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The influence of mechanical design parameters on roll-slip oscillations in locomotive drives*

Abstract

This paper deals with roll-slip oscillations in locomotive drives. Numerical simulation results are presented which demonstrate that roll-slip oscillations may arise if the contact conditions at the left and right wheel of a wheelset are different. Even if an adhesion controller can detect and reduce these vibrations within a few seconds the drive chain is still subject to high loads, there are noisy vibrations in the locomotive car body and the rail surface is damaged by periodic wear patterns. Usually, it is tried to avoid roll-slip oscillations by an optimal adhesion controller design. A different approach is presented in this paper. Instead of optimising a controller it is demonstrated how mechanical design parameters influence the proneness to roll-slip oscillations and for one locomotive type it is shown how a certain mechanical parameter combination helps to avoid roll-slip.

1. Introduction

Roll-slip oscillation in locomotive drives is an unstable vehicle motion and is usually associated with a slip velocity-traction force characteristic with a negative gradient at relatively high slip velocities. This characteristic was found during many experiments [2] [3]. Operating the locomotive beyond the maximum of the slip velocity-traction force curve introduces negative damping to the system and the vehicle dynamics can become unstable. This causes high mechanical loads in the drive chain, noisy
vibrations in the locomotive car body and periodic wear patterns on the rail surface.

Presumably, in [4] roll-slip oscillations in locomotive drives have been first thoroughly investigated using a simple numerical model of the mechanical drive chain. More recently, [5] and [6] are dealing with roll-slip oscillation and how control mechanisms can help to avoid this phenomenon. In this paper a different approach is presented. In addition to a control strategy which detects and reduces roll-slip oscillations it is tried to reduce the proneness to roll-slip by the mechanical design of the locomotive drive.

For one locomotive type numerical simulation results demonstrate that roll-slip oscillations may arise if the contact conditions at the left and right wheel of a wheelset are different. It is also shown that the adhesion controller of the locomotive detects these vibrations and the high amplitudes are reduced after a few seconds. But during this period of time the drive chain is subject to high mechanical loads. A mechanical design which had a smaller proneness to roll-slip would reduce the number of roll-slip occurrences during operation and would therefore lead to a longer life-time of the locomotive. It is therefore investigated how mechanical design parameters influence the proneness to roll-slip and for the locomotive type investigated it is shown which parameter combination helps avoiding roll-slip.

* This contribution is a slightly extended version of a paper presented at GAMM 2000, held in Göttingen in April 2000 [1]

2. The numerical simulation model

The modeled control part of the locomotive comprises the motor control and the adhesion control. The motor control is considered by measured transfer functions. The adhesion controller determines the optimal slip between wheel and rail, so that maximal traction forces are obtained [7] (cf. Figure 1): A speed sensor measures the response of the angular velocity of the rotor to the motor torque plus a sinusoidal test signal added to the motor torque. Based on the phase between filtered sinusoidal rotor speed response and the sinusoidal motor torque test signal the gradient of the slip velocity-traction force curve at the operating point is computed. The actual gradient is compared to a predefined desired gradient. If the difference between both is too large a new desired rotational rotor speed is calculated. This is the input to the speed controller which determines a new desired motor torque.

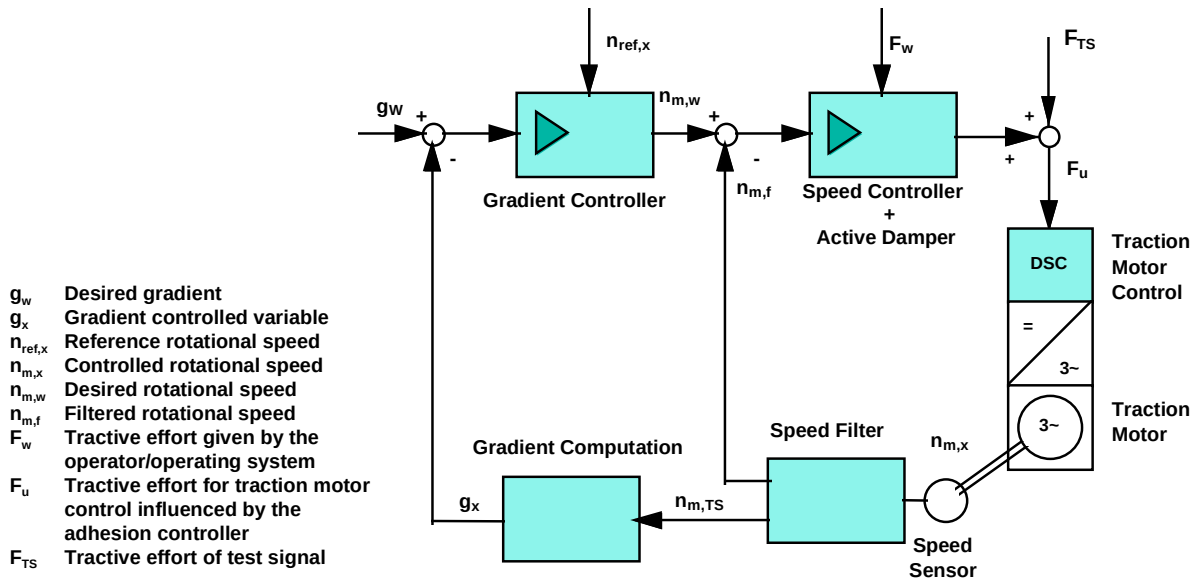


Figure 1: Illustration of the adhesion controller

The mechanical structure has been modeled using ADAMS/Rail. All parts are rigid and all springs and dampers are linear. The mechanical model is illustrated in Figure 2. It comprises half of the car body, one bogie, secondary and primary support, drive components and three wheelsets. The wheelset axle is flexible about the lateral axis. The locomotive type investigated is driven by a so-called nose-suspended drive, which consists of motor box, rotor, gear wheel and the motor box support. The gearwheel is fixed to the wheelset axle and is in the vicinity of the right wheel. The motor box is supported by the wheelset axle but can rotate about it. The motor box is connected to the bogie by the motor box support.

For the numerical simulation a mechatronical model has been set up within MATLAB/SIMULINK which comprises the mechanical structure, the control part and the interaction between mechanics and control.

3. Simulation results if contact conditions at left and right wheel are different

With the mechatronical model a time step integration has been performed to simulate the dynamical behavior of a locomotive which starts on wet rail. In Figure 3 the slip-velocity-traction force characteristics are shown which have been assumed for the numerical simulation.

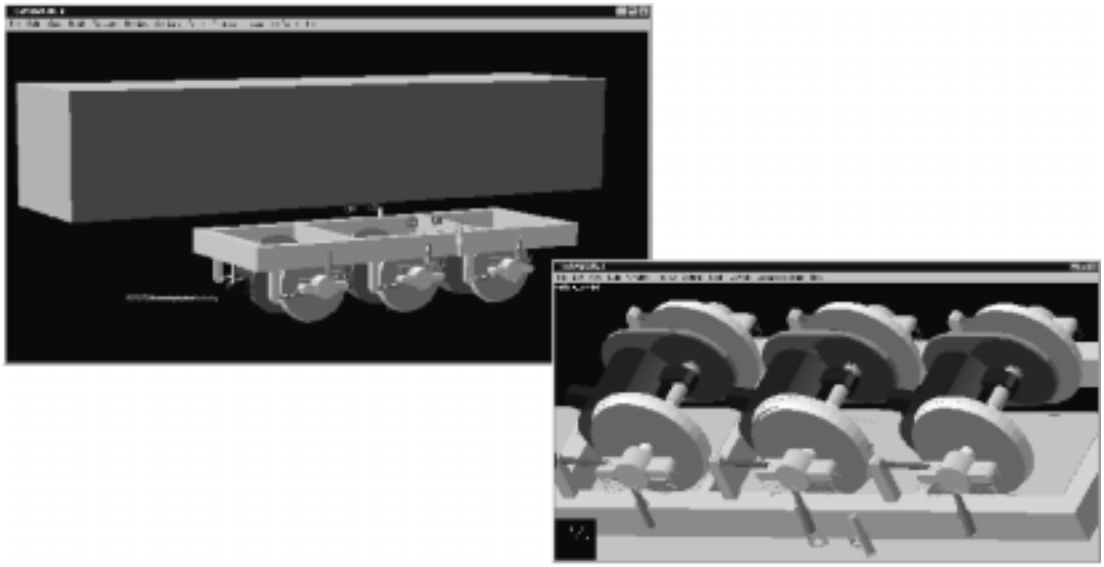


Figure 2: Illustration of the mechanical ADAMS model of the locomotive

At the beginning of the simulation the contact is the same for both wheels of a wheelset. But the contact is different at different wheelsets to consider conditioning effects caused by a preceding wheelset (Figure 3(a)). After ten seconds the contact at the right wheel changes (Figure 3(b)). This might be due to weather conditions: The sun is shining on one track side while the other side is in the shade. Contact conditions can also be different due to kinematic effecs: In the curve the rolling radii of left and right wheel are different and the translational velocities of inner and outer wheel are not the same. This results in different slip velocities at the right and left side of a wheelset and thus in different operating points on the slip velocity-traction force curve.

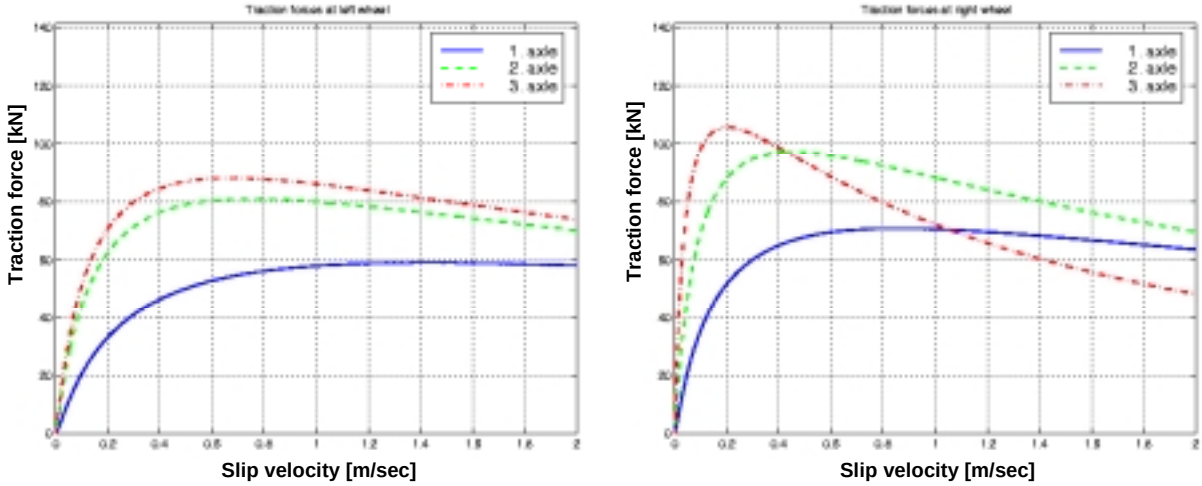


Figure 3: (a) Longitudinal contact condition at left and right wheel if t<10 sec, (b) longitudinal contact condition at right wheel after ten seconds

Figure 4 the outcome of the numerical simulation for the slip velocity at the left and right wheel of the third wheelset is plotted. First, the slip velocity increases till a predefined limit of 0.2 m/s is obtained. After four seconds the adhesion controller superposes a test signal of 11 Hz to the motor torque. The adhesion controller starts to change the slip velocity after 6 seconds until the right contact changes at t= 10 sec. A sudden drop is followed by a new increase until the vehicle dynamics become unstable and the slip velocity at the right wheel is oscillating with high amplitudes and a frequency of about 147 Hz. An eigenvalue analysis of the mechanical structure reveals that at this natural frequency the right wheel is rotating about the lateral axis. The rotation of right wheel and gearwheel is out-of-phase, the amplitudes of the rotation of the left wheel are small. The roll-slip oscillation arises since the right wheel of the third wheelset is operated at slip-velocities where the gradient of the slip velocity-traction force curve is negative. The controller detects the unstable motion and reduces the slip velocity until the gradient of the slip velocity-traction force curve is negative at all wheels. The amplitudes decrease and after a few seconds the vehicle dynamics is again stable.

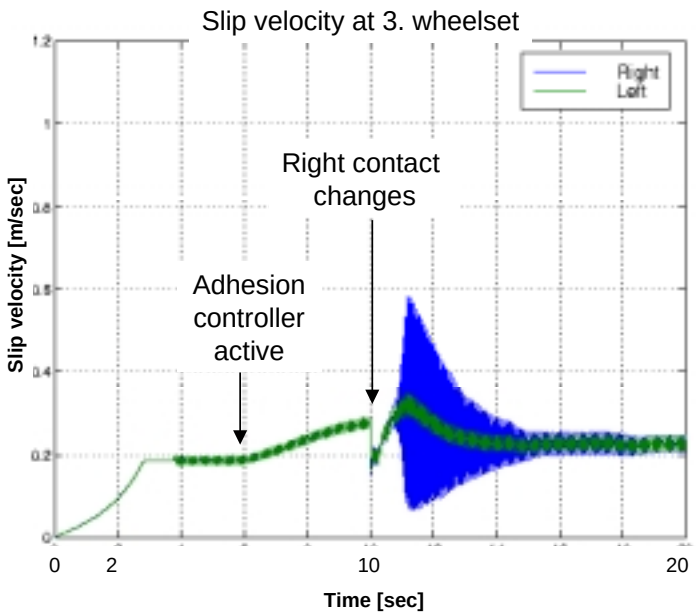


Figure 4: Slip velocity at left and right wheel of the third wheelset

4. Investigation of the influence of mechanical design parameters

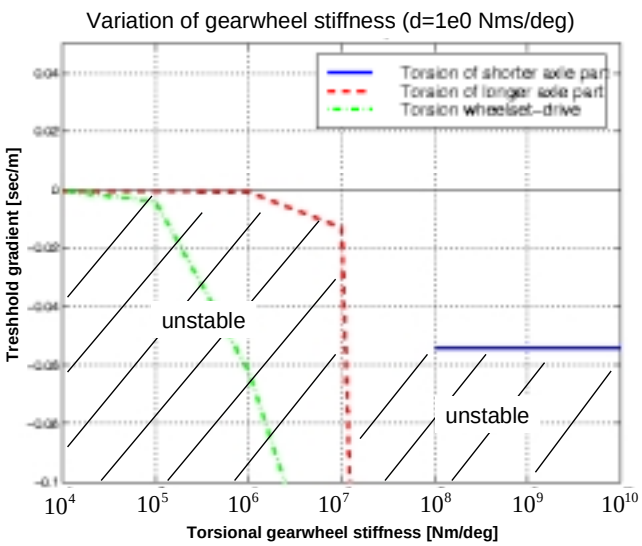
Figure 4 it is shown that the vehicle dynamics may become unstable if the contact conditions at the left and right wheel of a wheelset are different. It is also demonstrated that the adhesion controller detects the unstable motion and reduces the amplitudes of the oscillations after a few seconds. Nevertheless, the drive chain is subject to high mechanical loads during this period of time. It is now investigated how mechanical design parameters influence the proneness to roll-slip and for the locomotive type investigated mechanical design parameters are given which are likely to reduce the number of roll-slip occurrences.
For the investigation of the proneness to roll-slip the torsional stiffness and damping of the connection gearwheel-wheelset axle and the torsional stiffness of the wheelset axle between gearwheel and right wheel of a wheelset are varied. The investigation is performed in the frequency domain and at the first two wheelsets and at the left wheel of the third wheelset the gradient of the slip velocity-coefficient of friction curce is assumed to be zero while at the

right wheel of the third wheelset the gradient is varied from zero to a negative value. Note, that for the traction force at one wheel the relation

$$F_{traction} = \mu(\Delta v)\, N_{static}$$

is assumed, where μ is the coefficient of friction, Δv is the slip velocity and N_{static} is the static wheel load in vertical direction.

For each mechanical design parameter combination the eigenvalues of the linearized mechatronical model are calculated for different gradients at the right wheel of the third wheelset and the threshold gradient is determined, which is the minimal gradient where the vehicle dynamics is still stable. The outcome of this investigation is summarized in Figure 5(a), Figure 5(b) and Figure 6.



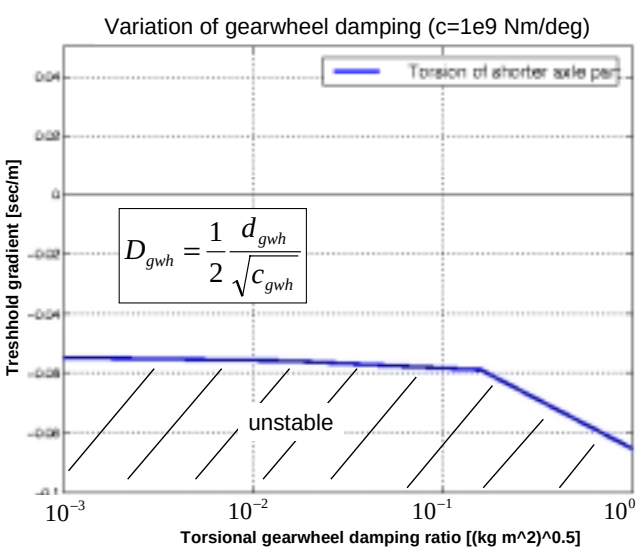


Figure 5: Threshold gradient at (a) different torsional stiffnesses and (b) different torsional damping coefficients of the connection gearwheel-wheelset axle

In Figure 5(a) the threshold gradient is plotted at different torsional stiffnesses between gearwheel and wheelset axle. At relatively small stiffnesses the proneness to roll-slip is high. Even for gradients only slightly smaller than zero the system becomes unstable. The corresponding natural mode is characterized by a torsion of the wheelset axle between gearwheel and left wheel. At higher stiffnesses the proneness to roll-slip clearly decreases and the vehicle dynamics becomes unstable if the gradient at the right wheel of the third wheelset is smaller than -0.055 s/m. The unstable motion is then characterized by a torsion of the wheelset axle between gearwheel and right wheel.

The threshold gradient at different torsional damping coefficients of the connection gearwheel-wheelset axle is plotted in Figure 5(b). For this calculation the torsional stiffness between gearwheel and wheelset axle has been set to $1x10^9$ Nm/deg. Along the x-axis a damping ratio is plotted which has been defined as $D_{gwh} = 0.5\, d_{gwh} / \sqrt{c_{gwh}}$, where d_{gwh} is the torsional damping coefficient and c_{gwh} is the torsional stiffness between gearwheel and wheelset axle. It reveals that the proneness to roll-slip decreases if the torsional damping increases.

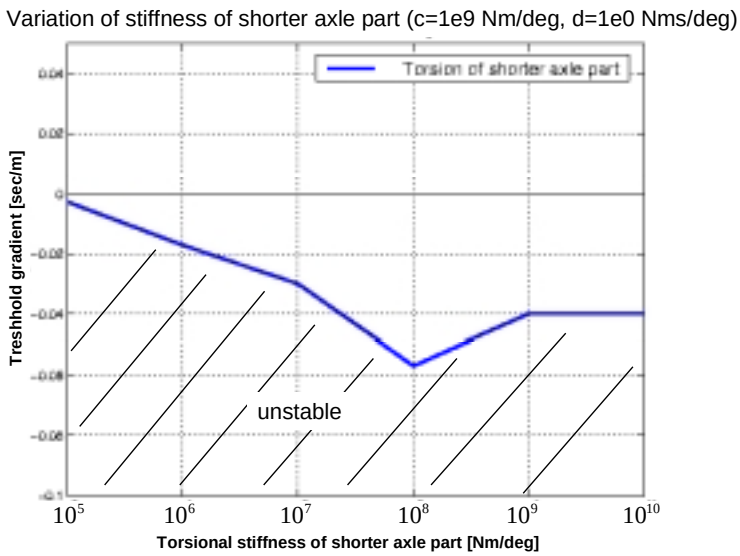


Figure 6: Threshold gradient at different torsional stiffnesses of the wheelset axle between gearwheel and right wheel

In Figure 6 the threshold gradient is plotted at different torsional stiffnesses of the wheelset axle between gearwheel and right wheel. For this calculation the torsional stiffness of the connection gearwheel-wheelset axle is $1x10^9$ Nm/deg, the corresponding damping coefficient is 1 Nms/deg. It is illustrated that the vehicle dynamics is most likely to remain stable if the torsional stiffness is relatively high.

5. Conclusions

In the paper presented a numerical model of an electrical locomotive has been introduced. The mechanical model has been modeled by ADAMS and the control part by MATLAB/SIMULINK. Within MATLAB/SIMULINK a mechatronical model of the locomotive consisting of these both parts has been set up. It has been used to carry out numerical investigations of the influence of mechanical design parameters of the drive chain on the proneness to roll-slip.

The outcome of the variation of mechanical design parameters is that the locomotive type investigated has a reduced proneness to roll-slip if the connection between gearwheel and wheelset axle is stiff and highly damped and if the torsional stiffness of the wheelset axle is relatively high. With these mechanical design parameters it is therefore likely to reduce the number of roll-slip occurrences and thus to increase the life-time of this locomotive.

Acknowledgements

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