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ABSTRACT

With the increase in hardware capabilities, the simulation of dynamic vehicle/track interaction (VTI) with a flexible track model especially a finite element (FE) based track model is possible. This may be handled via a co-simulation between multibody system (MBS) software and FE software. Meanwhile the simulation time is still too long. This paper proposes a new method of VTI simulation with a FE based track model. The new method extracts the characteristic data (mass matrix, stiffness matrix, damping matrix of elements and the rail node coordinates) from the FE track model. An integrated FE solver in the MBS software VOCO is used to calculate the dynamic response of the track. The communication between vehicle dynamic and track dynamic is carried out within VOCO. Voided sleepers are common defaults in ballasted tracks. Modelling of voided sleepers introduce non-linearity in the VTI. The new method shows a good agreement with co-simulation in the case of voided sleepers, with the new approach being much faster.

INTRODUCTION

Vehicle/track interaction (VTI) requires careful attention as it is the main cause of track damages and ground vibration. It also has an influence on the vehicle dynamics. A classic ballasted track is composed of rails, rail pads, sleepers, and ballast. The rail and the sleepers may be modelled by beams, while the rail pad and the ballast may be taken in account by joints connecting the rail, the rail pad, and the ground.

The excitation of the track results from the dynamics of the train, expressed by the wheel-rail (W/R) contact force. In order to model the whole VTI, we must either use a fully coupled scheme, or split the coupled problem, under some assumptions, into two sub-problems: vehicle dynamics and track dynamics. As shown in the first link of Figure 1, the vehicle is taken into

account by the wheel-rail contact force. In the second link, the displacements of the track under the wheel are introduced in the track geometry (Bezin et al. 2009).

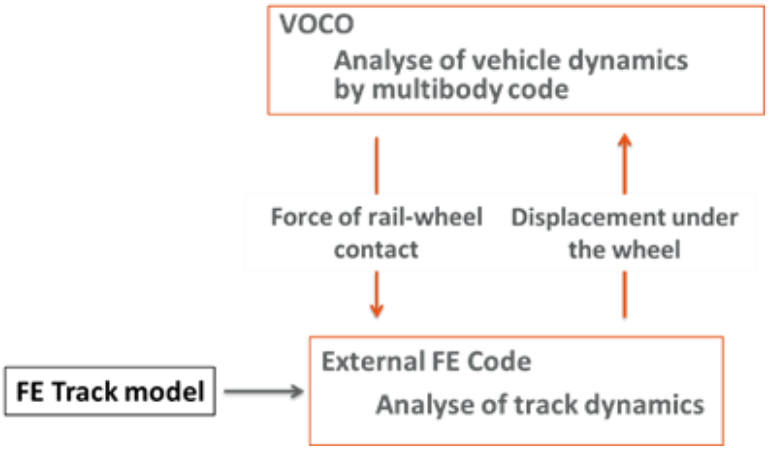

Figure 1. Co-simulation process between MBS and FE model.

Train dynamics may be simulated by a multibody system (MBS): in this study, the software VOCO is used. There are several methods to simulate the track dynamics. Among them, the FE method makes it possible to address complex geometries like switches and crossing (S&C) (Alfi and Bruni 2009) or bridges. In this study, a full transient FE analysis is performed in order to consider all the degrees of freedom of a 3D structure.

The feasibility of co-simulation between the third-party FE code and MBS VOCO has been demonstrated in a curve in the case of a S&C (Sebès et al. 2015), but the process is time consuming, for reasons that will be explained in the next section. On the other hand, track models directly implemented in MBS with an explicit time scheme have shown their efficiency in terms of computation times (Eickhoff et al. 2015) but they are still limited to relatively simple geometries.

A new method is proposed in order to combine the advantages of both approaches, enabling to address complex geometries with a reasonable computer time.

METHODOLOGY

As explained in the introduction, the VTI problem is seen as the coupling of two sub-problems. The principle of the coupling, as shown in Figure 1, is an exchange of data between the MBS code and the FE code. More precisely, the wheel-rail contact force is taken from the MBS code as an input for the FE code to assess the track displacement.

Wheel/rail contact is assessed with the semi-Hertzian method (Ayasse and Chollet 2005). The tangent forces are evaluated by a variant of FastSim (Kalker 1982), which is based on the local properties of a strip instead of an ellipse. A functional approximation of this variant is used: this so-called Chopaya function may be also seen as an improvement of the Shen-Hedrick-Elkins (Shen et al. 1983). The wheel-rail contact force contains three forces and three moments, which are derived from forces with lever arms.

The main issue concerns the exchange rate of data in the time loop. On the one hand if the frequency of data exchange is too small, the coupling process may not converge. On the other hand, exchanging data too frequently implies longer simulation times. The MBS code VOCO uses an explicit time scheme which time step is smaller than the time step of the implicit FE code. It seems reasonable to use independent time steps so as to perform only one FE analysis for several time steps of the MBS analysis to reduce the calculation time, but this approach still leads to an instability. Therefore, the current standard solution consists in using the same time steps for the MBS and the FE analysis.

In the case of the voided sleepers, the links between the sleepers and the ballast have some gaps, being a cause for nonlinearity.

In the new method depicted in the flowchart of Figure 2, the third-party FE implicit solver is replaced by a new explicit solver. Due to the explicit time scheme, the stable time step proves to be smaller than the standard co-simulation. A new strategy is proposed, which consists in integrating a FE solver as a subroutine in the MBS code VOCO, hence suppressing the exchange of data through external files. This internal FE solver imports the element stiffness, damping, mass matrices and boundary conditions defined in the external FE code.

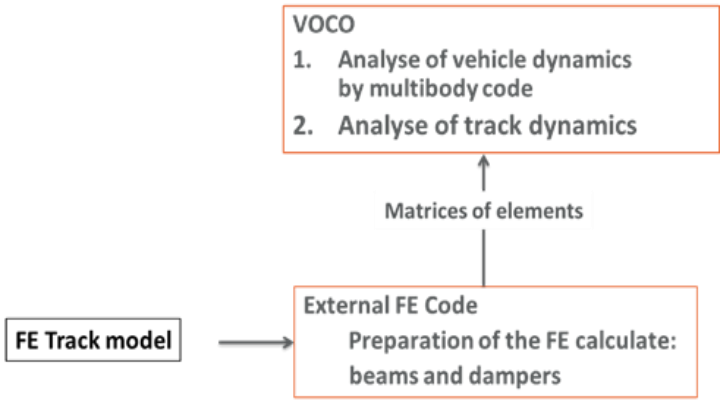

Figure 2. Integration of FE solver in VOCO.

The track dynamics is solved via the equation:

$$M\ddot{x} + C\dot{x} + Kx = F \tag{1}$$

Where M is the mass matrix, C is the damping matrix, K is the stiffness matrix, F is the vector of W/R forces, and x are the track degrees of freedom. The time integration scheme is the Euler explicit scheme. The algorithm of the track module is:

a) Initialize displacements and velocities to zero

b) Integrate velocities and displacements

$$\dot{x}_t = \dot{x}_{t-\Delta t} + \ddot{x}_t \Delta t$$

$$x_t = x_{t-\Delta t} + \dot{x}_t \Delta t$$

c) Calculate the accelerations

Rather than solving the full system, forces are assessed through a loop over the elements. The external force F is applied to the closest nodes to contact location, and then distributed by the Hermite interpolation function. The acceleration may be obtained from equation (1):

$$\ddot{x}_t = M^{-1}\left(F_{t-\Delta t} - C\dot{x}_{t-\Delta t} - Kx_{t-\Delta t}\right)$$

A lumped mass approximation is adopted for the expression of the global mass matrix M. Only the elementary stiffness and damping matrices associated to the active nodes are required.

According to the Courant–Friedrichs–Lewy (CFL) condition, the stable time step is inversely proportional to the maximal eigenfrequency. Complex geometries may introduce small elements leading to a small stable time step. To solve this problem, the so-called 'mass scaling' (MS) technique is used where an extra mass is added to the nodes that have a significant influence on the stable time step. Nonetheless a compromise is required between the time step and the physics.

CASE STUDY

A plain line track is considered with 4 nonlinear voided sleepers with a gap of 3 mm. Rails are modelled with Timoshenko beams supported on discrete sleepers, which are modelled as well as Timoshenko beams. The rails and the sleepers are connected by springs and dampers which represent the rail pads and fasten joints between them. All the nodes of ballast are blocked. The rail used in this study is UIC60, the inclination is 1/20. The track length is 80m with cycling conditions at both ends. The voided sleepers are positioned at 40 m. A TGV (French High-Speed Train) locomotive (Figure 3) is considered running at 87.5 m/s. The axle load is 16 tons. The vertical contact force will highly increase due to the lack of connection of sleeper because of the brusque variation of track flexibility. This represents a case study in order to validate VTI in nonlinear case. The characteristics of the track model are reported in Table 1.

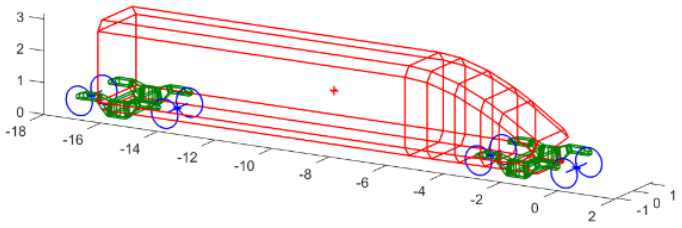

Figure 3. TGV locomotive.

Table 1. Characteristics of the FE track model

Definition	Value
Number of active nodes	3377
Total number of nodes	9005
Number of elements	28764

The vertical contact force is displayed on top of Figure 4. The rail displacement (bottom of Figure4) induces the amplification of the wheel-rail forces. The computing time of both methods

are compared in Table 4. The new method with mass scaling is approximately 250 times faster than the co-simulation method in this case.

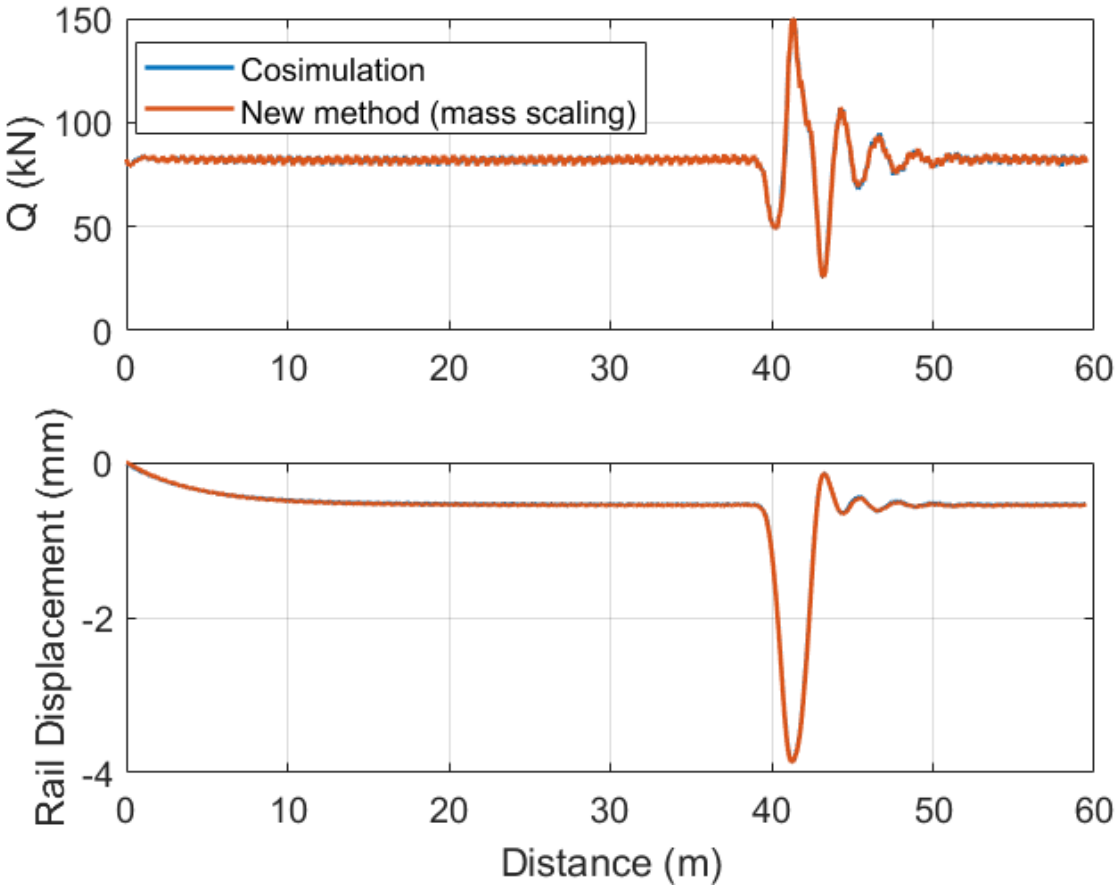

Figure 4. vertical contact force (top);
rail displacement under the wheel of the first train's axle (bottom).

Table 2. Comparison of CPU time

Method	Time step (ms)	Simulated time (s)	CPU Time (s)
Co-simulation	0.021	0.68	36771
New without MS	0.003	0.68	810
New with MS	0.016	0.68	149

CONCLUSION

A new method is proposed to address vehicle/track interaction of complex track geometries (S&C, bridges) in a reasonable computing time. The previous approach consisted in a co-simulation with a third-party FE solver. Gain in CPU time is obtained thanks to an explicit time

scheme and the removal of the input/output data flow between the MBS software and the FE solver. The third-party FE software is used only to provide elementary FE matrices to the explicit solver. They are capable to treat non-linear models. The first test cases show a good agreement between both approaches in the case of plain line. Further works should deal with switches and crossing.

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