Analysis of post-derailment dynamic behaviour of a railway vehicle and interaction with deformable containment structure

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EXTENDED ABSTRACT

1 Introduction and state of the art

Nowadays, railways plays and important role in land transportation, both of goods and passengers, and it is considered one of the safest means of transport. However, train derailments represent a relatively frequent cause of accidents and are likely to occur under different conditions: structural defects (both in tracks and running gears), bad quality of the infrastructure, problem occurring at wheel-rail interface, extreme weather, human error or impact with obstacles [1,2]. Some experiments have been carried out to reproduce and analyse controlled derailments [3,4], however it is extremely challenging and expensive perform these typology of experiments. Thus, mathematical models and numerical simulations are adopted to study derailment events [5,6]. The aim of this paper is to presents a non-linear multibody model for simulations in time-domain of the post-derailment behaviour of railway vehicle and the subsequent interaction with a derailment containment structure. The vehicle is schematized as a set of rigid bodies connected through different linear and nonlinear visco-elastic components representing suspension elements. In addition to this, a wheel-rail contact model and a model of the track are introduced. Regarding the schematization of the containment structure, a shells finite element model (FEM) has been adopted and MATLAB was used as the environment for the realization of the simulation package.

2 Methodology: vehicle and deformable containment structure model

The model considers a single vehicle with one carbody, two bogies and four wheelsets, all considered as rigid bodies. Each rigid body has six degrees of freedom (DOF), resulting in a total of 42 DOF system. Primary and secondary suspensions are modelled by a set of massless visco-elastic elements with non-linear lumped parameters. To this aim, non-linear compact force element (CMP) models of suspension components [7] are used, which allow to consider the stiffness or viscous damping properties along three directions defined in a component-specific reference system. Finally, a simplified model of wheel-rail contact is introduced with the aim of enabling a fast, yet sufficiently accurate calculation of the contact forces. The motion of all bodies in the model is defined with respect to an inertial reference frame (global reference frame) located at the origin of the track. The movement of each body is described using six independent coordinates, three describing the instantaneous position of the body's centre of mass (COM) and three angles describing the orientation of the body adopting the standard multibody formalism [8]. The equations of motion describing the vehicle motion are expressed as:

$$\boldsymbol{M}(\boldsymbol{x})\ddot{\boldsymbol{x}} = \boldsymbol{Q}_{\boldsymbol{v}}(\boldsymbol{x},\dot{\boldsymbol{x}}) + \boldsymbol{Q}(\boldsymbol{x},\dot{\boldsymbol{x}},t) + \boldsymbol{Q}_{\boldsymbol{ext}_{\boldsymbol{v}}}(\boldsymbol{x},\dot{\boldsymbol{x}},\boldsymbol{x}_{\boldsymbol{s}},\dot{\boldsymbol{x}}_{\boldsymbol{s}}) \tag{1}$$

Where $\boldsymbol{x}$ is the vector collecting the 42 independent coordinates of the system, $\boldsymbol{M}(\boldsymbol{x})$ is the configuration-dependent mass matrix of the vehicle, $\boldsymbol{Q}_{\boldsymbol{v}}$ is the vector of generalized inertia forces which are a quadratic function of the vehicle's velocity $\dot{\boldsymbol{x}}$, $\boldsymbol{Q}$ is the vector of the generalized forces acting on the vehicle: weight forces, suspension forces and wheel-rail forces, and finally $\boldsymbol{Q}_{\boldsymbol{ext,v}}$ is the impact forces in post-derailment phase that depends both on DOF of the vehicle and the deformable structure ($\boldsymbol{x}_{\boldsymbol{s}}$). In order to validate this model, the results of several simulations performed in standard (on track) conditions are compared with the results of the commercial software SIMPACK showing a close agreement with the two models. The trigger event adopted for the derailment mechanism is the failure of a primary suspension. Finally, the vehicle model is coupled with a dynamic finite element model (FEM) that represent the dynamics of the derailment containment structure. These two models interact through the exchanged forces once the vehicle impacts against the structure. From a mathematical point of view the equations of motion that describe the interaction between the two system are expressed as:

$$\begin{gathered}\boldsymbol{M}(\boldsymbol{x})\ddot{\boldsymbol{x}} = \boldsymbol{Q}_{\boldsymbol{v}}(\boldsymbol{x},\dot{\boldsymbol{x}}) + \boldsymbol{Q}(\boldsymbol{x},\dot{\boldsymbol{x}},t) + \boldsymbol{Q}_{\boldsymbol{ext,v}}(\boldsymbol{x},\dot{\boldsymbol{x}},\boldsymbol{x}_{\boldsymbol{s}},\dot{\boldsymbol{x}}_{\boldsymbol{s}}) \\ \boldsymbol{M}_{\boldsymbol{s}}\ddot{\boldsymbol{x}}_{\boldsymbol{s}} = -\boldsymbol{K}_{\boldsymbol{s}}\boldsymbol{x}_{\boldsymbol{s}} - \boldsymbol{R}_{\boldsymbol{s}}\,\dot{\boldsymbol{x}}_{\boldsymbol{s}} + \boldsymbol{Q}_{\boldsymbol{ext,s}}(\boldsymbol{x},\dot{\boldsymbol{x}},\boldsymbol{x}_{\boldsymbol{s}},\dot{\boldsymbol{x}}_{\boldsymbol{s}})\end{gathered} \tag{2}$$

Where the first system of equation represents, as the equations ((*1*), the vehicle equations of motion. Instead, the seconds system of equations in (2) is the dynamic FEM of the structure. The basic structural element is a rectangular plates and its inertial and stiffness matrices are defined in [9] and consequently assembled for the entire structure. Thus $\boldsymbol{x}_{\boldsymbol{s}}$ is the vector containing the DOF of the overall structure. As can be seen from equations (2) the terms that permits to the systems to interact are $\boldsymbol{Q}_{\boldsymbol{ext}_{\boldsymbol{v/s}}}$, that represents the Lagrangian components of the impact forces respectively on the vehicle and on the deformable structure. The method to compute the impact forces is based on the selection of suitable control points on the surface of the bogie frame and/or axle boxes (e.g. point P in Figure 1.a). The trajectory of each control point is followed during the motion of the vehicle, identifying the positions at which contact with the containment structure occurs (Figure 1.b). Impact forces between the vehicle and the wall are computed taking into account in an approximate way the local deformability of the structure using a Lankarani-Nikravesh contact model [10] whilst the overall deformability of the structure is modelled more accurately thanks to the finite element model schematization.

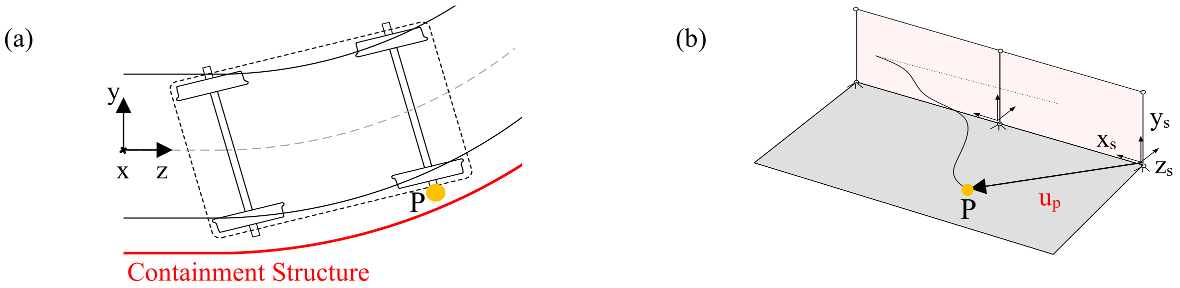

Figure 1- (a) Model of a bogie composing the vehicle and (b) finite element model of the deformable structure.

3 Results: Post-derailment simulation with deformable containment structure

The developed multibody/FEM model is applied to the case of a high-speed ETR-500 class locomotive running at 300 km/h along a curve with radius 5500 m. While the vehicle runs in the full curve section, the mechanical failure of one journal in the trailing wheelset of the front bogie is simulated by suddenly setting to zero the force transmitted by the corresponding primary suspension in all directions. This leads to the derailment of the front bogie and then to the impact of the same bogie with the derailment containment wall. As an example, Figure 2.a shows the deformed structure 1.5 ms after the start of the, instead Figure 2.b shows the bending moment at the base of the containment wall plotted vs. the distance travelled by the vehicle after the start of the impact.

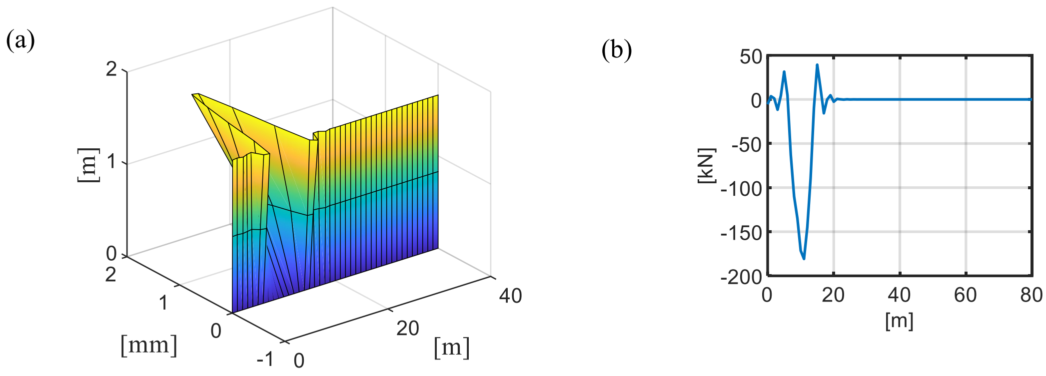

Figure 2 - At impact time: (a) Deformed of the structure (0-40 m)-(b) bending moment at the base of the structure (80 m).

4 Conclusions

In this paper, a model that simulates the dynamics of a derailed train is presented. The derailment is due to the failure of one axle journal in the vehicle and causes the front bogie of the vehicle to collide with a containment structure, schematized with a dynamic FEM. In the full paper, different derailment scenarios will be considered, computing for each of these the loads acting on the derailment containment structure. The results can be used for the structural sizing of the derailment containment structure.

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