Introduction to the Influence of Torsional Oscillation of Driving Wheelsets to Wheel/Axle Press-fitted Joint

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Abstrakt

Příspěvek se zabývá problematikou torzních kmitů hnacích dvojkolí vysoce výkonných hnacích kolejových vozidel (lokomotiv). Popisuje princip měření velikosti kolísání torzního momentu na dvojkolí. Zabývá se výpočtem lisovaného spoje náboje kola a sedla hnací nápravy.

Klíčová slova

Torzní kmitání dvojkolí, hnací dvojkolí

1. Introduction

The aim of the work is to map boundary conditions of dynamic loading of a wheel/axle press-fitted joint.

Axle of drive wheelset is among others stressed by torque. The basic component is torque from the drive, which is positive in a traction mode and negative in a dynamic braking mode. Wheelset, two wheel connected by axle, forms torsion system (Fig. 1.), where wheels with moments of inertia I_1 and I_2 are connected via axle with torsional stiffness k. As a result axle can be preloaded and consequently dynamically loaded in the form of torsional oscillation.

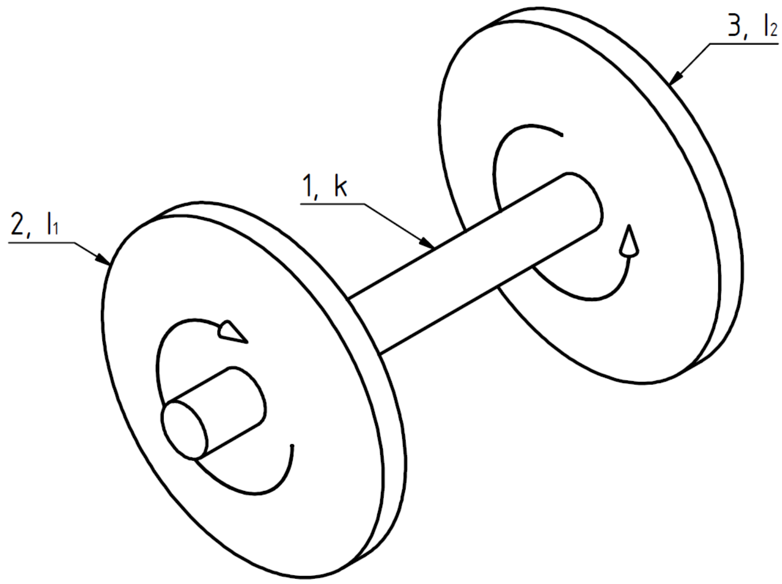

Fig. 1. *Schema of a wheelset – 1-axle, 2-left wheel, 3-right wheel*

1.1 Wheelset drive

There are two main solutions of wheelset drive of modern rolling stock. The first solution is a drive, where the axle wheel of gearbox is pressed on the axle (Fig. 2. left). In the second case

(Fig. 2. right) is torque transmitted via hollow shaft which surrounds the axle. In both cases, the torque transmitted through the left and right wheel corresponds to the current adhesion conditions. This means that in the ideal case, each wheel will transmit 50 % of the torque. Conversely, in the worst case one wheel will transmit 100 % of the torque (in suitable adhesive conditions). The difference is in the way of axle torsion loading.

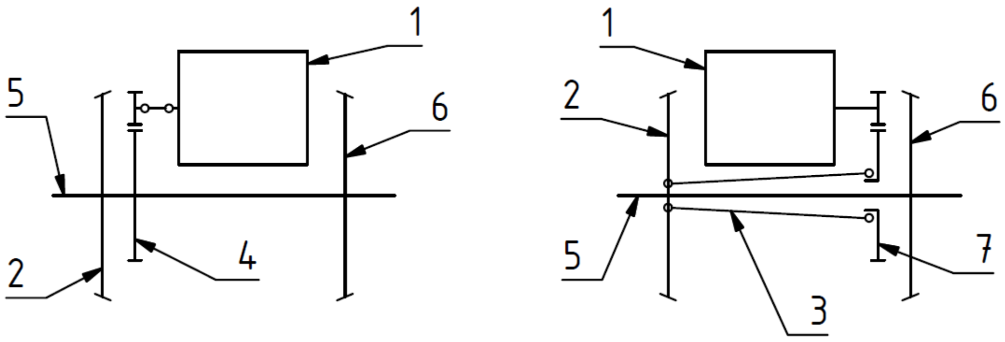

Fig. 2. *Schema of a wheelset drive – 1- traction motor, 2-left wheel, 3-hollow shaft, 4-axle wheel of gearbox, 5-axle, 6-right wheel, 7-gearbox; LEFT: Drive with axle wheel of gearbox press-fitted on the axle, RIGHT: Drive with hollow shaft surrounding the axle*

2. Wheelset torsion oscillations

Under certain conditions torsional oscillation of one wheel to another may develop. The basic condition for the formation of torsional oscillation of wheelset is different angular velocity of rolling between left and right wheel. The consequence is a torsion of axle which is not perfectly rigid. The transition from adhesion to slip does not occur on both wheels at the same time. If one wheel has lost traction, there is its unloading and twisting. At this point the torsional deformation of the axle is released and thus the longitudinal force on the wheel decreases, so that adhesion of the wheel can be restored. At the same time, the torque from the traction motor is transmitted to the second wheel, which remained in the adhesive conditions. This torque (determined for both wheels) can't be transferred on to the rail and consequently slip occurs on the second wheel. This condition can be described as the beginning of torsional oscillation of the wheelset when one wheel oscillates against the other with natural frequency.

2.1 Conditions for the formation of torsional oscillations

Any unevenness in the rolling of wheels leads to twisting of the system. In case of loss of adhesive contact on one of the wheels, stored energy is released and wheelset starts to oscillate. This may occur in the following cases:

- The sinusoidal movement of the wheelset along the straight track. This phenomenon is slow with a frequency that is a function of speed. For conventional rail vehicles, the value of this frequency in the order of Hz.
- Vehicle traveling through curved track. From the difference between the radii of the inner and outer rail higher peripheral speed of the wheel on the outside of the curve is required. This requirement is only partially compensated by conical wheel profile.
- Starting off on the adhesion limit. When transferring longitudinal forces between wheel and rail there is always difference between tangential velocity at the wheel surface and the body velocity. If the increase in this difference increases the tangential force, it is called effective slip. When exceeding the maximum (Fig. 3) which is given by the adhesion limit μ_m with increasing slip velocity tangential force decreases, it is called

slip. Adhesion conditions (limit of adhesion) depends on the instantaneous conditions on the track. These conditions are negatively affected e.g. by moisture or dirt on the track. For modern high performance traction vehicles, to achieve a high traction effort is possible only when the drive controller maintains high effective slip. For the drive control is very important but difficult to detect, when the effective slip changes to slip. The transition from the efficient slip in slip is a typical situation at the beginning of the development of torsional oscillation. A similar mechanism is also applied in dynamic braking mode.

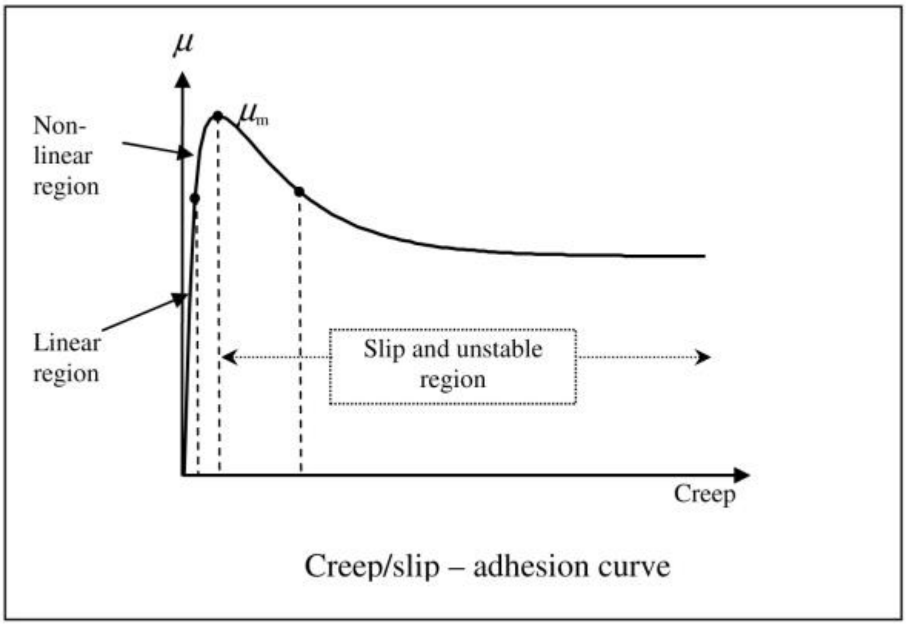

Fig. 3. *Creep/slip – adhesion curve, [1]*

3. Calculation of natural frequency of torsional oscillation

Wheelset is modeled as two masses connected by spring with stiffness k (Fig. 1). Within the analytical calculation the axle is replaced by tube with a constant cross-section. The torsional stiffness of the spring that replace the axle is determined as:

$$k = \frac{GJ_p}{l}, \tag{1}$$

where G is shear modulus, J_p is polar second moment of area and l is twisted length of the axle. Natural frequency is determined as [2]:

$$f = \frac{1}{2\pi}\sqrt{k\left(\frac{1}{I_1} + \frac{1}{I_2}\right)}, \tag{2}$$

where I_1, I_2 are moments of inertia of left and right wheel.
To confirm the result of the analytical calculation modal analysis by finite element method has been also performed. Table 1 shows the resulting natural frequencies normalized by analytically calculated frequency.

Table 1. *– Natural frequency of torsional oscillation*

Analytical calculation	FEM	Measured value
1	0,99	1,03

The calculated natural frequencies are in good agreement with values obtained from the measurements. The difference is mainly caused due to the simplifications of models both in the analytical calculation and the calculation by finite element method.

4. Description of measurement

Measurements were carried out to determine the maximum of the torsional moment that loads axle when a torsional oscillation occurs and the conditions under which this phenomenon occurs most often. The measurements were carried on vehicle powered by asynchronous traction motors. Test runs were carried out on straight track and in curve of small radius with cant. Measurements were carried out under various conditions of the track (dry/wet).
Strain gauges were used for measuring bending stress, torque on the axle and torque supplied to the wheelset. Speed of vehicle was also measured.

4.1 Data processing and evaluation

For the practical part, I got a data measured during the real experiment. Data processing was done in program Matlab. Data was taken with a high sampling frequency. To remove noise from the signal linear low-pass filter with Hamming's window was applied. Top of the figure 4 shows typical waveforms of torque supplied to the wheelset $M_{t,M}$ and the torsional moment in the axle $M_{t,A}$ when the vehicle starting on a wet track. At the bottom of the figure is a detail of single torsional oscillation. Torque values are normalized with nominal torque $M_{t,j}$ supplied to the wheelset with maximum traction effort. The figure shows that upon occurrence of the torsional oscillation the size of the axle torsional moment is several times higher than its nominal value. Duration of torsional oscillation depends on the speed of regulation of the traction motor controller.

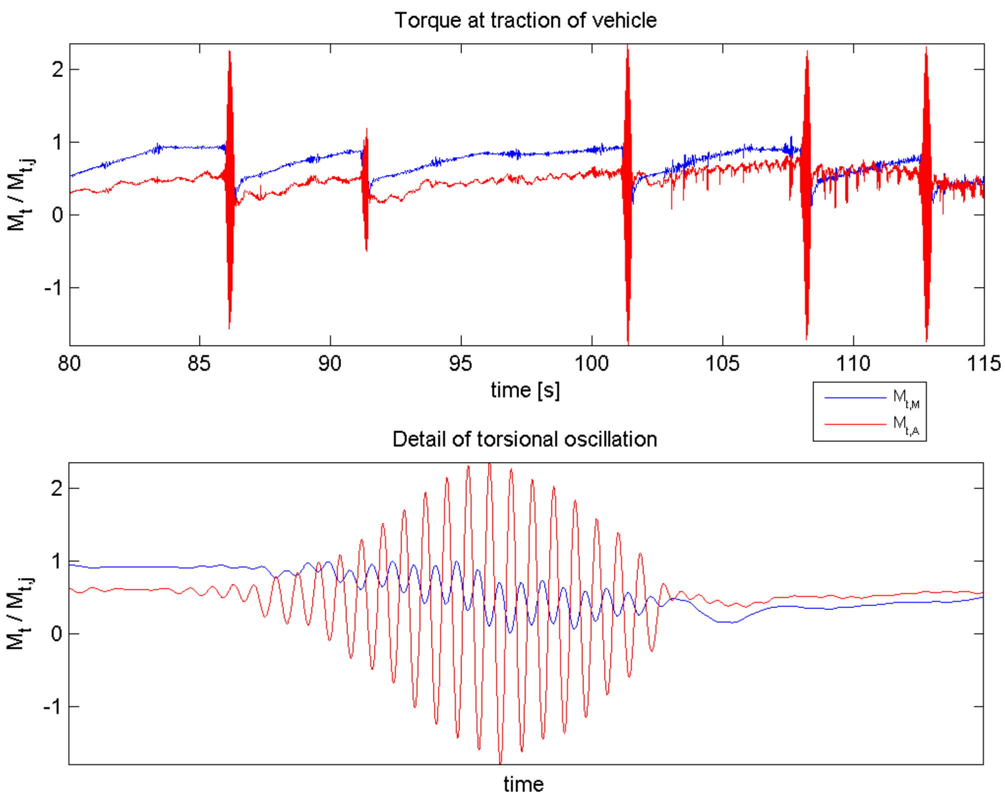

Fig. 4. *Torque at traction of vehicle*

The bending moment between the wheels was determined from the known dimensions of the axle and the measured bending stress as:

$$M_b = \sigma \frac{I_b}{d}, \tag{3}$$

where σ is measured bending stress, I_b is second moment of area about neutral axis and d is axle diameter of place where strain gauge was applied. Top of the figure 5 shows typical waveform of bending moment when the vehicle starting. Bottom of the figure 5 shows detail of bending moment in the time domain, when there was single torsional oscillation (Fig. 4. bottom). The bending moment is normalized by nominal bending moment $M_{b,j}$, which acts on the axle while the vehicle is in a straight track.

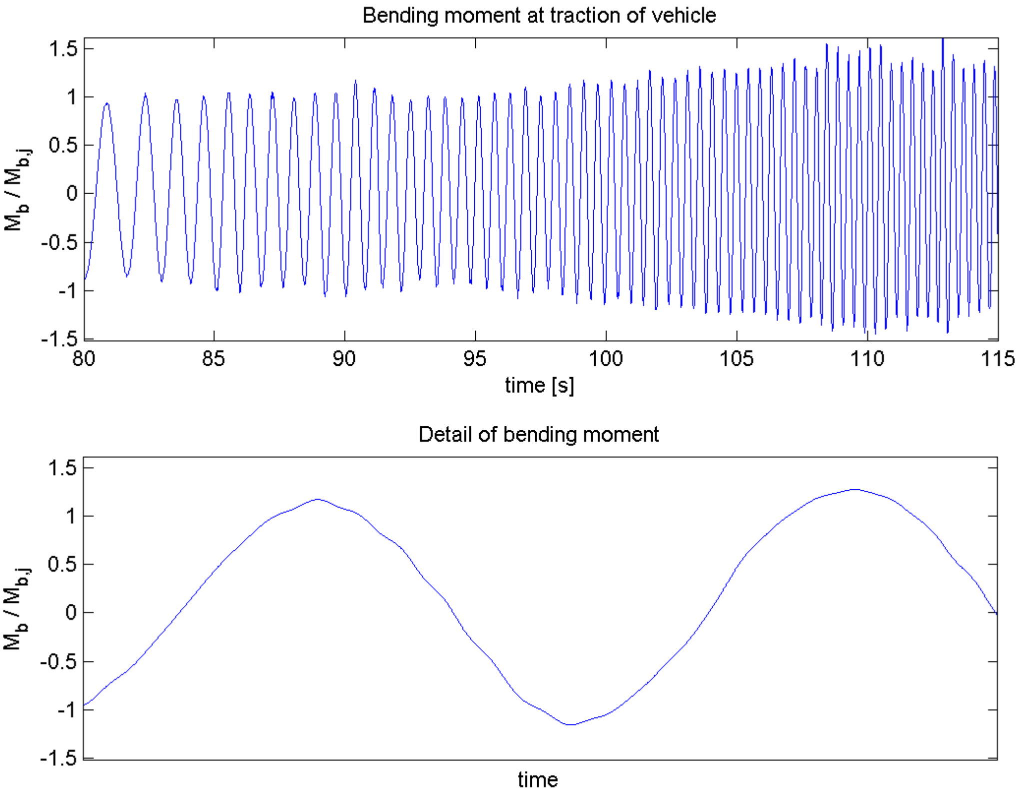

Fig. 5. *Bending moment at traction of vehicle*

To determine the frequency of the torsional oscillation signal was converted to the frequency domain by Fourier transformation. Figure 6 shows a typical frequency distribution when the vehicle starting on a wet track. Band of low frequencies corresponds to the speed of rotation of the wheelset. There is a visible component that corresponds to the power line noise. The band of frequencies that corresponds to the torsional oscillation of the wheelset is also seen here. Due to the small difference between frequency of power line noise and torsional oscillation frequencies the power line noise was not filtered. The picture shows case where the power of the noise was significant. In most other cases, the power on this frequency was negligible.

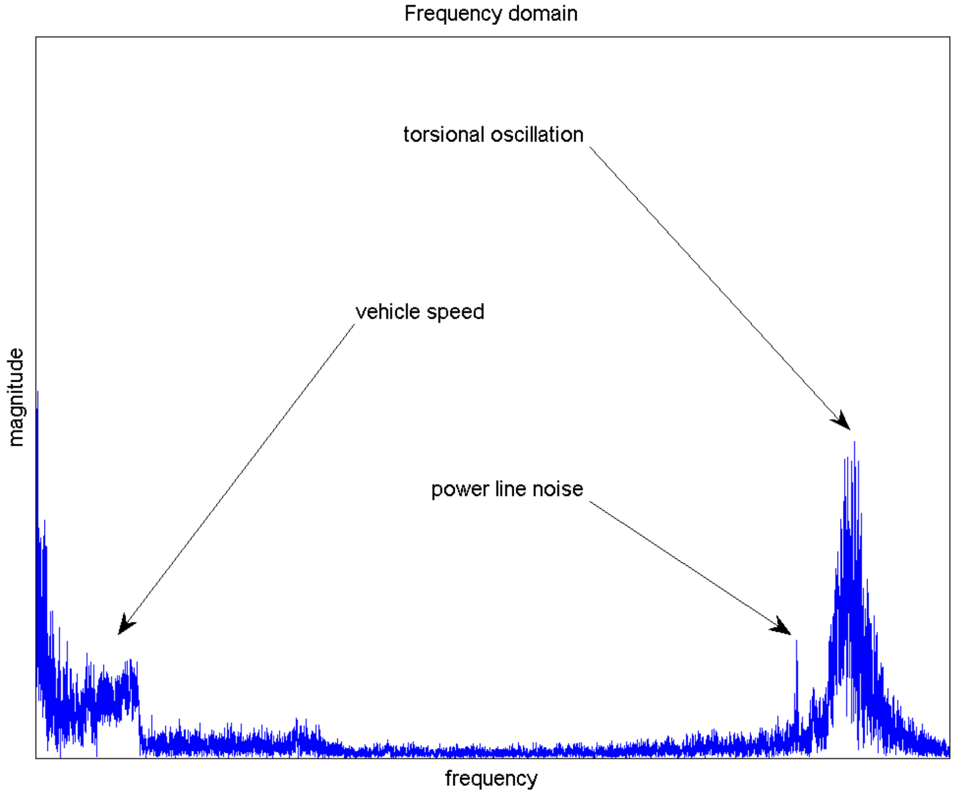

Fig. 6. *Frequency domain of torque signal*

5. Results

Torsional oscillation of the wheelset occurred when the vehicle starting off on a wet track, both on a straight track and in a curved track. When starting off on a dry track torsional oscillation occurred only at curved track. It can be concluded that the appropriate conditions for the development of torsional oscillation is different vertical load of the left and right wheel. Torsional oscillation occurred especially under worse adhesion conditions on the track.

The maximum value of the torque measured during traction mode reached higher values than in the electrodynamic braking mode. This phenomenon is related with different torque control of traction motors during acceleration and braking. The maximum drive torque is not limited by other than characteristic of the traction motor, while the maximum braking torque is limited by the design adhesion limit that is approximately $\mu_m = 0{,}15$.

Peak values of torque in the axle was up to 2.7 times of the nominal value $M_{t,j}$. Duration of the torsional oscillation is dependent on the method of control of the traction motor. In particular, it is the speed of detecting the occurrence of torsional oscillation.

Calculation of the first natural frequency of the wheelset is in good agreement with the measured value. Difference between the measured value and the analytical calculation is 3 %.

6. Conclusion

The amplitude of the torque in the presence of torsional oscillation can reach such values, it can leads to the wheel spin on the axle at press-fitted joint (Fig. 7). For this reason, it would be appropriate to simulate the effect of torsional oscillation to wheel/axle press-fitted joint and to determine the conditions under which this connection may slip.

The typical load will serve as a boundary condition in modeling of slippage at wheel/axle press-fitted joint.

Fig. 7. *Wheelset – press-fit slippage, [3]*

List of symbols

I_1, I_2	moments of inertia of left and right wheel	(kg·m^2)
k	torsional stiffness of the axle	(Nm·rad^{-1})
μ_m	adhesion limit	(-)
G	shear modulus	(MPa)
J_p	polar second moment of area	(m^4)
l	twisted length of axle	(m)
f	natural frequency of torsional oscillations	(Hz)
$M_{t,A}$	torsional moment in the axle	(Nm)
$M_{t,M}$	wheelset input torque	(Nm)
$M_{t,j}$	torque at maximal traction force	(Nm)
M_b	bending moment	(Nm)
$M_{b,j}$	bending moment while vehicle stays on straight track	(Nm)
σ	bending stress	(MPa)
I_b	second moment of area about neutral axis	(m^4)
d	axle diameter	(m)

References

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