Development of Flexible Track Models for Railway Dynamics Applications

Extended Abstract

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Abstract

The dynamic analysis of railway vehicles involves the construction of three independent models: the vehicle model; the track model; and the wheel-rail contact model. In this work, a multibody formulation is used to describe the kinematic structure of the rigid bodies and joints that constitute the vehicle model. A methodology is also proposed in order to create detailed three-dimensional track models, which include the flexibility of the rails and of the substructure. This approach uses a finite element methodology to represent the rails as beams supported in a discrete manner by spring-damper elements that represent the flexibility of the pads, sleepers, ballast and substructure. The inclusion of flexible track models is very important to study realistically the dynamic behaviour of railway vehicles, especially the impact of train operations on the infrastructure and the damages on vehicles provoked by the track conditions. This topic has a significant economic impact on the vehicles maintenance and life cycle costs of tracks. The wheel-rail contact formulation proposed here allows obtaining, online during the dynamic analysis, the contact points location, for any three-dimensional motion. The methodology proposed to build flexible track models is validated by comparing the results with the ones from ANSYS, showing that the proposed methodology is appropriate to railway applications. In this work a post-processing tool is also developed to assess if a given vehicle is conform to the norms and regulations in practice. Furthermore it allows assessing quantitatively the dynamic behaviour of the vehicle in different operation conditions, being used for vehicle approval.

Keywords: Railway Dynamics; Flexible Railway Track Models; Realistic Railway Operations; Vehicle-Track Interaction; Vehicle Approval.
1 Introduction

The railway system is increasingly becoming a key-player in worldwide transport policies. Modern high speed trains are able to compete with other transportation and for longer distances the railway system is still the most economical mean for transportation.

The use of profiled-flanged steel wheels running on steel tracks was a brilliant concept in the early days of this industry. Nevertheless, its simplicity masked the complexity of the contact phenomenon, where the contact forces strongly influence the dynamic behaviour of the vehicle. The increasing demands for network capacity put pressure on the existing infrastructures and the effects of these changes have to be carefully considered, as such requirements bring new problems to control the wheel-rail wear and to maintain the vehicle stability and reliability.

The European Strategic Rail Research Agenda [1] and the European Commission White Paper for Transports [2] have identified key scientific and technological priorities for rail transport over the next 20 years. One of the points emphasized is the need to reduce the cost of approval for new vehicles and infrastructure products with the introduction of virtual certification.

Recent computer codes for railway applications use specific methodologies that, in general, only allow studying each particular phenomenon at a time that fail to capture all the dynamics of the complete railway system and relevant coupling effects. In this work lies in the development of computational tools that are able to model the vehicle, the track and the subgrade, where they are integrated in a common and reliable tool and the interaction among them is considered. Then, the dynamic analysis is processed to determine if a given vehicle would be accepted to operate on the track by the industry.

The use of valid models of the railway track is necessary to correctly determine the dynamic behaviour of the railway vehicle, which implies using flexible track models to account for the deformation, wear, sags and maintenance state of the track.

In this work the dynamic behaviour of the railway vehicle is studied using a multibody formulation [3-5]. The relative motions between the bodies of the system are restrained by using appropriate kinematic constraints. The track flexibility is included in the formulation by using finite element models [6,7]. A generic wheel-rail contact detection formulation [8,9] is introduced here to determine the contact points location, without need to use pre-computed lookup tables.

The pre-processor tool developed in this work to build the flexible track model allows dynamic analysis for much longer distances than the traditional approach. Moreover, its results are validated by comparison with the ones obtained from ANSYS in a static analysis where the track is loaded with wheelset loads. Also a comparative analysis between the use of
moving loads and realistic vehicle forces is performed in order to analyse the validity of the State of the Art, where moving loads that represent the vehicle is more often considered.

A computational post-processing tool was also developed here. It assesses if the vehicle fulfils the requirements defined by international regulations [10,11]. This tool is used here to compare the performance of different vehicles in several railway tracks at different speeds.

2 Railway Vehicle Models

The dynamic analysis of a multibody system [3-5, 12-14] involves the study of its motion and forces transmitted during a given time period, as a function of the initial conditions, external applied forces and/or prescribed motions. A multibody model is composed by a collection of bodies interconnected by joints and/or force elements. The dynamic analysis of a multibody system involves the solution of a system of second order differential equations [15,16].

Due to trainset configuration, it is assumed that the dynamic behaviour of each vehicle has a non-significant influence on the others and, therefore, each vehicle of the trainset can be studied independently. In this way, the vehicle model introduced here is composed only by one trailer unit of the trainset. The trailer vehicle is composed by one carbody that is supported by two bogies through a set of mechanical elements that constitute the secondary suspension. Each bogie includes the wheelsets, which are in contact with the rails, and another group of mechanical elements that constitute the primary suspension.

The first step for modelling a railway vehicle using a multibody formulation is the division of the group in several subsystems, which are simpler to handle. This strategy allows building each subsystem independently, being the whole vehicle model built by assembling the subsystems, as shown in Figure 2.1.

![Figure 2.1: Vehicle multibody model](image)

For each subsystem it is necessary to provide the information about the rigid bodies, kinematic joints and linear and/or nonlinear force elements. The relative motion between the bodies is limited by kinematic joints [3], which restrain relative degrees-of-freedom between the bodies.
connected by them. The suspension components, such as springs and dampers that connect the rigid bodies, are modelled as force elements. These are responsible for transmitting the internal forces that are developed in the system as function of the relative motion between the bodies.

3 Development of Advanced Track Models

The performance of railway vehicles is dependent on the track conditions, as the loads induced on the vehicle by the track and the corresponding forces transmitted to the track by the vehicle also depend on the track geometry. Therefore, the accurate description of the track is essential for the dynamic analysis of railway systems.

A railway track is generally composed by the rails, which are supported by the sleepers through the pads. The sleepers rest on an elastic bed made up of supporting layers as ballast, sub-ballast, form layer and subsoil, as represented in Figure 3.1.

![Figure 3.1: Main components of the railway track in (cross-section view)](image)

Despite being considered as rigid by many authors and computational tools, the railway track exhibits some flexibility, which originates track irregularities, hence the necessity of developing computational models that allow studying that flexibility and the irregularities that follow.

In this work the railway track system is modelled with linear finite elements. The rails and sleepers are modelled by using Euler-Bernoulli beam elements \cite{17}, while the foundations and rail pads are represented by spring-damper elements acting in the six degrees of freedom, as shown in Figure 3.2 and Figure 3.3.

![Figure 3.2: Main components of the track model (cross-section view)](image)
In this work, a pre-processing tool was developed in order to build detailed flexible track models using a finite element formulation. The pre-processing tool builds a given track using its geometry as a pathway reference and places along it the different track segments on the intended order, each of them with their own elements. The track geometry is obtained from the designed track layout and including the measured track irregularities.

The methodology used here to build the track model takes into account the influence of all elements, allowing the presence of transitions. While other approaches also allow these features, few allow a practical evaluation of a long track due to the computational cost of studying the soil properties. The methodology considered here uses a discrete foundation that allows for dynamic analyses on longer tracks than the traditional approach. To capture the dynamic behaviour of the track, an integration algorithm was implemented based on the implicit Newmark’s trapezoidal rule [18].

A realistic flexible track model was built and subjected to wheelset loads of a railway vehicle, as depicted in Figure 3.4. The results obtained from a static analysis were compared against the ones provided by ANSYS 12 on a similar analysis in order to validate the proposed methodology. The results obtained show that the maximum deformation of the track is 2.9 mm on the vertical direction and on the node where the load is applied, being the negligible on the other directions.
When comparing the results, it is observed that the maximum relative error for the track vertical deformation is less than 0.04%, corresponding to a maximum absolute error of $57.4 \times 10^{-9}$ m. These results demonstrate that the proposed finite element methodology represents the track flexibility in an appropriate manner and it is quantitatively validated for static loads.

Similar dynamic analyses were also performed on a realistic curved track, as presented in Figure 3.5. These analyses intended to compare two loading cases, the first where moving loads are applied to the track and the second where realistic vehicle forces are used, as to validate the State of the Art that more often uses moving loads. Here the maximum vertical deformation is 6.19 mm and is found on the left rail, while the maximum transversal deformation is 0.29 mm and the longitudinal deformation negligible.

![Figure 3.5: Realistic Flexible track model](image)

Although there are differences between the use of moving loads and realistic vehicle forces, these are minimal, allowing the correct study of the track using either of them when the contact forces are considered independent from the deformation of the rail. A far more accurate result would come from a dynamic analysis where the co-simulation is considered, allowing for the correct calculation of the track deformation and contact forces, since these two are interconnected and interdependent.

4 Definition of the Post-Processing Tool

The results obtained from a railway dynamic analysis are kinematic data and kinetic data, unfortunately these results vary greatly, becoming impossible to compare similar analyses and obtain significant conclusions. In order to become comparable to other analyses, the results need to be filtered and processed, from where it is possibly to analyse the safety and comfort of the case study.
This chapter describes the post-processing tool that was developed in this work to perform all filtering and data processing that are required to assess the dynamic performance of the railway vehicle according to the international regulations EN 14636 [10] and UIC 518 [11]. To comply with the requirements defined in these norms a set of values must be determined. These characterise the behaviour of the vehicle on the different zones of the track, being derived from measured or simulated data, namely accelerations and forces exerted on the vehicle, which are filtered and processed. This process is represented in Figure 4.1.

Figure 4.1: Schematic representation of the Post-Processing Tool

These assessment values include the forces that the vehicle applies on the rails, the forces that the vehicle bogies, wheelsets are subjected to and the accelerations on the bogies or wheelsets and on the carbody. These are then transformed into characteristic values for the vehicle on the track, through specific methods involving filtering and data processing on different track sections.

Two different methods can be used to approve vehicles: the Normal Method that uses all assessment values, with the exception of the sum of the lateral axle box forces; while the Simplified Method only uses accelerations and has the option to use the sum of the lateral axle box forces as assessment values.

The industry specifies a series of limit values on all characteristic values. These limit values are then divided into three categories: the safety limit values that ensure that the vehicle will not be in any risk of derailment, the track loading limit values that ensure that the track will not be damaged by the passage of the vehicle and the comfort limit values that ensure that the vehicle is comfortable enough to be used for passengers transportation. To certificate the validity of a given vehicle to travel on a given track, the vehicle must respect all these limit values.
5 Post-Processor Application

The post-processor tool is applied here to two case studies using the Simplified Method and only considers the accelerations measurements. Both case studies are processed in the same manner. Table 5.1 shows the required data for a Simplified Method analysis.

<table>
<thead>
<tr>
<th>Assessment Value</th>
<th>Symbol</th>
<th>Filtering for Evaluation</th>
<th>Method of Classification</th>
<th>Characteristic Values</th>
<th>Grouping and Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running Safely</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration at Bogie</td>
<td>y^r</td>
<td>Low-pass filter: 10 Hz</td>
<td>Random Sampling Method</td>
<td>h_2 = 0.15%</td>
<td>Per wheelset group: x(h_2) and</td>
</tr>
<tr>
<td>Outer wheelsets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[x(h_1)] for left hand curves</td>
</tr>
<tr>
<td>Acceleration in Vehicle Body</td>
<td>y^r</td>
<td>Low-pass filter: 6 Hz</td>
<td>Random Sampling Method</td>
<td>Per end group: x(h_2) and</td>
<td></td>
</tr>
<tr>
<td>End I, II</td>
<td></td>
<td></td>
<td></td>
<td>[x(h_1)] for right hand curves</td>
<td></td>
</tr>
<tr>
<td>Instability Criterion</td>
<td>y^r</td>
<td>Band-pass filter: 0.4-4 Hz</td>
<td></td>
<td></td>
<td>Per end group: x(h_2) and</td>
</tr>
<tr>
<td>All instrumented wheelsets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[x(h_1)]</td>
</tr>
<tr>
<td>Ride Characteristics</td>
<td></td>
<td></td>
<td></td>
<td>h_0 = 50.0%</td>
<td>Per end group: x(h_0) for right hand curves</td>
</tr>
<tr>
<td>Acceleration in Vehicle Body</td>
<td>y^q</td>
<td>Low-pass filter: 20 Hz</td>
<td>Random Sampling Method</td>
<td>h_2 = 0.15%</td>
<td>x(h_0) for left hand curves</td>
</tr>
<tr>
<td>End I, II</td>
<td></td>
<td></td>
<td></td>
<td>h_2 = 99.85%</td>
<td>Per end group: x(h_2) and</td>
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<tr>
<td>z^q</td>
<td></td>
<td>Band-pass filter: 0.4-10 Hz</td>
<td></td>
<td></td>
<td>[x(h_1)]</td>
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<tr>
<td>rms-parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>rms-values</td>
</tr>
</tbody>
</table>

Table 5.1: Conditions for the processing of the measuring signals for the Simplified Method from UIC 518 [11]

In the first case the lateral accelerations at the bogie exceed both the safety limits for such acceleration and the stability limits and the both lateral and vertical accelerations in the vehicle body exceed the quality limits imposed for a comfortable ride. As a result, the vehicle cannot circulate at the analysed speed, but it is likely that at a lower speed these concerns cease to exist and so further research is required. In the second case all safety and ride characteristics limit values are respected and, therefore, the vehicle can operate on the analysed track at the analysed speed. Further analyses are required to determine the vehicle maximum operating speed on the track considered here.

In Table 5.2 is presented a resume of the characteristic values for both case studies and their comparison with each other and their limit values. Here, red indicates that the limit value was exceeded, orange indicates that the values exceed 75% of the limit value, yellow indicates that the values exceed 50% of the limit value, green indicates that the values exceed 25% of the limit value and white indicate that the values are inferior to 25% of the limit value.
### Assessment Values

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Case 1 [g]</th>
<th>Case 2 [g]</th>
<th>Limit Values [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \dot{y}_S )</td>
<td>2.5313</td>
<td>1.0437</td>
<td>1.1417</td>
</tr>
<tr>
<td>( \dot{y}_S )</td>
<td>0.1664</td>
<td>0.1494</td>
<td>0.2650</td>
</tr>
<tr>
<td>( \ddot{z}_S )</td>
<td>0.1883</td>
<td>0.0751</td>
<td>0.3058</td>
</tr>
<tr>
<td>( \ddot{y}_S )</td>
<td>0.6475</td>
<td>0</td>
<td>0.5708</td>
</tr>
</tbody>
</table>

#### Table 5.2: Characteristic Values for the analysed case studies

### 6 Conclusions and Future Development

The accurate evaluation of the loads imposed to the railway infrastructure by trainsets and the damages on vehicles provoked by the track conditions have been attracting the attention of railway industry in recent years. The increasing demands on railway transportation require improvements of the network capacity, which can be achieved either by increasing the speed of the traffic or by increasing the axle loads. However, both options place pressures on the existing infrastructures and the effects of these changes have to be carefully considered.

The main goal of this work is to develop advanced computational tools for railway dynamics, with innovative methodologies that are handled in a co-simulation environment, where all physical phenomena can be integrated. This includes the detailed representation of the vehicle, track, subgrade and the interaction among them. The two main tools developed in this work are: a) the pre-processor that builds the flexible track model from provided geometric and material properties for the track and its elements, and; b) the post-processor that computes the results of the dynamic analysis in order to determine if a given vehicle is acceptable to operate on a given track at the proposed speed.

The mathematical models of the railway vehicles are created using a multibody formulation. On the other hand, the flexible track model uses the finite element methodology. Between the multibody and the finite element codes lies the contact model, connecting the vehicle’s wheels and the track’s rails using a co-simulation procedure. Although other procedures exist, the use of a contact penalty formulation demonstrates to be enough to obtain all main contact features.

From the results obtained in the present work, it can be concluded that the proposed numerical tools are valid and that finite element methodology, proposed here to represent the track flexibility, is suitable for railway applications.
The developed post-processing tool intends to verify if the a given vehicle-track combination is within the safety and comfort parameters defined by EN 14636 [10] and UIC 518 [11], which are commonly used by the railway industry. This tool was developed and demonstrated in two case studies. One failed to meet all required criteria and the other complies with all requirements.

Although the co-simulation procedure required to perform the dynamic analysis of the railway vehicle running on the flexible track isn’t complete, the results taken from both the pre-processing and post-processing tools developed in this work are valid and useful when integrated on a complete dynamic analysis package.

References