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Improved railway wheelset–track interaction model in the high-frequency domain

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HIGHLIGHTS

- 3D Moving Element Method (MEM) to model the track is proposed.
- The model considers an Eulerian coordinate system attached to the moving vehicle.
- The resulting formulation permits to reduce the computational cost compared to the FE models commonly used.
- The proposed 3D MEM track model is suitable to describe the high frequency dynamics.

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ABSTRACT

As it is well known, there are various phenomena related to railway train–track interaction, some of them caused by the high frequency dynamics of the system, such as rolling noise when the vehicle runs over the track, as well as squeal noise and short-pitch rail corrugation for curved tracks. Due to these phenomena and some others unsolved so far, a large effort has been made over the last 40 years in order to define suitable models to study the train–track interaction. The introduction of flexibility in wheelset and rail models was required to have a more realistic representation of the wheel–rail interaction effects at high frequencies. In recently published train–track interaction models, the rails are modelled by means of Timoshenko beam elements, valid up to 1.5 kHz for lateral rail vibration and up to 2 kHz for vertical vibration. This confines the frequency range of validity for the complete train–track model to 1.5 kHz.

With the purpose of extending the range of validity above 1.5 kHz, a 3D track model based on the Moving Element Method (MEM) is developed in this paper to replace the Timoshenko beam considered in earlier studies, adopting cyclic boundary conditions and Eulerian coordinates. The MEM approach considers a mobile Finite Element (FE) mesh which moves with the vehicle, so the mass of the rail 'flows' with the vehicle speed but in the opposite direction through the mesh. Therefore, the MEM permits to fix the contact area in the middle of a finitely long track and to refine the mesh only around the contact area, where the forces and displacements will be more significant. Additionally, a modal approach is adopted in order to reduce the number of degrees of freedom of the rail model. Both strategies lower substantially the computational cost. Simulation results are presented and discussed for different excitation sources including random rail roughness and singularities such as wheel flats. All the simulation cases are carried out for a Timoshenko beam and a 3D MEM track model in order to point out the differences in the contact forces above the range of validity of the Timoshenko beam.

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1. Introduction

The complexity of the train–track interaction comes from the vibration coupling between the railway vehicle and the track, in which wheel–rail contact forces couple both sub-systems and their surface imperfections, such as rail roughness and wheel out-of-roundness, excite the global system. Unwanted phenomena such as damage of the rolling surfaces in the form of high levels of noise and vibration [1], corrugation [2], wheelset axle fatigue [3] and stress damage may appear in some cases due to large levels of vibration and dynamic fluctuations of the contact forces.

Many suitable train–track interaction models have been developed over the last 40 years, incorporating more recently flexibility in the wheelset in order to widen the frequency range of analysis [1,4]. Finite Element (FE) models have strongly entered in railways research to extend the frequency range above 1 kHz to address the rolling noise phenomenon [5,6] and, only very recently, further works have considered the inertial effects due to wheelset rotation running on a tangent [3] and curved track [7].

Historically, a frequency domain approach has been used to address the moving load problem by means of the Fourier Transform Method (FTM) and a moving coordinate system. Mathews [8,9] considered an arbitrary load moving along an infinite beam resting on an elastic foundation and solved the problem by using FTM. Jézéquel [10] utilised the same methodology for an Euler–Bernoulli infinite beam (considering the rotational and transverse stiffness) with a Winkler foundation subjected to a concentrated force moving with constant speed. Other extended focus [11] is based on a time domain approach based on Timoshenko flexible beam model which considers a simply supported infinite beam subjected to moving loads.

These mentioned works consider rail beams as continuum and solve the equation of motion through an analytical approach. This makes them inappropriate when replacing a moving load by a complete moving vehicle system of massive number of degrees of freedom; for instance, the Timoshenko beam is only valid up to 1.5 kHz for lateral rail vibration and up to 2 kHz for vertical vibration [1]. Therefore, researchers have widely been using the well-known Finite Element Method (FEM), which physically discretises the track into a finite number of elements. Numerical time-stepping integrators are needed to solve the resulting equations of motion after assembling the element matrices. The FEM permits to extend the range of validity above the previous limit of 1.5 kHz and allows hence the complete wheelset–track model to comprise high frequency dynamic phenomena.

While considering a fixed global coordinate system in the FEM, the vehicle moves along the elements with time, thus the load vector has to be updated at each time step of the integration scheme. Additionally, there is the need of truncating the infinitely long track into a finite one with two corresponding artificial boundary ends, but the vehicle is moving forwards to the 'downstream' side. Therefore, the rail length required for reasonable simulation time-spans (without the vehicle exceeding the 'downstream' end), while preserving the refinement of the mesh, leads to an unapproachable number of degrees of freedom in the FEM.

To overcome both problems, Koh et al. [12] presented a formulation called Moving Element Method (MEM) based on an Eulerian coordinate system attached to the moving vehicle, instead of a fixed coordinate system. This method was initially adopted for a finite Euler–Bernoulli beam (1D). A new class of finite elements associated with the moving coordinate system is defined. Hence, the mesh is moving with this mobile frame and consequently the material of the rail 'flows' into this mesh. Another way to look at it is that these conceptual (not physical) elements 'flow' through the rail with the moving vehicle. This relative motion requires considering the material derivative for the formulation of the rail dynamics. The concept was afterwards extended to 2D moving elements in order to study moving load on continuum [13].

The novelty of the present article is the extension of the MEM concept to a tangent 3D track extruded from the UIC60 profile, adopting a FE technique and introducing cyclic boundary conditions [14]. The new methodology is herein referred to as the 3D Moving Element Method (3D MEM) and replaces the Timoshenko beam considered in earlier studies [2,3,7]. The 3D MEM avoids the moving vehicle exceeding the 'downstream' boundary end since this class of moving rail elements is attached to the vehicle. In fact, the vehicle remains fixed on a unique moving rail element instead of crossing from one element into another. This has two immediate and important consequences: firstly, there is no need to update the force or displacement vectors in the contact area because they are fixed on the same element; secondly, it permits to refine the mesh just around the fixed contact area, where forces and displacements are more pronounced. Both are hence important advantages in terms of computational cost compared to the FEM models commonly employed.

The 3D MEM formulation developed in Section 3 is utilised to compute numerically the resulting linear equation of motion, obtaining the element matrices and assembling them in global matrices by following the standard FE technique. These global matrices are not time dependent, and therefore they can be precalculated before the simulation starts and enable to adopt a modal approach. Using modal coordinates, the displacement vector of any point from the rail can be calculated through modal superposition. The number of modes calculated from the equation of motion is truncated to reduce the number of degrees of freedom of the governing system of differential equations and Newmark scheme is used to solve it at each time step.

Regarding the wheelset, a flexible model negotiating a tangent track developed by Martínez-Casas et al. [3] is used. This model also takes into account the gyroscopic and inertial effects associated with the rotation by using Eulerian-modal coordinates, which reduce the dimension of the dynamic system and thus the computational cost. Only one single wheelset is incorporated instead of one complete bogie in order to simplify the computational problem, and forces are prescribed at the primary suspension seats, according to a procedure described in Section 2.1.