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Calibrated Superstructure Model for Ballast Condition Monitoring in Turnouts

G. Prinz, J. Fuchs and B. Luber

Rail Systems, Virtual Vehicle Research GmbH, Graz, Austria

Abstract

Increasing demands for reliability and safety in rail transport require a detailed understanding of the vehicle-track interaction. However, in turnout zones, where track properties change, standard multi-body dynamic models using a co-running track formulation reach their limits. In particular, the interaction of sleepers and ballast cannot be accurately modelled. To overcome this problem, an extended superstructure model with individual sleepers and elastic rails, modelled as reduced finite element bodies, is proposed. The model order of the rails is reduced by modal reduction to accurately capture eigenfrequencies up to 1500 Hz. Furthermore, the model is calibrated with measured data from a turnout in Austria and shows good agreement with the data. In ongoing research, the model is being used to develop a condition monitoring system and a prediction model for ballast settlement in turnout areas.

Keywords: multi body dynamics, switches & crossings, railway turnouts, superstructure model, flexible body, model order reduction.

1 Introduction

Turnouts (switches and crossings) are crucial components of the railway transportation system as they are safety critical, and their components are highly loaded by the passing vehicles. These high loads can cause premature wear and ballast deterioration which influence the vehicle dynamics and may decrease the riding comfort. Therefore, it is essential to implement a strict inspection and maintenance regime to detect and prevent excessive wear and failures in turnouts. Currently, inspection and maintenance are mainly performed manually by specialised personnel at fixed time intervals. This is because standard track inspection vehicles are currently unable to perform detailed inspections in turnout areas. However, manual inspections only provide information at a specific point in time and require track closures to reduce the risk to workers involved.

An analysis of the Austrian railway network reveals that the life cycle costs (LCC) of a turnout are seven times higher than open track of the same length [1]. One of the main reasons for the high LCC in a turnout is the increased deterioration rate of the ballast compared to open track. This is mainly caused by high impact forces in the crossing panel, and the varying stiffness along the turnout. These factors can reduce the riding comfort and may damage the ballast, leading to a reduction in superstructure stiffness or even hollow zones under the sleepers. Therefore, it is important to inspect the ballast condition for safe operation. However, measuring the stiffness or condition of the ballast typically requires specialised superstructure measurement systems, such as ground-penetrating radars [2, 3].

In ongoing research, a model-based method is developed to estimate the ballast condition and to detect zones of high ballast deterioration. For this purpose, a detailed superstructure model is needed. This model should capture the vehicle-track interaction and the sleeper-ballast interaction in sufficient detail.

Data-driven methods, such as described in [4], can give estimates and trends of the ballast condition based on measurement data from standard track inspection vehicles. However, with purely data driven models, it is difficult to identify the underlying factors which lead to ballast deterioration.

Usually, multi body dynamic (MBD) simulations are conducted to investigate the effects of the vehicle-track interaction. For most purposes it is sufficient to use a co-running track model which moves with the corresponding wheelset. Especially in turnouts, where the lengths of the sleepers change and therefore influence the mass of the track and its reception, this kind of model is unsatisfactory.

Recent publications [5, 6] show, that there is an increasing research interest in detailed superstructure models, since a profound understanding of the underlying mechanisms of vehicle-track interaction in turnouts is needed to develop methods for simulating the whole railway system. The model of [5,6] incorporates the rails and sleepers as elastic beam elements to account for their respective elastic behaviour. However, the model focuses primarily on the crossing panel and does not include the switch panel and the transition zone to the short sleepers at the end of the turnout.

Therefore, an extended superstructure model with elastic rails and, to increase the computational efficiency, rigid sleepers is proposed, where the whole length of a turnout can be modelled and investigated.

2 Extended superstructure model

The proposed superstructure model consists of two elastic rails, modelled as reduced finite element models, rigid sleepers with lengths according to the turnout layout and bushing elements to represent the stiffness and damping of the ballast and the rail pads, respectively. In contrast to the common co-running model of the superstructure, this model is not moving with the wheelsets but fixed in location, see Figure 1. This allows the investigation of individual sleepers, their interaction through the elastic rails, and the corresponding vehicle response.

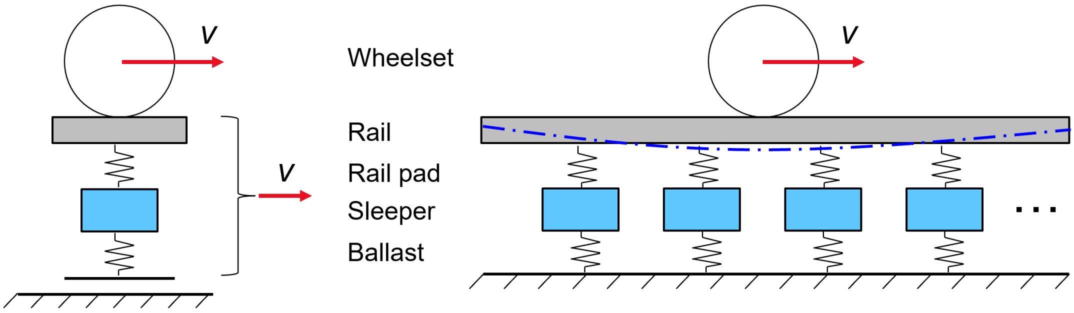

Figure 1: Schematic representation of the standard superstructure model (left) and the extended superstructure model (right).

Contrary to the *FlexTrack* module of Simpack [7], where the whole superstructure is modelled with a finite element method (FEM) software, this model only implements the two rails as elastic bodies via the *FlexBody* module. Because the same elastic rails can be used, there is no need for separate FEM models for different turnout layouts. Furthermore, it is assumed that this model is computationally more efficient than an elastic model of the whole superstructure, as the sleepers are modelled as rigid bodies to reduce the overall complexity. However, it is possible to model the sleepers as elastic bodies as well, but then the complexity and the computation time are increased. It is also possible to model only particular sleepers as elastic bodies for e.g. the detailed investigation of the load distribution underneath the sleepers in the crossing panel.

2.1 Elastic body modelling

The rails are modelled in a CAD software with a simplified 60E1 geometry, where the radii and chamfers are not modelled, because their influence on the elastic properties is negligible and to simplify the following meshing and FEM simulations. The CAD model of the rail is exported as STEP-file and further processed with the *Flexbodytoolbox* [8], see Figure 2. This process consists of meshing, FEM modal analysis, model order reduction (MOR) and exporting the data in a flexible body file format, or *Standard-Input-Data* (SID) for Simpack according to [9].

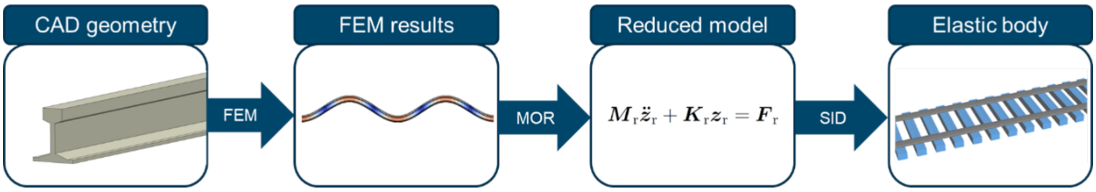

Figure 2: Workflow of integrating elastic bodies into MBD simulations.

2.2 Model order reduction

The MOR is the core of this process, where the number of degrees of freedom (DoF) is reduced without significantly influencing the elastic properties of the model. The full FEM model of the rail consists of 39 065 nodes, whereas after the reduction only 3295 nodes and 135 eigenmodes are retained. This reduction is necessary, because the number of DoF of the full FEM model is too high to be processed in an MBD software.

As reduction method, the modal reduction (MR) [10] is used, because of its efficiency and accurate representation of the eigenfrequencies and eigenmodes. The reduction method MR is based on the representation of the displacement vector in the mode superposition method [11]. With this representation, the nodal displacement vector $\boldsymbol{u}$ can be described by the matrix of eigenvectors $\boldsymbol{\Phi}$ and the modal coordinates vector $\boldsymbol{q}$. The eigenvector matrix $\boldsymbol{\Phi}$ is composed in columns of the eigenvectors and usually non-quadratic, as only a limited number of eigenvectors are computed. To acquire the transformation matrix $\boldsymbol{T}$, the nodal displacements are separated into main-nodes and sub-nodes according to Eq. (1). This is necessary, as only the main nodes are retained during the reduction process.

$$\boldsymbol{u} = \begin{pmatrix} \boldsymbol{u}_m \\ \boldsymbol{u}_s \end{pmatrix} = \begin{pmatrix} \boldsymbol{\Phi}_m \\ \boldsymbol{\Phi}_s \end{pmatrix} \boldsymbol{q} \tag{1}$$

To relate the nodal displacement of the sub-nodes $\boldsymbol{u}_s$ with the displacement of the main-nodes $\boldsymbol{u}_m$, the upper part of Eq. (1) must be solved for $\boldsymbol{q}$ with

$$\boldsymbol{q} = \boldsymbol{\Phi}_m^+ \boldsymbol{u}_m \tag{2}$$

where $\boldsymbol{\Phi}_m^+$ denotes the Moore-Penrose-inverse of $\boldsymbol{\Phi}_m$. Eq. (2) is then substituted into the lower part of Eq. (1) and therefore relates the nodal displacement of the sub-nodes to the nodal displacement of the main-nodes. The whole displacement vector $\boldsymbol{u}$ can then be written as

$$\boldsymbol{u} = \begin{pmatrix} \boldsymbol{u}_m \\ \boldsymbol{u}_s \end{pmatrix} = \begin{pmatrix} \boldsymbol{I} \\ \boldsymbol{\Phi}_s \boldsymbol{\Phi}_m^+ \end{pmatrix} \boldsymbol{u}_m = \boldsymbol{T} \boldsymbol{u}_m \tag{3}$$

where $\boldsymbol{T}$ denotes the transformation matrix, which is used to perform the reduction of the mass matrix $\boldsymbol{M}$ and the stiffness matrix $\boldsymbol{K}$ according to Eq. (4) and (5), respectively.

$$\boldsymbol{M}_{\mathrm{red}} = \boldsymbol{T}^{\mathrm{T}}\boldsymbol{M}\boldsymbol{T} \tag{4}$$

$$\boldsymbol{K}_{\mathrm{red}} = \boldsymbol{T}^{\mathrm{T}}\boldsymbol{K}\boldsymbol{T} \tag{5}$$

Based on these reduced matrices and the coordinates of the main-nodes, the SID according to [9] can be calculated and saved into a file which contains the information of the elastic body and how it is represented in the MBD. This file is then included in the MBD model to assign elastic properties to the rail bodies.

2.3 MBD model

The superstructure model consists of 150 sleepers, two elastic rails with a length of 90 m each, and force and coupling elements. Each sleeper is connected to the reference coordinate system via two bi-linear bushing elements which represent the ballast stiffness and damping, and two linear bushing elements which represent the rail pads and the fastening elements where the elastic rails are coupled. For the wheel-rail contact calculation, it is necessary to define an auxiliary body, which holds the rail profile information. This auxiliary body is connected to the elastic rail body via a kinematic coupling to a moved marker, see Figure 3. This is necessary, because the elastic rail body cannot be used as counterpart for the wheel, as the wheel-rail pair element can only be defined between bodies with no relative longitudinal movement [12].

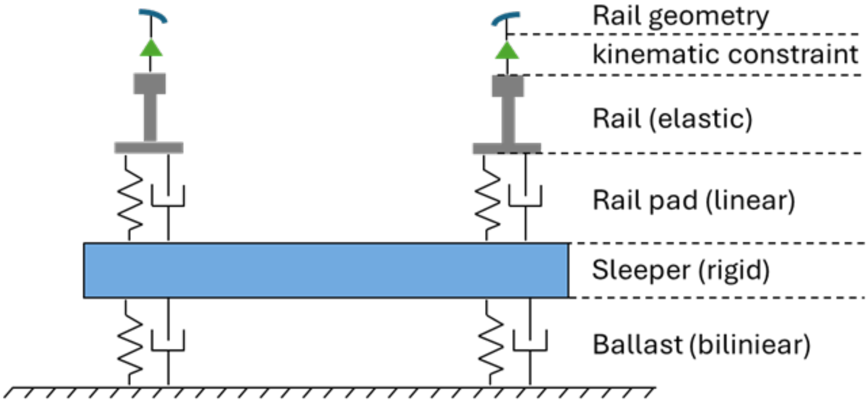

Figure 3: Schematic view of the MBD superstructure model.

The lengths of the individual sleepers are modelled in accordance with the project turnout of type EW60-500-1:12L, and range from 2.2 to 4.3 m. The sleepers are modelled orthogonal to the trough route, whereas in reality, the sleepers in the crossing panel are slightly twisted to make a compromise of load distribution for the diverging and through route, see Figure 4. The influence of this modelling simplification is believed negligible, as the angles are small (< 10°) and only the trough route is analysed. Furthermore, the rails of the diverging route and the check rails are not modelled as elastic bodies, but their stiffening influence is accounted for with vertical bushing elements between neighbouring sleepers.

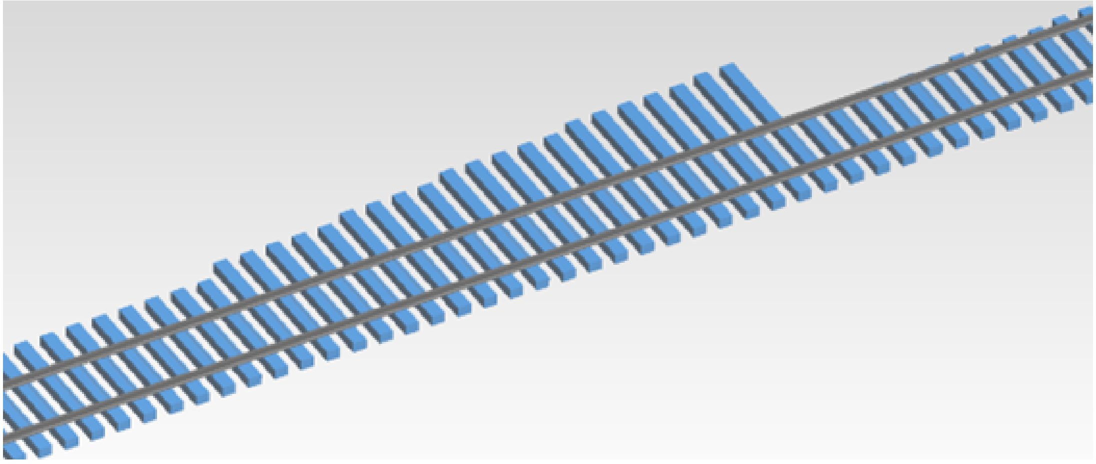

Figure 4: Visualisation of the crossing panel of the MBD superstructure model.

3 Model calibration

The model was calibrated with measurement data from test runs in Austria, which were conducted within the Rail4Future project. In this project, a turnout of type EW60-500-1:12L, see Figure 5a, was equipped with acceleration-, laser-, and inductive sensors as well as strain gauges [13]. The test vehicle, see Figure 5b, was equipped with accelerometers on the axle boxes of one wheelset and a line camera for gathering visual information of the track. The data generated by the measurement campaign was used to parametrise the MBD model.

For this purpose, the sensor signals were synchronised to the simulation data to assess the according signals of the individual sensors. With the synchronised signals it is possible to compare the simulation results with the measurement at the correct locations. For the parametrisation of the ballast stiffness, sleeper displacement measurements were used. The stiffness in the model was adjusted so that the vertical sleeper deflection due to the vehicle load corresponds with the measured deflections. Since not all sleepers in the turnout zone were equipped with displacement sensors, it was assumed that the general ballast stiffness, per meter sleeper length, is constant for all sleepers. With the identified general stiffness, the simulation results closely resemble the measured deflection of the sleepers in all regions of the turnout, except after the transition from the long to the short sleeper. In this region, the measured deflection of the short sleeper was considerably larger than in the simulation. This indicates that the ballast in this region is deteriorated and that hanging sleepers may be present.

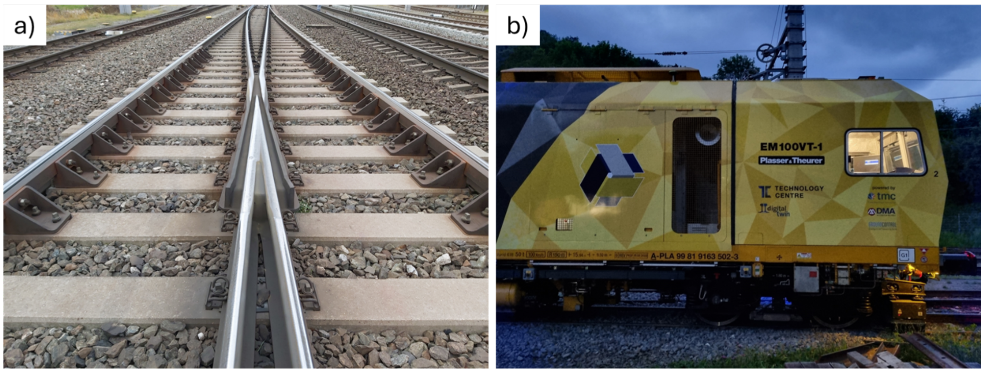

Figure 5: Crossing panel (a) of the project turnout and test vehicle (b) for the measurement runs.

To investigate this phenomenon, a gap under the short sleepers in the transition zone was defined in the model. The results with the modelled gap show a closer agreement with the measured sleeper deflection, although a considerable difference remains, see Figure 6.

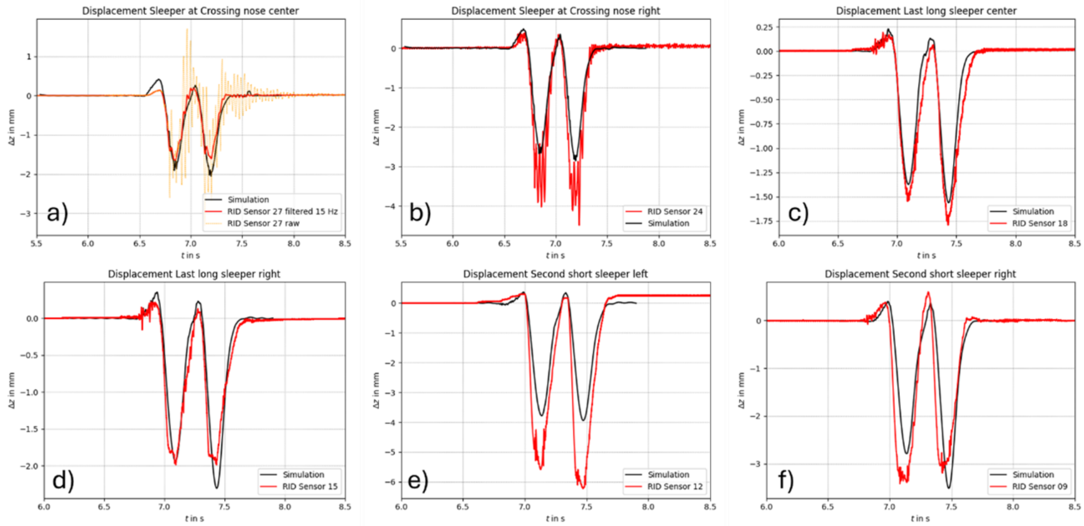

Figure 6: Comparison of measured and simulated sleeper displacements.

This supports the assumption from [13] that in this area large settlements occur, or the ballast is highly worn, which is plausible as high loads occur at the transition from long to short sleepers.

4 Conclusions & Contributions

The calibrated model shows good agreement with the measured vertical sleeper displacement in almost all investigated areas, except at the transition from the long to the short sleepers after the crossing panel. A possible reason for this could be a heavily worn ballast with high settlements in this area. Another reason may be, that the sleepers in this area are bending significantly due to the high loads from the transition, which is not accounted for in the model.

However, the model allows detailed investigations of the influence of different superstructure defects. Modelling of hanging sleepers, stiffness defects, or transitions allow an investigation of their respective influence on the dynamic vehicle response and the loads on the ballast. This can be used to aid the condition monitoring based on measurement data from the track inspection vehicle, e.g. to help identifying limits of the track condition.

In ongoing research, the model is used to estimate the ballast stiffness based on the vehicle's dynamic response. For this purpose, an optimisation algorithm minimises the difference between simulated and measured axle box accelerations of the track inspection vehicle, by adjusting the model parameters. The adjusted ballast stiffness parameters then provide another important aspect for assessing the current ballast condition.

Although this model was developed for and calibrated on a single turnout, it can easily be adopted for investigations in open track or other turnouts. An integration of a settlement model allows investigations of the ballast deterioration and its influence on the vehicle and track dynamics.

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