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Study of the influence of damage on the response of a bogie frame using a flexible multibody methodology

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Abstract

The bogie frame is a safety-critical component of railway vehicles that motivates frequent visual inspections to allow the timely detection of damage. Monitoring the condition of the bogie frame during the operation using a sensor system could improve the maintenance strategy of railway vehicles. However, it is not clear how damage can be detected during the operation using the measured response of the bogie frame. This work aims at identifying the sensitivity of the structural response of the bogie frame to damage, in particular fatigue cracks, using computational tools. This task is supported by an improved flexible multibody methodology formulated to deal with flexible bodies described by solid finite elements characterised by three nodal degrees of freedom (DoFs). The implementation includes suitable reference conditions, the use of the component mode synthesis, and the application of the virtual bodies methodology. The simulations involve different locomotive models running on a realistic straight track with irregularities. The results show that the flexibility of the bogie frame affects the structural response in the mid-frequency range. The presence of a synthetic crack in the bogie frame model causes differences in the acceleration signals measured by virtual sensors. These differences in vibrational behaviour create the opportunity to assess the condition by comparing nominal and measured signals and associating the differences of the signals with damage magnitude using adequate monitoring techniques.

Keywords: Structural Flexibility; Multibody Systems; Virtual Bodies; Railway Dynamics

1 Introduction

The bogie frame is an important subsystem of railway vehicles that motivates frequent visual inspections to guarantee that damage is detected before the condition degrades at an exponential rate. Therefore, there is a potential benefit of complementing the visual inspection with online condition monitoring techniques. At present, however, comprehensive methodologies to monitor the condition of the bogie frame are still limited. One noteworthy example is the approach proposed by Hong et al. [1] that is based on the concept of guided elastic waves and is supported by the use of a sensor set installed on the bogie frame.

Multibody formulations allow simulating the response of railway vehicles during the operation, including the wheel-rail contact that provides the realistic loading of the vehicle components [2]. Flexible multibody simulations are a common tool to study the effect of track excitation [3] or for fatigue life estimation [4]. This work is developed using an established flexible multibody formulation, proposed by Ambrósio and Gonçalves [5], that comprises the use of reference conditions [6], the component mode synthesis [7], and the virtual bodies methodology [8]. This formulation is further developed by Pagaimo et al. [9] to allow dealing with flexible models described by finite elements with only three displacement degrees of freedom (DoFs) and no angular DoFs. The contributions to the flexible multibody methodology include the formulation of a rigid-flexible joint to connect rigid and flexible bodies in the context of the virtual bodies methodology.

This work aims at investigating the effect of damage on the structural response of the bogie frame using multibody simulations of the vehicle-track interaction. This task is the foundation for the wider goal of defining a methodology to monitor the condition of the bogie frame, to complement the current visual inspection.

2 Methods

Multibody simulations are a popular approach to simulate the vehicle-track interaction. The multibody models comprise a set of bodies that represent the components that account for most of the inertia of the system, interconnected by force elements and kinematic joints that represent the suspension elements. The interaction between the bodies and their environment, such as wheel-rail contact, results in the application of external forces to the system [2].

In this work, the positions and orientations of the bodies are described using Cartesian coordinates and Euler parameters, respectively. Perfect kinematic joints are described by algebraic constraint equations that define contributions to the Jacobian matrix of the system $\mathbf{\Phi_q}$ and to the vector of the right-hand side of the acceleration constraint equations $\boldsymbol{\gamma}$. The vector of Lagrange multipliers $\boldsymbol{\lambda}$ is introduced in the vector of the unknowns of the system. Force elements and imperfect kinematic joints develop forces due to the relative motion of the bodies, contributing to the force vector $\mathbf{g}$. Figure 1 summarises the multibody simulation algorithm used in this work.

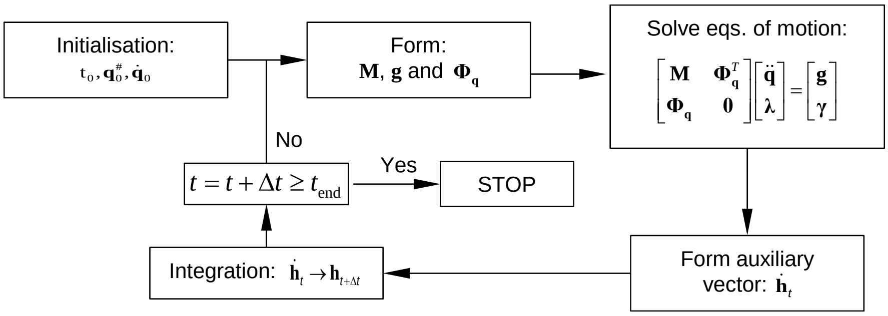

Figure 1 – Direct integration algorithm of the multibody simulation.

Multibody systems can also include flexible bodies when their structural flexibility plays a relevant role on the overall dynamics of the system, or when the deformations of the body are of particular interest. The equations of motion of a flexible multibody system are given by:

$$\begin{bmatrix} \mathbf{M}_{rr} & \mathbf{M}_{rf} & \mathbf{\Phi}_{\mathbf{q}r}^T \\ \mathbf{M}_{fr} & \mathbf{M}_{ff} & \mathbf{\Phi}_{\mathbf{q}f}^T \\ \mathbf{\Phi}_{\mathbf{q}r} & \mathbf{\Phi}_{\mathbf{q}f} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{q}}_r \\ \ddot{\mathbf{u}}' \\ \boldsymbol{\lambda} \end{Bmatrix} = \begin{Bmatrix} \mathbf{g}_r \\ \mathbf{g}_f \\ \boldsymbol{\gamma} \end{Bmatrix} - \begin{Bmatrix} \mathbf{s}_r \\ \mathbf{s}_f \\ \mathbf{0} \end{Bmatrix} - \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_{ff} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \mathbf{0} \\ \mathbf{u}' \\ \mathbf{0} \end{Bmatrix} \tag{1}$$

where the vector of nodal accelerations $\ddot{\mathbf{u}}'$ is one component of the vector of the solutions. The stiffness matrix $\mathbf{K}_{ff}$, and the lumped mass matrix of the flexible body $\mathbf{M}_{ff}$ are standard outputs from any available finite element code. $\mathbf{M}_{rf}$ is the matrix of the inertia coupling terms between the rigid and flexible motions. $\mathbf{s}_r$ and $\mathbf{s}_f$ are the rigid and flexible components of the vector of quadratic velocity terms, respectively. The use of mean axis reference conditions enforces the uniqueness of the flexible displacement field [6]. The virtual bodies methodology allows connecting rigid and flexible bodies using a standard library of kinematic joints developed to exclusively connect rigid bodies [8]. The component mode synthesis [7] approach reduces the total number of degrees of freedom of the system, improving the computational efficiency when dealing with large or complex structures. The flexible multibody methodology used in this work is described in detail by Pagaimo et al. in [9].

3 Results

This work contributes to the objective of defining a condition monitoring system for the bogie frames of a six-axle diesel-electric locomotive. The multibody models used in this work are an adapted version of the model presented by Millan et al. [10]. The simulations involve the locomotive running at a constant speed of 60 km/h on a straight track section with track irregularities. The bogie frame geometry is modelled and discretised using approximately 45000 structural tetrahedral solid elements. A modal analysis is run on a standard finite element software to obtain the lumped mass matrix, the matrix of modes of vibration and the associated natural frequencies, that are inputs to the multibody software MUBODyn. The outputs of the simulations are the accelerations of various points on the bogie frame. This work focuses on the lateral acceleration of point *P*, depicted in Figure 2, positioned near the welded connection between a transversal beam and a sideframe of the bogie.

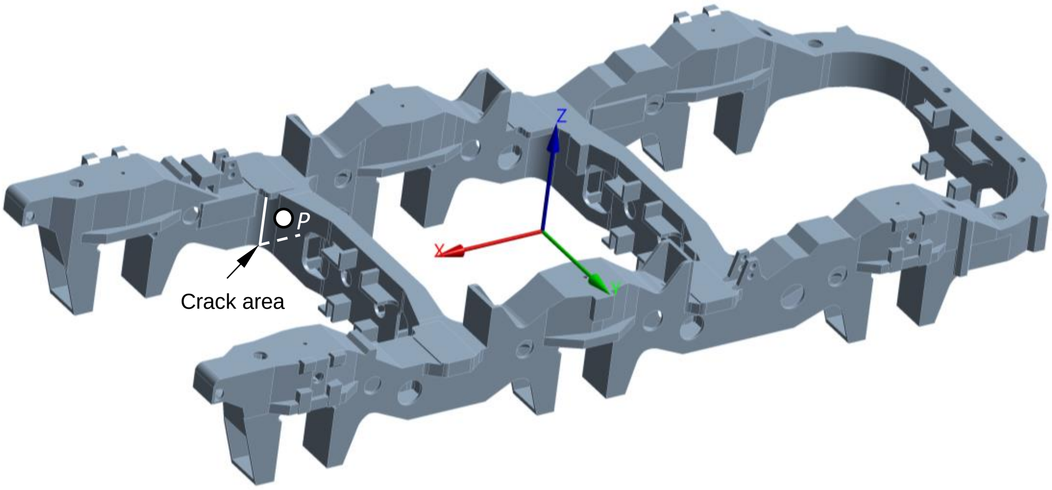

Figure 2 – Position of point *P* and the syntethic crack location in the bogie frame.

The first two simulations compare the bogie behaviour using a locomotive model with a rigid bogie frame and a second model considering the flexibility. Figure 3 shows the lateral acceleration of point *P* is affected by the bogie frame flexibility. Using the flexible bogie model, the lateral acceleration exhibits a higher frequency content superimposed on the lower frequency content.

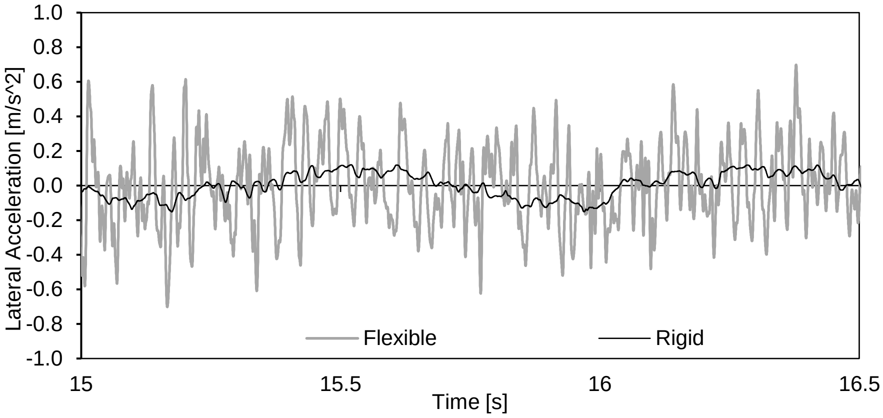

Figure 3 – Lateral acceleration of point *P* using a flexible bogie frame model and a rigid body model.

Figure 4 shows the PSD estimates of three different simulations: the two simulations described above, and a third simulation involving a flexible bogie frame model that includes a synthetic crack on the welded connection between a transversal beam and the sideframe, near point *P*. The peak frequencies of the responses of the models without damage are associated with approximately the same frequencies, up to a threshold of 20 Hz. This result suggests the two models represent the rigid-body motion of the vehicle with the same accuracy. The figure also compares the results of the simulations using the flexible models that represent the nominal and abnormal condition of the bogie frame. The damage explains the differences in the PSDs of the accelerations of point *P*. These differences can be associated with the condition using adequate condition indicators.

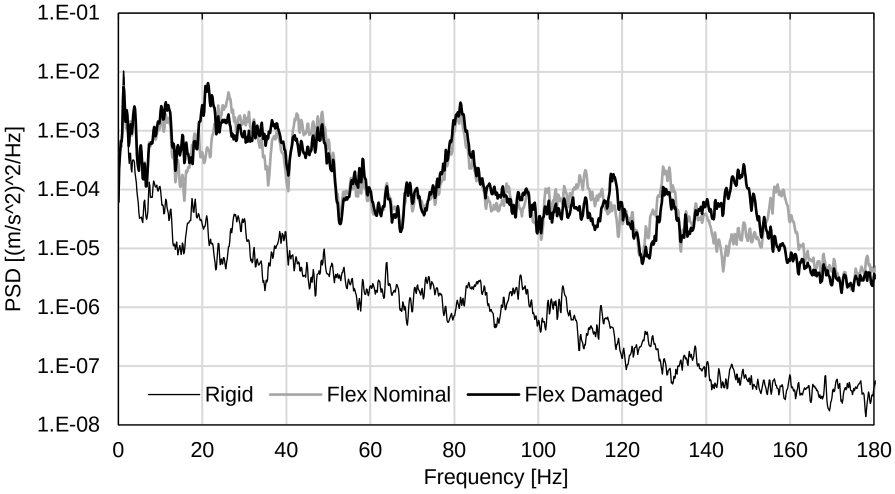

Figure 4 – PSD of the lateral acceleration of point *P* considering different bogie frame models.

4 Conclusions and Contributions

This work addresses the investigation on the sensitivity of the dynamic behaviour of a bogie frame to structural damage. This task is enabled by an updated flexible multibody methodology, that enables simulating the vehicle-track interaction in realistic operation conditions and delivers the signals measured by virtual sensors. The flexible multibody methodology is formulated considering a floating frame of reference and assuming the use of finite elements with three nodal degrees of freedom. The methodology includes the use of adequate reference conditions, the component mode synthesis, and the virtual bodies methodology, supported by the use of a novel formulation of a rigid-flexible joint.

Two simulations involve the comparison of the vehicle behaviour using first a model comprising rigid bodies only and a second model where the leading bogie frame is represented by a flexible model. The results show that, as widely established by other authors in the literature, the flexibility affects the response of the bogie frame exclusively above the low-frequency range.

To simulate the behaviour of the vehicle with a faulty bogie frame, a third model is developed involving a flexible bogie frame with a synthetic crack on a transverse beam. The results show that the presence of the synthetic crack affects the acceleration signals of a virtual sensor positioned in the vicinity of the crack. The differences in the signals measured by virtual sensors on the structure can be associated with the bogie condition if adequate condition indicators are identified and condition monitoring methodologies are formulated.

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