Indirect wheel-rail force sensing of a flexible multibody train bogie model: A Kalman filter-based state-input estimation

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EXTENDED ABSTRACT

1 Introduction

For the development of condition monitoring and active safety systems in railway applications, it is key to have a good view on the dynamics of the system. This can be seen in light of safety to detect instabilities, e.g. hunting, to conditioning monitoring, e.g. train-wheel forces and wear, but also in light of assessing external factors influencing these monitoring solutions. This includes estimating track conditions (e.g. switches faults, cracks, non-straightness of the track), and other occurrences that are present in the measurements (e.g. aerodynamic loading due to another train passing by on a neighboring track or due to entering/leaving a tunnel). In order to obtain this information in a reliable, and cost-efficient manner, a flexible multibody model of a train bogie is developed and integrated in an extended Kalman filter [1]. This allows measurements to be used to estimate and thus indirectly measure certain load forces, e.g. wheel-rail forces and aerodynamic loading forces, whose effects can be seen in the measurements.

2 Reference Model

The reference model is a flexible multibody model developed in an in-house Matlab code, called the MultiBody Research Code (MBRC) [2]. This is further detailed in [3]. Original technical drawings of the train bogie under investigation were used to make a CAD model and Finite Element (FE) model of the bogie subframe. The technical drawings also allowed to derive the different lumped spring and damping values that should be used and the connection locations to the bogie subframe. This step was necessary over using lumped primary and secondary suspension characteristics because the locations where forces are applied cannot be condensed into one location when they are applied to a flexible component. The reference model also uses a contact model. The contact detection was performed by representing the contacting surfaces (i.e. the wheels and rails) by Non-Uniform Rational B-Splines (NURBS) surfaces. These representations were based on the ISO-norms that are used to manufacture the wheels and tracks. A Bounding Volume Hierarchy (BVH) approach along with the Separating Axis Theorem (SAT) and a Newton-Raphson approach using an analytical gradient for local refinement allowed for contact detection to be performed between the NURBS surfaces, including multiple contact patches that may enter into contact or go out of contact. The contact forces were determined by assuming Hertzian contact for the normal force, and a linear Kalker model for the tangential forces (i.e. the rolling contact friction forces). As the linear Kalker model uses slip as a measure to define the friction forces, it is discontinuous at standstill. In order to produce initial conditions that are not at standstill, an additional short simulation is run using a viscous damping model instead of the friction model to generate initial generalized coordinates and initial generalized velocities. As the actual simulation starts, there will be some transients present due to the modeling inaccuracy that this incurs, but as the startup phase is not the operational conditions of interest, this is not a problem.

3 Extended Kalman Filter Model

The intended use of the model is to correlate measurement data in the form of accelerometers, strain gauges, gyroscopes, and displacement sensors with variations in the contact forces, and external loading conditions that cannot be properly accounted for in the model due to their large uncertainty. The considered scenario is replicated by generating virtual measurement data for validation purposes. In order to do so, the original flexible multibody model is used. This can generate any output for the virtual experiment. For an initial virtual experiment that is set up using this approach, the model used in the extended Kalman filter is the same, except for the Young's moduli used in the Hertzian contact force computation for both the wheel and the rail. They are both reduced by 10% as this modifies the resulting normal force, and the lateral force generated by the model as any estimated normal force is not used in the tangential force computation. The forces to be estimated are three forces and three torques on each of the two train bogie wheelsets. This means that twelve forces will be estimated in total. The goal is to estimate wheel-rail forces but as the wheelset are currently modeled as rigid, only six linearly independent force components can be estimated per wheelset. And for simplicity these are chosen to be three forces and three torques in the center of gravity of each wheelset.

4 Analysis Results

The results of this initial virtual experiment can be seen below. Figure 1 shows the vertical force on the rear wheelset as well as its diagonal a posteriori covariance. All forces are scaled with a random number for confidentiality. The expression shows that there is a transient initially due to the change in Young's modulus and later due to the change in friction model. It also shows that the lack in normal force due to the reduced Young's modulus is compensated. This could also have been compensated via a larger penetration depth, but then the acceleration signals used by the Kalman filter as an error measure would deviate more, and the Kalman filter would compensate for this anyways. Figure 1 also shows that the covariance stabilizes, which means that the estimation of the force itself is stable. Figure 2 shows the longitudinal acceleration at the front wheelset's left-hand side connection. This figure shows that the longitudinal dynamics are compensated, and that the Kalman filter is set up to only compensate for the lower-frequency dynamics. Figure 3 finally shows a comparison between the reference longitudinal forces and the estimation results. Note that the latter includes both the contact forces with reduced Young's moduli and the estimated forces. This figure shows that the total longitudinal force is estimated correctly, but the distribution between the front and rear wheelsets doesn't immediately stabilize. This comes down to filter set-up and tuning as only a small component of the virtual sensor signals are due to the distribution of the longitudinal forces over the wheelsets.

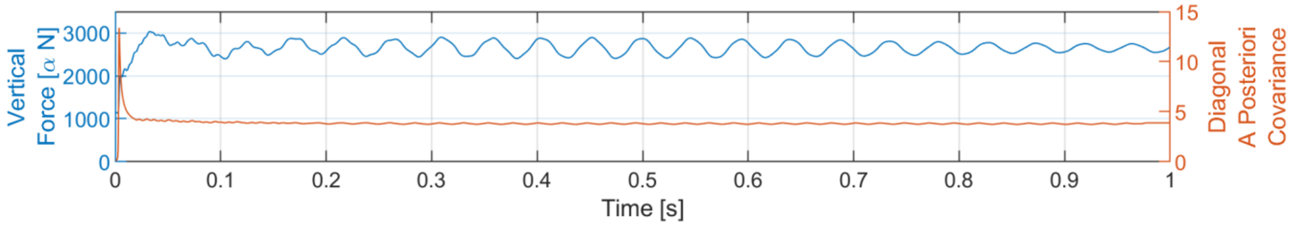

Figure 1: Estimated Vertical Force on Rear Wheelset

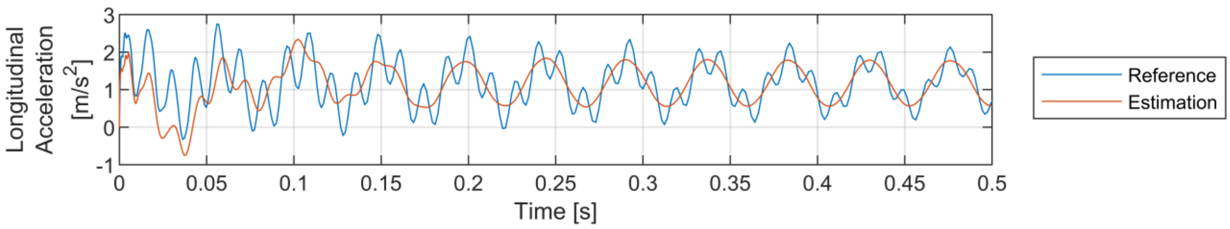

Figure 2: Longitudinal Acceleration Front Wheelset at the Left-Hand Side Connection

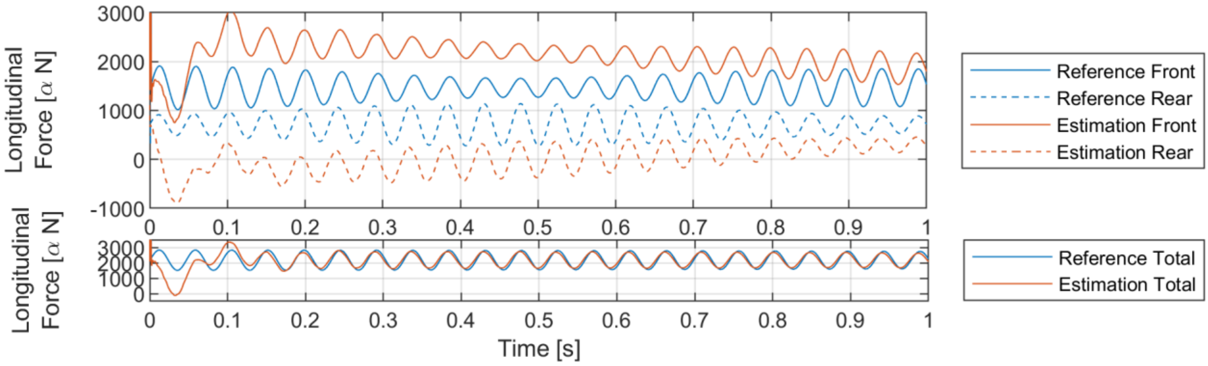

Figure 3: Longitudinal Forces

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