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On the real-time estimation of the wheel-rail contact force by means of a new nonlinear estimator design model

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A R T I C L E I N F O

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A B S T R A C T

The dynamics of the railway vehicles is strongly influenced by the interaction between the wheel and the rail. This kind of contact is affected by several conditioning factors such as vehicle speed, wear, adhesion level and, moreover, it is nonlinear. As a consequence, the modelling and the observation of this kind of phenomenon are complex tasks but, at the same time, they constitute a fundamental step for the estimation of the adhesion level or for the vehicle condition monitoring. This paper presents a novel technique for the real time estimation of the wheel-rail contact forces based on an estimator design model that takes into account the nonlinearities of the interaction by means of a fitting model functional to reproduce the contact mechanics in a wide range of slip and to be easily integrated in a complete model based estimator for railway vehicle.

1. Introduction

Rail transportation is undergoing fundamental changes in technologies that contribute to affect the overall transportation efficiency, capacity and reliability. Recent developments concern new train control systems, high-speed passenger rails, advances in railcar and intermodal equipment design, smart systems for vehicle and track health monitoring [1,2]. Overall these areas of interest are strongly influenced by the wheel-rail contact phenomenon. Indeed, the wheel-rail interaction represents a key factor for the whole railway vehicle dynamics because the forces developed at the interface are the fundamental inputs that determine the behaviour of the whole system. The knowledge of the forces is an important step to increase the effectiveness of the railway vehicle dynamics control systems and condition monitoring systems. The control of the longitudinal dynamics is, for example, conditioned by the status of the wheel-rail contact [3] and the interaction forces are the variables more directly affected by changes in adhesion levels or wear. For instance, low adhesion can cause traction and braking issues with the consequence of an increasing of operational risks. Current wheel slip/slide prevention systems adopted in railway vehicles aim to employ all the available adhesion in order to maximize their performance; they are based on the control of the slip ratio that has to be contained in a range which limits are function of the actual adhesion [4,5]. So, real-time informations on the status of the wheel-rail contact is absolutely crucial for the vehicle dynamics control systems, making their intervention modulated on the basis of the adhesion information. Wheel-rail contact forces change in normal running conditions if adhesion level modifies and therefore their estimation is of fundamental importance to have a direct knowledge of the wheel-rail contact status. At the same time, the knowledge of the wheel-rail contact forces is crucial for all the model based approaches finalized to monitor the railway vehicle states and parameters, making them more effective and

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reliable, as it can be seen for suspension condition monitoring [6], or suspension fault detection [7,8]. Indeed, these procedures are often based on assumptions on the wheel-rail contact model (such as linearized contact models with constant creep coefficient) and, consequently, changes in the interaction forces should cause false behaviours in the estimated parameters, making the procedure ineffective. The wheel-rail contact forces are influenced by adhesion, track irregularities, vehicle speed, wheel-rail profile. Moreover, the contact phenomenon is strongly nonlinear and this makes the estimation of the wheel-rail contact forces a challenging aspect.

This paper presents a new model based technique for the real time estimation of the wheel-rail contact force that is characterized by the employment of an estimator design model that includes a nonlinear model for the contact forces. The typical approaches adopted for the wheel-rail contact force observation are based on the estimation of the creep coefficients or on the estimation of forces and moments considered as states of an augmented state vector [9] with no informations as concerns the nonlinear behaviour.

The approach proposed in this paper is finalized to estimate the wheel-rail contact forces in normal driving conditions (no tractive or braking torque applied) and, therefore, with no longitudinal dynamics informations, and with the aim to take into account the nonlinear behaviour of this kind of interaction. So, the idea aims to account for the nonlinearities with respect to the slip ratio through an interaction model simple enough to be integrated in an estimator design model and therefore with the double target of being able to reproduce the physical phenomenon but simple enough to reduce the computational load of the model-based observers. The proposed technique is based on a fitting nonlinear model for the wheel-rail interaction that interacts with the vehicle components dynamics in a more complete estimator design model. The proposed interaction model is estimation oriented and, in order to capture the whole interaction, employs a hyperbolic tangent that can adapt itself by means of two parameters to be identified. The whole procedure is tested and validated employing a nonlinear vehicle model as simulation one, constituted by the commercial software SIMPACK [10].

The paper is organized as follows: Section 2 describes the estimation model and the approaches adopted for comparison, Section 3 illustrates the employed estimation technique while Section 4 shows the simulation results. The conclusions are drawn in Section 5.

2. Estimator design model

The structure of the model adopted in the synthesis of the estimators of the wheel rail contact forces can be schematically described as constituted by two set of equations: the first one refers to the vehicle states (vehicle set equations), the second one refers to the wheel-rail contact states (contact set equations). The vehicle set equations is selected taking into account the fundamental dynamics that affect the contact phenomenon at the wheel-rail interface and the measurements that can be made on board. On this basis, the estimator design model is constituted by a half vehicle body, due to the negligible dynamic coupling of the two bogies by means of the softness of the secondary suspension. Moreover, it refers to normal running conditions, and so the longitudinal dynamics is neglected, and on the more influent modes affecting the railway vehicle dynamics, i.e. the lateral and yaw ones. So, the wheelsets and the bogie have two degrees of freedom (lateral and yaw) while the vehicle body is characterized by the lateral degree of freedom only. As concerns the estimation technique, the extended Kalman filter, widely tested in the railway field [9,11], has been adopted assuming the vehicle equipped with five common

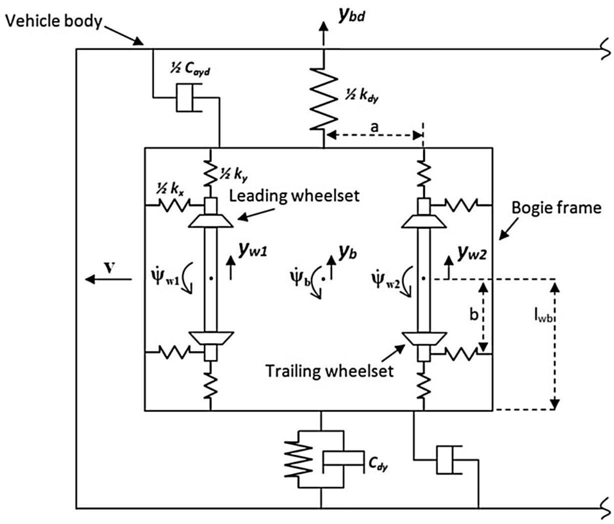

Fig. 1. Half vehicle body.