markovic, Kostic and Bojovic [5]. They made a mathematical model of a wheelset that was powered via a direct current (DC) motor. The results showed that the stator voltage increases and starts to oscillate when adhesion is lost and the wheelset oscillates. Both the oscillations of the voltage and the oscillations of the wheelset had the same frequency (equal to the natural frequency of the wheelset). This means there had to be a connection between both oscillations.

A method of reduction of the oscillations has been described in an article by Biker and collective [6]. Authors dealt with an idea of using of brake discs elastically connected to the wheels which may serve as torsional dampers.

3. Presented Outputs of the Research

A computational model of a driving vehicle has been made in the frame of a student grant SGS No. SGS14/184/OHK2/3T/12. The vehicles parameters correspond to parameters of currently operated locomotives that are used via state or private companies throughout Europe.

The model is composed of two main parts – mechanical and electrical. The first one calculates dynamics of the vehicle (general dynamics, drive dynamics, contact between the wheel and the rail), the second one contains superior control structure (simplified model of a traction motor, stick slip protection).

The outputs of the model have been time courses of wheelsets oscillations. These courses have verified that the oscillations may emerge in the situation, when a vehicle operates with higher amount of the torque and the adhesion between the wheel and rail must be rapidly decreased. More detailed description can be found in the article „Analysis of occurrence of torsion oscillations in wheelset drives used in modern railway vehicles“ [7]. Another important output was a fact that the higher oscillations may appear within higher velocities of the vehicle. It is a situation when the vehicle operates with almost maximum value of the torque and the output power. These oscillations are responsible for higher twisting of the axle and may lead to defects on press fitted joint according to high inertia forces.

3.1. Parameters of Simulation

As an object of interest has been chosen a modern Taurus type locomotive. The analysed vehicle has a tractive power P_{max}=6400 kW (temporary 7200 kW), tractive effort F_{max}=274 kN and operates with maximum velocity v_{max}=230 km/h. The aim of the simulations was to bring on the loss of adhesion and emerge torsional oscillations of the wheelset.

The vehicle was tested in the velocity range between 36 and 72 km/h. This had to ensure higher values of the torque and power of the traction motor.

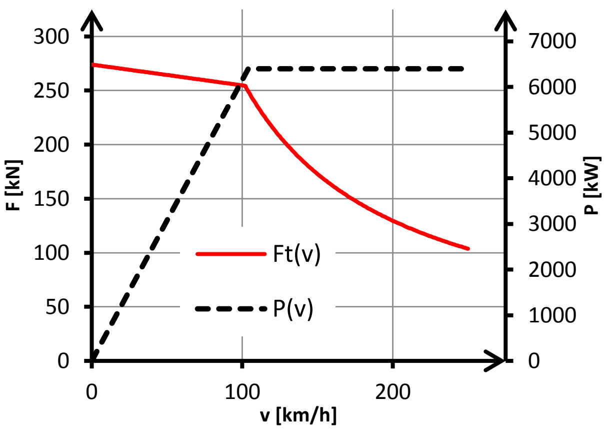

Fig. 3. *Traction characteristics showing pulling force Ft and output power P.*

The vehicle was loaded with a resist force *O(v)*. The purpose of this force was to simulate real operating conditions. This force was approximately equal to the tractive effort of the vehicle. Reasons were following:

a. the vehicle had approximately constant velocity with a small amount of acceleration
b. wheel forces on the front wheelset have been reduced due to the interacting forces

Ad a. – this situation simulates acceleration of the vehicle which pulls a heavy freight train. The locomotive operated with a maximum amount of a friction between the wheel and the rail.
Ad b. – reduction of the wheel forces lowers a maximum transmissible tractive effort. The wheelset will be more susceptible to a slippage, when the adhesion is suddenly decreased.

The vehicle operated with a high amount of the adhesion during the simulations. The adhesion was suddenly rapidly decreased. The adhesion was understood as an input with a major influence in the frame of research.

3.2. Simulation Outputs

Different time courses of velocities and adhesion lead to different oscillations of the wheelset. Generally, it is possible to state that higher velocities are bound with higher amplitudes of oscillations. One of these time courses is in fig. 4. The figure displays twist of the axle during velocity v=72 km/h (20 m.s^{-1}). The axle is slightly twisted in the left part of the image due to the torque that is transmitted and divided between both wheels. In the mid part of the image the adhesion is lost and the wheelset starts to oscillate. The oscillations and the axle twist disappear in the right part of the image, when the stick slip protection makes an intervention and decreases the torque.

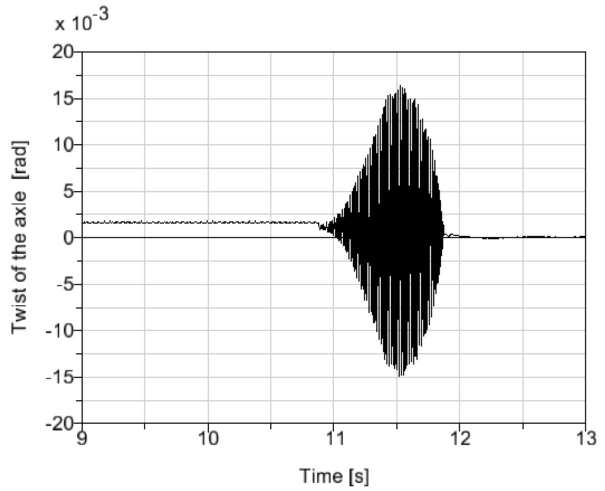

Fig. 4. *Time course of the oscillation.*

Fig. 5 displays analysis of the time course. It shows amount of the torque in the axle and angular acceleration of oscillating wheels.

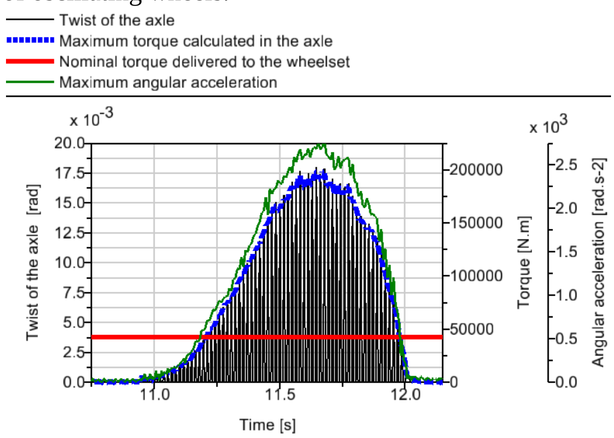

Fig. 5. *Analysis of the oscillation*

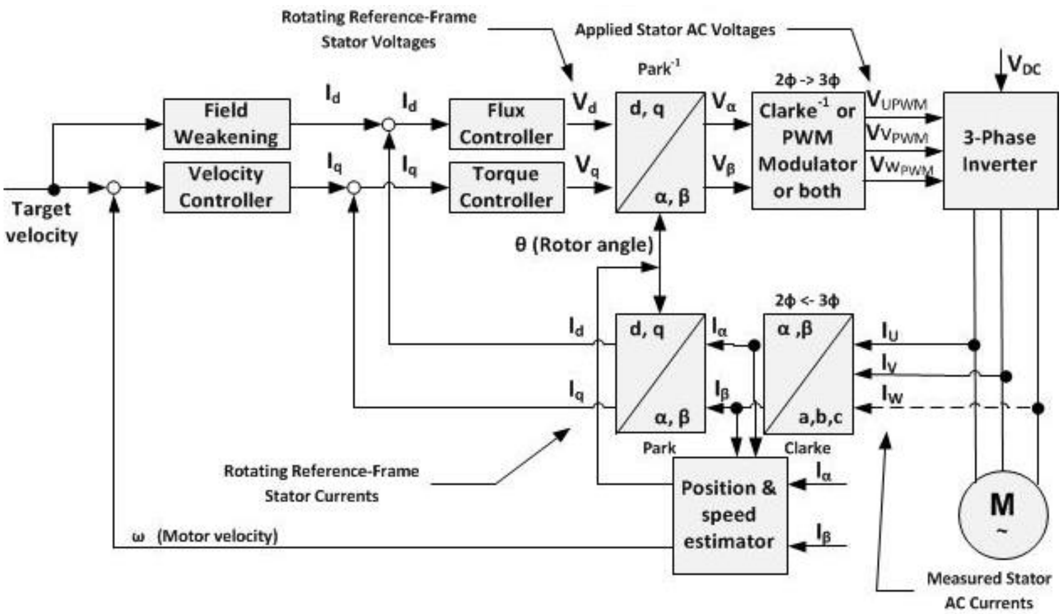

Fig. 6 *Vector control of the torque [9]*

The time courses reveal a very high supremum values of the torque in the axle according to the eq. (1). Values of the axle torque may be several times higher than maximum nominal values. Analogically to this, the angular accelerations have very high amplitudes according to the eq. (2).

$$M_t = k_t \varphi \qquad (1)$$

$$\ddot{y}_0 = y_0 \omega^2 \qquad (2)$$

Presented maximums may be a source of mentioned problems and may lead to failures described in chapter 1 (Introduction). This leads to a tendency to reduce these oscillations and protect the wheelset against hazardous consequences.

4. Relation Between Electrics and Mechanics

4.1. Extension of the Simulation Model

Detailed description of the asynchronous motor was the main focus of the last year of the research. The motor was up to then done as simplified substitution via the second order transfer function. Although this allowed to count with a base inertia of the mechanical events, the electrical values were not described at all. This is the reason why new model blocks have been added into the model – asynchronous motor and its control structure.

The model of the motor is based on a description of an asynchronous machine. The model is described via voltage (3) and flux equations (4), see [8]. The model supposes that all of the parameters are constant during the operation (mainly resistances and inductance).

$$\begin{aligned}
u_{1\alpha}(t) &= R_1 i_{1\alpha}(t) + \frac{d\Psi_{1\alpha}(t)}{dt} \\
u_{1\beta}(t) &= R_1 i_{1\beta}(t) + \frac{d\Psi_{1\beta}(t)}{dt} \\
u_{2\alpha}(t) &= R_2 i_{2\alpha}(t) + \frac{d\Psi_{2\alpha}(t)}{dt} + p_p \omega_m(t) \Psi_{2\beta}(t) = 0 \\
u_{2\beta}(t) &= R_2 i_{2\beta}(t) + \frac{d\Psi_{2\beta}(t)}{dt} - p_p \omega_m(t) \Psi_{2\alpha}(t) = 0
\end{aligned} \qquad (3)$$

$$\begin{aligned}
\Psi_{1\alpha}(t) &= L_1 i_{1\alpha}(t) + L_h i_{2\alpha}(t) \\
\Psi_{1\beta}(t) &= L_1 i_{1\beta}(t) + L_h i_{2\beta}(t) \\
\Psi_{2\alpha}(t) &= L_2 i_{2\alpha}(t) + L_h i_{1\alpha}(t) \\
\Psi_{2\beta}(t) &= L_2 i_{2\beta}(t) + L_h i_{1\beta}(t)
\end{aligned} \qquad (4)$$

The torque is described via eq. (5)

$$M(t) = \frac{3}{2} p_p \left(i_{1\beta}(t) \Psi_{1\alpha}(t) - i_{1\alpha}(t) \Psi_{1\beta}(t) \right) \qquad (5)$$

The three-phase machine has been simplified into the two-phase machine. Alternating values has been converted into direct values via Park's transformation [9]. This allows to control the alternating current motor as a direct current motor.

$$\begin{aligned}
i_{1d} &= i_{1\alpha} \cos\gamma + i_{1\beta} \sin\gamma \\
i_{1q} &= -i_{1\alpha} \sin\gamma + i_{1\beta} \cos\gamma
\end{aligned} \qquad (6)$$

The torque of the motor is then described via following equation

$$M_m \approx k \cdot i \qquad (7)$$

This allows simple control of the torque and it is also suitable for observation of its dynamics.

The motor is controlled via an indirect torque control method [10]. This allows to control the amount of the produced torque and a field weakening, which is necessary to increase the speed of the motor above the nominal value. The scheme of the control is shown in fig. 6.

4.2. Oscillations in the Drive

The simulations have been done with the use of the newly made control structure. The aim was to determine if the oscillations are transmitted via the drive chain and how their consequences can be. The attention has been focused on the angular speed of the rotor ω_m that is an input of the voltage equations. The speed is shown in fig 7, which represents a situation when the adhesion is decreased and the wheelset starts to oscillate.

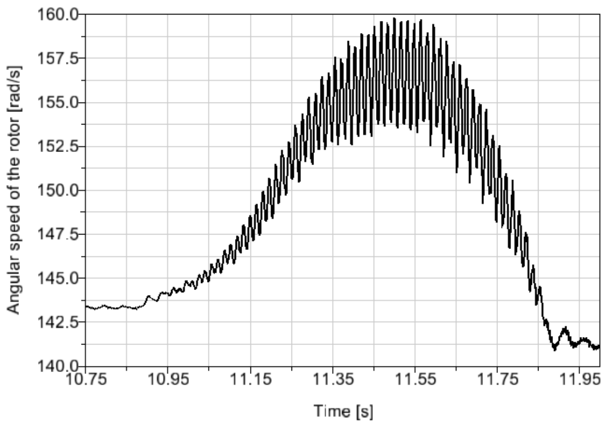

Fig. 7. *Angular speed of the rotor.*

The graph shows that the rotor oscillates similarly to the wheelset with the same frequency. This means the oscillations are transmitted from the wheelset via the drive chain to the rotor. These oscillations affect dynamics of the motor. Their influence shows the time course of the control current i_{1q}. The current starts to wave when the wheelsets oscillations emerge. The superposed current oscillations are clearly visible after few moments. These oscillations have the same frequency as the wheelsets oscillations. It is therefore clear that both oscillations are interlinked.

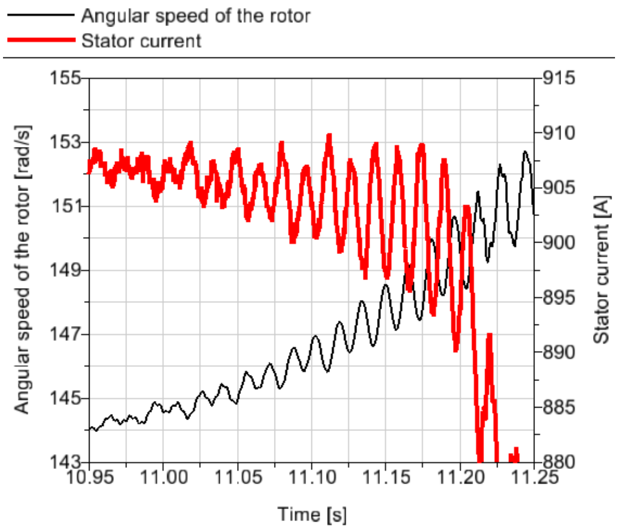

Fig. 8. *Angular velocity of the rotor and the stator current.*

The corrugation of the current can be detected and it allows to detect the origin and the development of the oscillations. This kind of detection may be a few hundredths or tenths of the second faster than the standard stick slip protection. This detection may be used as an additional impulse for reduction of the torque, which

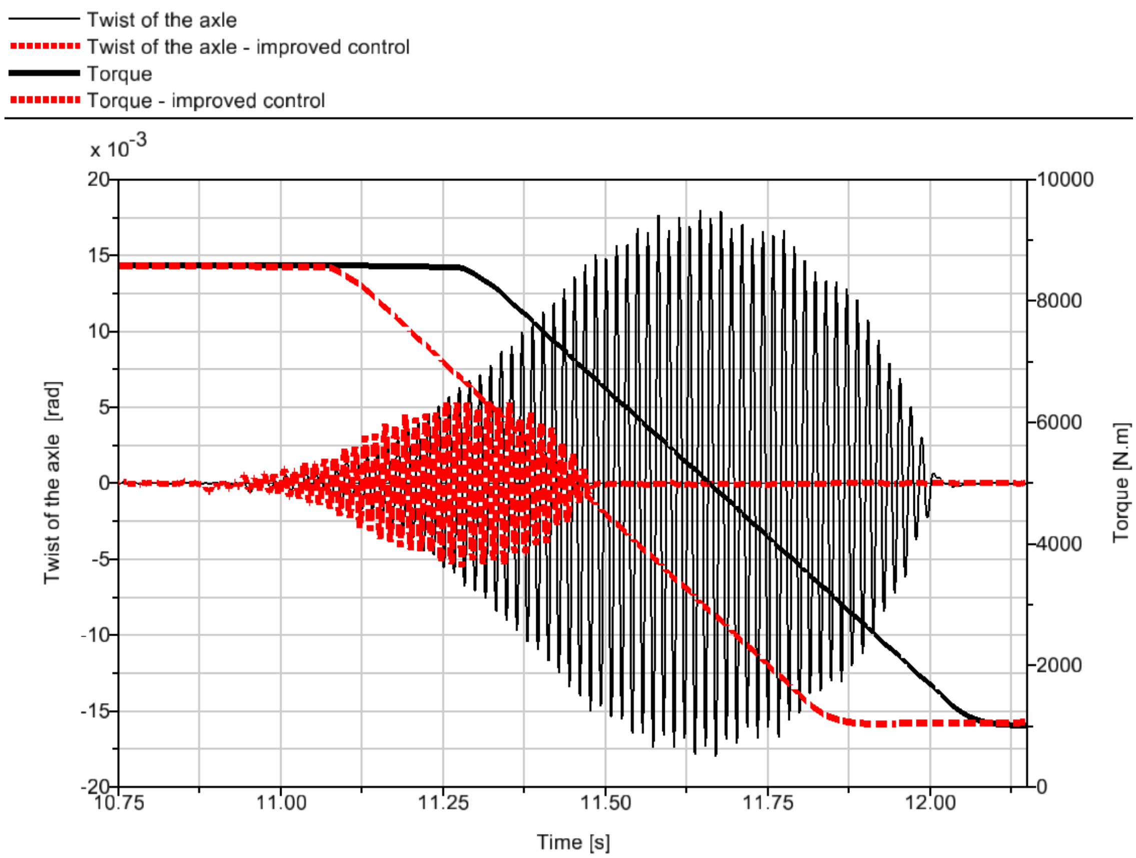

Fig. 9. *Time courses of the oscillations*

may be helpful as a prevention of high oscillations The fig. 9 compares two time courses of the wheelsets oscillations. The black line is the original time course, the red line is the time course with improved control.

The comparisons result is a notable reduction of the amplitude and time duration of the oscillations. The oscillation has been reduced approximately to one third of the original time course.

5. Summary

This text describes a method of detection and reduction of the torsional oscillations in the powered wheelsets that are used in modern railway vehicle. According to the simulation results the mechanical oscillations of the wheelset may be transmitted through the drive chain into the motor. This affects time courses of its electrical values, which may be used as a way of detection and an impulse to intervention.

The research presented was focused on the use of the fully suspended drive. The other types of drives were not considered in the research. Consequences of the dynamics of the partially suspended drive will be investigated in the frame of a grant No. SGS17/077/OHK2/1T/12. The grant should also have an experimental part that should be made on an experimental testing device. This will be used as a basis for author's PhD thesis.

Acknowledgement

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List of Used Symbols

μ	coefficient of the friction (1)
i_{jk}	current (A)
γ	angle (rad)
F_i	force (N)
J_i	inertia momentum (kg.m^2)
k	coefficient(1)
k_t	torsional stiffness of the axle (Nm.rad^{-1})
L	inductance (H)
M_i	torque (Nm)
M^*	required torque (Nm)
P_i	power (kW)
p_p	number of pole pairs (1)
R	resistance (Ω)
t	time (s)
u	voltage (V)
v	velocity (m.s^{-1}, km/h)
y_0	amplitude (m)
φ	twist of the axle (rad)
Ψ_{jk}	magnetic flux (Wb)
ω	angular velocity (rad.s^{-1})

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