Integrated vehicle dynamics control for a mechatronic railway running gear

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Abstract

Safety is especially for high-speed railway traffic one of the main aspects that has to be continuously improved to sustainably strengthen the railway sector and shift the modal split. To overcome the limitations of passive systems, an active control of mechatronic running gears provides essential advantages. In the present work, the focus is on the active control of lateral and longitudinal dynamics which are closely coupled via the tangential wheel-rail contact. Therefore, the introduced integrated control concept combines lateral and longitudinal control tasks. After the description of the lateral and longitudinal sub-level controllers the benefits of the integrated control are demonstrated. A comparison of the developed concept with a reference control using a preallocated torque for the lateral track guidance is drawn. The results of a simulation including volatile wheel-rail conditions and a jump in the desired lateral position underline the potential of integrated control to reduce braking distances and simultaneously improve lateral stability.

Keywords: integrated control, track guidance, braking distance.

1 Introduction

Safety is especially for high-speed railway traffic one of the main aspects that has to be continuously improved to sustainably strengthen the railway sector and shift the modal split. To overcome the limitations of passive systems, an active control of mechatronic running gears provides essential advantages. In the present work, the focus is on the active control of lateral and longitudinal dynamics which are closely coupled via the tangential wheel-rail contact.

In the field of longitudinal dynamics control, there are two main control goals: (i) repeatability of braking distances in stopping brake scenarios and (ii) reduction of braking distances in emergency brake scenarios. In [1] a deceleration-based control concept addressing repeatability is validated in field tests. A control algorithm for emergency brake maneuvers especially under bad and volatile environmental conditions is presented in [2]. However, both control concepts address only longitudinal dynamics and neglect the lateral component.

Regarding lateral dynamics, active control concepts can be distinguished between actuator-steered and motor-steered approaches [3]. Actuator-steered approaches as described in [4] are primarily applied for undriven wheelsets. For driven wheelsets the integration of a linear actuator results in unnecessary costs and a higher maintenance effort which can be avoided by using a motor-steered control. An example for a motor-steered lateral dynamics control is developed in [5]. A characteristic aspect of motor-steered methods is that usually a certain constant amount of the maximum motor torque is allocated for lateral control. However, this allocation might lead to a suboptimal brake performance in emergency brake scenarios, when a part of the maximum motor torque is unused because lateral control does not need its whole allocated torque. In a similar way the performance of lateral control might be unnecessarily be restricted in scenarios with a constant speed, when longitudinal control does only need a very small torque if any and almost the complete motor torque could be used for lateral control.

These two cases underline that a holistic improvement of comfort and safety demands for an integrated vehicle dynamics control, which covers lateral and longitudinal control tasks. In the present work such a combined integrated control strategy for a mechatronic running gear with driven independently rotating wheels (DIRW), see **Fehler! Verweisquelle konnte nicht gefunden werden.**, is presented. Furthermore, to demonstrate the benefits of this control concept, initial results are illustrated and discussed.

Figure 1: Experimental running gear in 1:5 scale at the Institute of System Dynamics and Control in Oberpfaffenhofen, Germany

2 Methods

In this section a control concept is introduced intending to replace the torque allocation used in other control frameworks. Instead of the fixed allocation the integrated concept situationally distributes the maximum available torque τ_{max} to lateral and longitudinal control. In this way, any loss of lateral stability is avoided and simultaneously the braking distance is reduced. The maximum available torque is limited by two aspects: (1.) by the hardware, (2.) by the maximum available adhesion.

The lateral subcontroller used in this paper is specifically developed for the lateral control of DIRWs, see [6]. The aim is to generate a robust control design which ensures stability of the running gear dynamics over the entire speed operating range. The demanded motor torque of the lateral control is defined as a differential torque between left and right wheel

$$\tau_{y,ij} = \pm[k_y \quad k_\psi \quad k_{\dot{\psi}}]\begin{bmatrix} y_i \\ \psi_i \\ \dot{\psi}_i \end{bmatrix}, k_y = 63 + 9.7 \cdot v_x, \quad k_\psi = -17 + 49 \cdot v_x,$$

$$k_{\dot{\psi}} = 3 + 3.35 \cdot v_x, \tag{1}$$

with the indices i = (front, rear wheel-carrier), j = (right, left wheel), lateral position y_i, yaw angle ψ_i, and yaw rate $\dot{\psi}_i$ of the wheel-carrier as well as the longitudinal vehicle speed v_x.

The basic assumption of the integrated control architecture is that the lateral controller should continuously set its demanded torque $\tau_{y,ij}$ to avoid instability and to prevent wheel flange contact. Thus, in case (1.) the brake torque is

$$\tau_{x,i} = \tau_{max} - abs(\tau_{y,ij}). \tag{2}$$

This torque $\tau_{x,i}$ is applied to both wheel motors of one wheel-carrier in the same rotational direction. The resulting motor torque reads

$$\tau_{ij} = \tau_{x,i} + \tau_{y,ij}. \tag{3}$$

In case (2.) when τ_{ij} causes the wheels to slip into the unstable macro slip area, the commanded torque is reduced. This task is realized via a bang-bang longitudinal controller based on [2]. It detects the stable and the unstable adhesion area by the evaluation of the following criterion

$$\dot{\alpha}_{ij} \cdot \dot{s}_{ij} < 0, \tag{4}$$

with the time derivatives $\dot{\alpha}_{ij}$ and $\dot{s}_{ij}$ of the wheel-rail adhesion and the slip, respectively. In the stable area, the controller raises to a defined high deceleration torque, whereas it drops to a low deceleration torque when the maximum adhesion is exceeded.

The last aspect of the longitudinal control tackles the fact that at the left and right wheel different contact conditions might occur. In order to avoid an unintentional differential torque due to the longitudinal control, the torques of left and right wheel are linked via the min-function

$$\tau_{x,i} = min(\tau_{x,il}, \tau_{x,ir}). \tag{5}$$

3 Results

To demonstrate the advantages of the integrated control concept, a combined track guidance and braking scenario is generated. The simulation environment consists of the developed control architecture and an analytic plant model of the running gear pictured in **Fehler! Verweisquelle konnte nicht gefunden werden.**. The wheel-rail contact in the plant model is implemented according to Polach theory [7], since this allows a realistic consideration of the adhesion behavior around its maximum value. The maximum motor torque per wheel is 2.5Nm. In addition to the integrated control a reference control with an allocated lateral torque of 0.4Nm is simulated, so that a reasonable comparison can be drawn.

The test scenario starts with an initial vehicle speed of v_0=16 m/s. During the simulation a desired trajectory for the lateral motion y_{des} is commanded. It imitates a hunting motion with an amplitude of 10mm and a frequency of 1Hz. At time t = 4s, a positive offset of 10 mm is applied to the hunting signal. This excitation is included to test the perturbation of longitudinal and lateral control. In addition, for an adequate analysis of the longitudinal controller, its performance under different contact conditions is verified by varying friction parameters. In detail, the maximum wheel-rail friction coefficient $\mu_{x,0}$ is reduced from its initial value 0.55 to 0.15 for the time domain $t \in [1.0s, 3.5s]$ at both right wheels and for $t \in [1.0s, 4.0s]$ at both left wheels.

The simulation results can only be roughly discussed due to the limited space. Regarding the longitudinal dynamics, the reference controller has a longer braking distance. This comes from the fact that a certain part of the fixed motor allocation remains unused and is therefore squandered. In numbers, the braking distance can be reduced by the integrated control by almost 5% from 72.6m to 69.2m.

For the evaluation of lateral dynamics, the RMS value of the deviation between desired and actual position is compared. While the RMS value is 9.5 mm for the reference control, it is only 2.1mm for the integrated control which is equal to a reduction of 78%. Figure 2 showing the results of desired and lateral position reveals that even before the jump in y_{des}, the lateral controller in the reference configuration struggles with the reduced wheel-rail friction. In the end, the integrated control proves its worth and the advantages are clearly demonstrated.

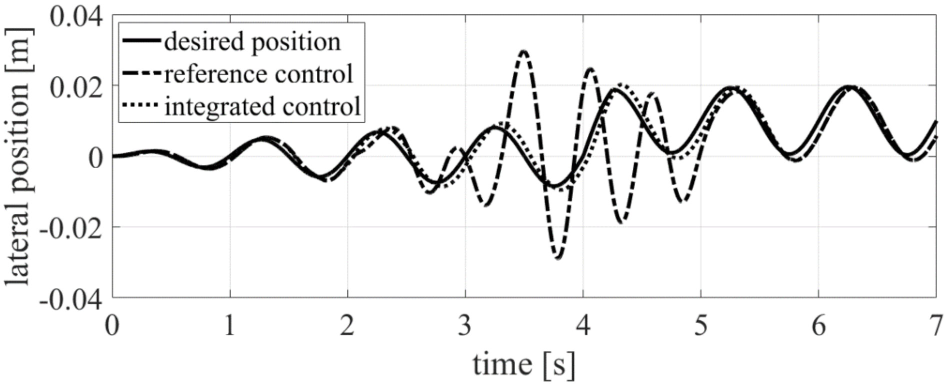

Figure 2: Desired and actual lateral position in the test scenario using reference and integrated control

4 Conclusions and Contributions

The present paper introduces an integrated control concept that combines lateral and longitudinal control tasks. After the description of the lateral and longitudinal sub-level controllers the benefits of the integrated control are demonstrated. Therefore, a comparison of the developed concept with a reference control using a preallocated torque for lateral track guidance is drawn. The results of a simulation including volatile wheel-rail conditions and a jump in the desired lateral position underline the potential of integrated control to reduce braking distances and simultaneously improve lateral stability.

So far, the sub-level controllers are not specifically optimized for a cooperation in the integrated control architecture. Thus, the performance might be even further improved, e.g. when the lateral control synthesis takes the maximum motor torque into account instead of only an allocated, lower part of τ_{max}. Another aspect that will be tackled in the future is the distinct consideration of emergency brake scenarios. More precisely, the interrelation between lateral and longitudinal adhesion behavior as part of the tangential contact have to be investigated in detail to determine a reasonable strategy for the distribution of the motor torque. Finally, the integration and testing of the developed control concept in a hardware environment is a necessary and important next step to confirm the simulation results and validate the performance. In this context the 1:1 scale test rig, which is currently built up at the Institute of System Dynamics and Control in Oberpfaffenhofen [8], will be used as an advanced test environment.

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