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Estimation of lateral and cross alignment in a railway track based on vehicle dynamics measurements

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ABSTRACT

Monitoring the condition of the infrastructure based on measurements coming from in-service trains is a recent trend in the policies of railway infrastructure managers and is seen as a major factor to reduce maintenance costs retaining the present levels of passengers' ride comfort and availability of the lines.

Aim of this paper is to develop and assess model-based methods for the identification of geometric track irregularities from acceleration measurements taken on-board vehicles travelling on the track. In particular, the paper focusses on the identification of lateral alignment irregularities, a yet unsolved problem which turns out to be much more demanding compared to the identification of longitudinal level irregularities due to the relative wheel-rail motion in lateral direction which occurs on account of the peculiar geometry of wheel-rail contact.

The paper presents three different approaches to the estimation of the lateral and cross-level track irregularities, one defined in the frequency domain and two in the time domain. For each method, an assessment is performed based on numerical experiments in which virtual measurements from vehicle-mounted sensors are obtained by means of numerical simulations performed using a multi-body model of a railway vehicle. For the method defined in the frequency domain, a first application to line measurements is presented.

1. Introduction

Maintaining railway tracks to appropriate standards of quality in terms of their geometry is pivotal for infrastructure managers (IMs) to meet the required standards for safe operation and to ensure appropriate ride comfort levels for the passengers. However, the maintenance effort required to properly maintain the track is extremely high, and represents a major cost issue for the IMs. In recent years, many railway administrations have been implementing strategies for the continuous monitoring of track geometry as a means to identify the portions of the track in need of maintenance, thereby increasing the efficiency of maintenance actions.

The monitoring of track geometry is usually performed by means of track recording vehicles (TRV) which provide an accurate measure of deviations from the ideal track geometry using laser-optical systems [1]. This is however a complex and highly expensive process, as dedicated trains and sophisticated measuring instruments need to be bought, maintained and operated. As a consequence, the distance in time between two consecutive TRV recordings of track geometry on a same line section is often not optimal.

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A way to overcome this problem would be to measure track geometry using in-service vehicles: this would allow the continuous monitoring of track condition in a cost-efficient way. However, the sophisticated optical systems used on TRVs are expensive and require continuous maintenance, so it is not possible to use this type of equipment on in-service vehicles and instead simpler and more robust systems for the measure of track geometry need to be developed. Alternatively, track geometry can be observed using measurements of the vehicle's running dynamics: this can be done using robust and relatively inexpensive transducers, typically accelerometers or gyroscopes, but the development of suitable data treatment and identification methods is required to achieve an accurate estimate of track geometry. A discussion of perspective and problems with the use of in-service vehicles for the monitoring of railway tracks can be found in [2].

Different methods to estimate track irregularities from measurements of the vehicle's running dynamics have been proposed. The simplest strategy consists of double integration of axle-box measurements to retrieve the absolute displacement of the wheel and hence the track geometry [3–5] this method presents however some serious drawbacks: first of all, double integration results in a drift that needs to be removed by filtering out long wavelength results. Furthermore, the maximum acceleration experienced by the axle-box may exceed 100 g on account of short wavelength components of irregularity, but the amount of acceleration caused by long wavelength irregularities is normally well below 1 g, which makes the estimation of long wavelength components of irregularity extremely challenging.

To overcome these limitations, model-based methods have been proposed: in [6], a frequency decomposition of track irregularity and of the vehicle's acceleration measured at different positions (axle-boxes, bogie frame, car-body) is performed. Then, a pseudo-inversion of the Frequency Response Function (FRF) matrix derived from a 6 degrees of freedom (DOF) dynamic model of the vehicle is introduced to identify the inputs of the system (vertical and cross alignment) from the measure of the outputs (vehicle acceleration). In [7,8] the same decomposition of track irregularity in harmonic components is exploited, but a simpler 2 DOF model is used, allowing for the analytical treatment of the input–output relationship in the frequency domain, but providing a less detailed description of vehicle dynamics. In [9] track irregularities are identified using a Kalman-filter based inverse analysis technique, the input-output relationship being defined by either a 6 DOF vehicle model similar to the one used in [6] and a simplified 4 DOF model.

All the above mentioned references deal with the estimation of longitudinal level irregularities only, whilst published scientific literature concerning the estimation of lateral alignment of the track is relatively scarce at present. Indeed, the estimation of lateral track irregularities is challenging due to the relative wheel-rail motion in lateral direction which occurs on account of the peculiar geometry of wheel-rail contact. This means that the displacement of the wheel is not directly representative of the track's alignment as it happens with the estimation of vertical irregularity components.

In [1] results are reported concerning the estimation of lateral irregularities performed by double integration of either lateral bogie acceleration or bogie yaw rate measure by a gyroscope. The Authors conclude that the accuracy of these estimates is not fully satisfactory, especially for shorter wavelengths of irregularity, due to the motion of the bogie relative to the track. The paper also reports an attempt to correct this discrepancy using a second-order dynamic model whose parameters are identified comparing the horizontal alignment as measured by a TRV on a sample section and the gyroscope signal on the same signal, but this turned out to be only partly useful, as the model developed is inherently valid only for the speed of the test used for calibration.

According to a similar strategy, in [10] compensation filters are derived using a Mixed Filtering approach to perform the estimate of both vertical and lateral track irregularities using a combination of axle-box mounted and bogie mounted accelerometers. However, the improvement provided by the correction filter in the estimate of lateral irregularity for wavelengths in the range 3–25 m is minor. It should be remarked that this is the range of wavelengths in which wheel-rail relative displacements are more significant. In [11] a robust observer defined in the time domain is defined and used to estimate lateral alignment irregularities. Also in this case, however, the motion of the wheelsets relative to the track is neglected, resulting in a pass-band of the method up to 3 rad/s so that, for the vehicle speed of 20 m/s assumed in the work, the method can only estimate lateral alignment irregularities having wavelength greater than 42 m approximately.

The aim of this paper is to develop and assess model-based methods for the identification of track irregularity, focussing on lateral alignment and cross alignment. To this aim, a mathematical model representing the lateral, roll and yaw motion of a single railway vehicle and incorporating a linear model of wheel-rail contact is firstly developed. The model considers the vehicle as formed by seven rigid bodies: one carbody, two bogies and four wheelsets. For each body lateral movements, yaw rotations and roll rotations are considered, resulting in 34 states and 8 inputs for the model. Different techniques are then developed for the estimation of track irregularity. The first one is defined in the frequency domain and is based on the pseudo-inversion of the Frequency Response Function (FRF) matrix derived from the linear vehicle model. The other two methods are defined in the time domain and consist of unknown input estimation techniques using a deterministic observer and a stochastic observer respectively. The accuracy of irregularity estimation is assessed for the three methods by means of numerical experiments in which virtual measurements from axle-box mounted, bogie mounted and car-body mounted accelerometers are obtained from numerical simulations performed using a fully 3D, non-linear multi-body model of the vehicle in excess of 100 states.

The paper is organised as follows: in Section 2 the dynamic model of the single vehicle is derived, with special focus on the linear model of wheel-rail contact forces, whereas the full matrices describing the model are reported in Appendix A. Section 3 describes the three methods developed for the identification of track irregularity. Section 4 reports about the assessment of the three methods based on numerical experiments. Section 5 concerns application to real measurements. Some concluding remarks are provided in Section 6.