Abstract

In this thesis, multibody models based on the Alfa Pendular and the Light Rail Vehicle 2000 are developed and analysed in realistic operation scenarios. The close contact with industry allowed the construction of realistic detailed models including the elements which compose the suspension system, which are represented as equivalent force elements in the multibody formulation. Joints with clearance and bushings elements were also used in order to improve the fidelity of the models.

These models were simulated in several scenarios considering rigid railway tracks. Different types of tracks were generated, namely straight and curve tracks with and without irregularities. The irregularities considered here were measured in Portuguese railway network. These different scenarios were studied in order to analyse the dynamic performance of the vehicles.

In order to visualize the wheel-rail interaction, a graphical tool was developed. This tool allows the visualization with precision of the relative motion of each wheelset of the vehicle with respect to the rails. In order to understand how contact develops, the candidate points to be points of contact are also presented in the wheel and rail surfaces.

The software used here is able to run simulations in a batch mode with a variation of the model based on selected criteria. This capability was used to implement a procedure to compute the Critical Speed automatically and also integrated with an optimization method to identify vehicle models with maximum Critical Speed. The optimal models are obtained designing a new suspension system.

Keywords: Railway Vehicle Models; Dynamic Analysis; Wheel-Rail Animation; Batch Mode Simulations; Critical Speed; Real Tracks Generation.
1. Introduction

The transportation of people and goods is of fundamental importance in any society. Among the different transportation modes, railway has an irreplaceable position being many of the modern society developments based on its modernization. The technological advances in the railway vehicles technology, among others, have been increasing extraordinarily due to the market demands. The transportation of people has to be faster with an improved comfort and safety. The capability of the freight railway transportation to move larger quantities improves also the competitiveness with respect to the other type of transportation. For all the reasons stated, research and development in railway dynamics plays a role in the development of new solutions for vehicle technologies being the central motivation for the work now presented.

In the early age of the railway, the design of the infrastructure and the vehicles was based on a strategy of trial and error. Then, with the scientific and technological advances, the design process became more robust, reliable and efficient. Issues such as maintenance costs, safety and comfort are among the factors which require continuing improvements. Such as in many others engineering fields, the research work is fundamental to provide more solutions and to lead to technological advances. Computational approaches lead to design processes of fundamental importance that ultimately lead to cheaper and more reliable products and reduce the needs for experimental testing, reducing the associated high costs. The multibody simulation is one of the major computational methodologies used for railway studies in what railway dynamics is concerned. Therefore, the understanding and development of the railway dynamic tools and models to address vehicle-infrastructure compatibility is the main objective of this work.

2. Functional Characteristics of Railway Vehicles

The wheelset constitute a main system of the railway vehicle as it guarantees the vehicle guidance on the track. Regarding the configuration of the wheel profile, the tread and flange have important aspects to mention. The conical configuration of the treads allows two different behaviours. When it is running in a straight track, the hunting motion is verified [1] as shown in Figure 2.1 (a), and in a curved track, for proper velocity the wheelset can adopt a pure rolling motion [2] as presented in Figure 2.1 (b). The aim of the flange is to keep the vehicle in the track when the contact with conic part of the wheel is exceeded.

Figure 2.1: (a) Hunting motion on a straight track; (b) Conical wheelset on a curved track
In Figure 2.2 two different primary suspensions are presented. The main function of this suspension level assures the steering capabilities and stability behaviour of the whole vehicle being, ultimately, responsible for its Critical Speed (CS).

![Primary suspension](image)

**Figure 2.2:** Primary suspension of the: (a) Alfa Pendular (AP) vehicle; (b) Light Rail Vehicle 2000 (LRV)

The main function of the secondary suspension is to minimize the vibrations, resulting from the vehicle-track interaction, transmitted to the carbody, improving the comfort of passengers and reducing the problems associated to the structural fatigue. Figure 2.3 presents two different secondary suspensions.

![Secondary suspension](image)

**Figure 2.3:** Secondary suspension of the: (a) AP vehicle; (b) LRV vehicle

The motor bogies, responsible for the traction, transmit the traction forces to the railway vehicle through the bogie-carbody connection. In turn, the free bogies are pulled by the vehicle carbody by bogie-carbody connections. In Figure 2.5 the bogie-carbody connection for AP and LRV vehicles are presented.

![Bogie-carbody connection](image)

**Figure 2.5:** Bogie-carbody connection for AP and LRV vehicles

The dynamic performance of the railway vehicles is strongly dependent of the track conditions. To achieve the accurate track representation, it is necessary to use an appropriate modelling approach. Here, the track pre-processor implemented by Pombo [3] is used. This strategy implies the definition of the track centreline with a representative group of nodal points. Each nodal point is...
defined by three coordinates, $x$, $y$ and $z$, and by the cant angle, $\varphi$. The pre-processor also includes the track irregularities. The most common way to classify them is to consider four types of irregularities: alignment level; longitudinal level; cant variation and gauge variation. At the end, the track is composed by two independent rails, the right and left, which are discretised by a set of nodal points defined by the position vector $r$ and by orientation vectors, namely, the tangent, $t$, normal, $n$, and binormal, $b$, vectors, as is depicted in Figure 2.5.

![Figure 2.4: Bogie-Carbody connection of the: (a) AP vehicle; (b) LRV vehicle](image)

Figure 2.4: Bogie-Carbody connection of the: (a) AP vehicle; (b) LRV vehicle

![Figure 2.5: Position and orientation of the rails with their local coordinate frames](image)

Figure 2.5: Position and orientation of the rails with their local coordinate frames

The interaction between the vehicle and the track is represented by an appropriate contact model. This computational model requires the definition of the wheel and rail contact geometries. Figure 2.6 presents schematically the construction of the wheel and rail surfaces as revolute and swapping surfaces. These surfaces are defined by a set of nodal points that describe the wheel and rail profiles cross sections, by the nominal radius of the wheel and by the track geometry provided by the track pre-processor mentioned before.
3. Multibody Dynamic Formulation

In Figure 3.1 the algorithm of the DAP-3D Program [3] is presented. The formulation implemented here follows the multibody methodology described in the literature [4]. Moreover, this program has already implemented all the features required to perform studies with joints with clearance and bushings [5,6].

![Diagram of DAP-3D Program algorithm](image)

**Figure 3.1: DAP-3D Program algorithm**

In order to visualize the wheel-rail interaction, a graphical tool was developed [7]. This tool allows the visualization with precision of the relative motion of each wheelset of the vehicle with respect to the rails. In order to understand how contact develops, all candidates to contact points are also presented in the wheel and rail surfaces. This animation tool allows the personalization of the view perspective. Figure 3.2 (a) presents two cameras. These cameras allow capturing the images presented in Figure 3.2 (b) which are of fundamental importance to visualize the contact and, ultimately the motion of the system.

![Position and orientation of the cameras V1 and V2](image)

**Figure 3.2: (a) Position and orientation of the cameras V1 (fixed on body Background) and V2 (fixed on body rail) and (b) images captured by cameras V1 and V2**
4. Applications to Cases of Study

In this work, two different vehicles were modelled, namely the Alfa Pendular (AP) and the Light Rail Vehicle 2000 (LRV). The models developed here were created with high level of detail. Furthermore, in the case of the LRV vehicle, worn joints [5,6] were also included.

To evaluate the CS, the lateral motion of each body of the multibody model is monitored during the dynamic analyses. At a given velocity, all bodies follow a sinusoidal trajectory, in terms of lateral motion, with approximately constant amplitude, as shown in Figure 4.1. This velocity is designated Critical Speed. Considering the characteristic behaviour presented, a function in the DAP-3D computer code to determine automatically the CS was implemented. This tool allowed the determination of the CS of the AP and LRV vehicles are 230 km/h and 137 km/h, respectively.

Another study considered here was the dynamic analysis of the vehicles on a straight track with measured track irregularities. In these studies, it was observed that the range of lateral accelerations on the carbody of the AP vehicle is 10 times lower than on the LRV, as is shown in Figure 4.2. Regarding the vertical accelerations on the wheelsets, a reasonable agreement was obtained, as depicted in Figure 4.3. This result suggests that, the vertical excitation on the wheels strongly depends on the track conditions. When the vehicles were studied in a track with severe irregularities, problems with the numerical methods used to determine the contact points were experienced. This is, in fact, a current problem of multibody dynamic formulation [8]. In the studies performed here, high values of the derailment index Y/Q were obtained, as shown in Figure 4.4. Then, using the wheel-rail animation tool developed in this work, it was verified that contact losses occur on the wheel tread, as presented in Figure 4.5.
Figure 4.2: Lateral accelerations induced on the carbody of (a) AP; (b) LRV

Figure 4.3: Vertical accelerations on the leading wheelset of the AP and LRV

Figure 4.4: Derailment index Y/Q on the left wheels of the four wheelsets
Figure 4.5: Animation of the wheel rail interaction: (a) Flange contact; (b) Loss of contact

The last scenarios considered here to study the dynamic performance of the vehicles include curved tracks. First it was defined the principle of the Non-Compensated Accelerations (NCA), which is the resultant of the centrifugal and gravitational acceleration in the local lateral direction of the carbody as it is presented in Figure 4.6 (a). The NCA is calculated as:

\[
NCA = a_{c,\phi} - a_g = \frac{V^2}{R} \cos(\phi) - g \sin(\phi)
\]  

(4.1)

where \( V \) is the vehicle velocity, \( R \) is the nominal radius of the curve and \( \phi \) is the cant angle. With this expression, the equilibrium speed \( V_{NCA=0} \) was computed, which accomplish the condition \( NCA = 0 \), improving the comfort of the passengers. Then, two more velocities were considered, namely \( 1.5 \, V_{NCA} \) and \( 0.5 \, V_{NCA} \). The simulations performed using these velocities allow to emphasize the importance of the condition \( NCA = 0 \), as it is presented in Figure 4.6 (b)

5. Critical Speed Optimization

The primary suspension system is the main responsible for the steering capability and stability behaviour of the whole vehicle. For this reason, the properties of mechanical elements that compose
the primary suspension is considered when optimizing the CS. These are the stiffness, damping and dimension values of some force elements, as represented in Figure 5.1. Notice that only the force elements are considered because these are the cheaper to change, but also preliminary study on the impact of these parameters in the CS was performed. It was concluded that the variables $c_{\text{vert}}$ and $c_{\text{lat}}$ are not relevant when varied in a window of $+/-$20% of the initial value.

For the optimization, the Pattern Search method was used. The first initial guess to the design variables, which is demanded by the method, corresponds to the original properties of the primary suspension elements of the AP model. It is also necessary to define the bounds for each design variable. Variation ranges of $[0.5x_0;1.5x_0]$ for the stiffness and damping parameters and of $[0x_0;2x_0]$ for the dimensions were considered here, being $x_0$ the initial value of each variable.

![Figure 5.1: Mechanical components that define the primary suspension](image)

In this study, four optimizations are made. In the first three, the design variables are considered separately in the optimization procedure. In the fourth optimization, all variables are used at the same time, as listed in Table 5.1. By using all design variables at the same time, allowed an increase of 86% (430km/h) of the initial CS, which is considerably higher than the results obtained in the other optimizations. For the optimal model, the comfort of the passengers was improved, due to the reduction of lateral accelerations, and the wheel-rail forces were kept approximately equal.

### Table 5.1: Results of the optimizations

<table>
<thead>
<tr>
<th>Variables Optimized</th>
<th>Critical Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_{\text{long}},k_{\text{lat}},c_{\text{long}}$</td>
<td>350.0 [Km/h] (52%)</td>
</tr>
<tr>
<td>$k_{\text{vert}}$</td>
<td>243.7 [Km/h] (6%)</td>
</tr>
<tr>
<td>$a, b$</td>
<td>232.5 [Km/h] (1%)</td>
</tr>
<tr>
<td>All variables</td>
<td>430.0 [Km/h] (86%)</td>
</tr>
</tbody>
</table>

6. Conclusions and Future Developments

The development of realistic and detailed multibody models of railway vehicles is important to assess their dynamic behaviour in different scenarios. The dynamic results, such as the lateral accelerations on the carbody, were well related with the physical characteristics of the vehicles. In the scenario where real tracks are considered, it was concluded that the vertical accelerations on the wheelsets depends strongly on the track geometry and irregularities. In scenarios with curved tracks, the condition $NCA = 0$ to determine the best velocity in terms of comfort was verified.
The optimization study performed here allow to conclude that just by changing the characteristics of the mechanical elements present in the vehicle suspension it is possible to improve significantly the vehicle stability. The development of the wheel-rail animation tool was also an important development of this work. This tool allows the visualization of the dynamic behaviour of the wheelsets along the track. Events like loss of contact on the wheel tread and flange contact, which are of primordial importance to predict derailment, are detected with this animation tool, being unnoticed otherwise.

Future developments are directed towards the improving improvement of the accuracy of the multibody models, namely by including active suspension elements. Depending on the track foundation, the relevance of the flexibility can be more or less important. To solve this problem, the co-simulation approaches are recommended to link the multibody formulation, to model the vehicle, and finite element, to represent the track. In order to study the wear in the wheel and rail surfaces, the development of appropriate contact models are also required. By taking advantage of the batch mode simulations and the optimization capabilities, model validation and completed design processes of railway vehicles are possible.

References