



HAL
open science

A new dynamic vehicle/track interaction method with a finite element track model

Demeng Fan, Michel Sebès, Aquib Qazi, Emmanuel Bourgeois, Hugues Chollet, Cédric Pozzolini

► To cite this version:

Demeng Fan, Michel Sebès, Aquib Qazi, Emmanuel Bourgeois, Hugues Chollet, et al.. A new dynamic vehicle/track interaction method with a finite element track model. Second International Conference on Rail Transportation, Chengdu China, 5-6 July 2021., Jul 2021, Chengdu, China. hal-03321862v2

HAL Id: hal-03321862

<https://hal.science/hal-03321862v2>

Submitted on 8 Mar 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

A new dynamic vehicle/track interaction method with a finite element track model

Demeng Fan^{1,3}, Michel Sebès², Aquib Qazi^{3,4}, Emmanuel Bourgeois¹, Hugues Chollet², Cédric Pozzolini³

¹ Université Gustave Eiffel, COSYS-LISIS, IFSTTAR, F-77447 Marne-la-Vallée, France

² Université Gustave Eiffel, COSYS-GRETTIA, IFSTTAR, F-77447 Marne-la-Vallée, France

³ ESI Group, Paris, France

⁴ Laboratoire Navier, UMR8205, Ecole des Ponts, IFSTTAR, CNRS, UPE, Champs-sur-Marne, France

demeng.fan@univ-effiel.fr

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. The classical method using co-simulation between multibody software (MBS) 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 information (mass matrix, stiffness matrix, damping matrix of elements and the rail node coordinate) from the FE track model. An integrated FE solver of MBS VOCO is employed to calculate the dynamic response of the track. The communication between vehicle dynamic and track dynamic is all carried out within VOCO. The voided sleepers are common defaults, the non-linearity in the model of voided sleepers cause difficulties for the simulation. The new method shows a good agreement with the classic method in the case of voided sleepers, with the new approach being much faster than the classical approach.

Keywords: Vehicle-track interaction, Switch and Crossing (S&C), Finite element, voided sleeper, Algorithm

1.1 Introduction

Vehicle/track interaction 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, which can be represented by the wheel-rail contact force. To model the whole VTI, we must use a fully coupled scheme, or under some assumptions to split the coupled problem into two sub-problems: vehicle dynamics and track dynamics. As a first link as shown in Figure 1, the vehicle is taken into account by the force of wheel-rail contact. In the second link, displacements of the track under the wheel are introduced in the track geometry [1].

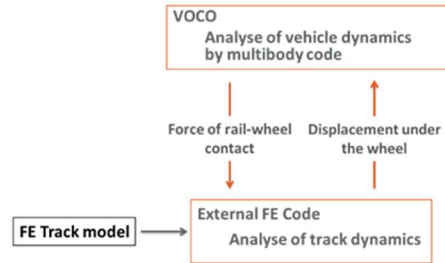


Figure 1. Classical train-track interaction method

Train dynamics may be simulated by a 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) [2] or bridges. In this study, a full transient FE analysis is performed in order to take in account 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 [3], 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 scheme have shown their efficiency in terms of computation times [4] 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.

2 Methodology

2.1 Classical method

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 computing of displacement of track solved by the FE code.

Wheel/rail contact is assessed with the semi-Hertzian method [5]. The tangent forces are evaluated by a variant of FastSim [6], 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 [7] method when spin is present. The wheel-rail contact force contains three forces and three for each contact: the longitudinal force F_x , the lateral force F_y , the vertical force F_z and the moment around the axe x M_x , axe y M_y and axe z M_z .

The first question occurs in the exchange rate of data. On one hand if the two software exchange data too slowly, the contact force or the displacement under the wheel is no more the data requested, the simulation cannot converge. On another hand,

exchanging data too fast implies using an extremely small-time step, and hence longer simulation times. It is necessary to specify the time step adopted in the coupling process. The MBS code VOCO uses an explicit time scheme whose time step is much smaller than that of the FE code (which uses an implicit time scheme). 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 leads to an instability problem. Therefore, the standard solution consists in using the same time steps for the MBS and the FE analysis. This method here is the ‘classical train-track interaction method’.

In the classical method, two coordinate parameters are available to adjust the difference between the VOCO and the third-party FE software coordinate. The first parameter is used to accord the original point location in the longitudinal direction. The second parameter will be applied in the case when VOCO and the third-party FE software use different units. All the node number and their coordinates in the third-party FE software are offered to VOCO by the track model.

In the case of the voided sleepers, the links between the sleepers and the ballast have some gaps. The tolerance on the convergence criterion on the forces and moments is larger than the default: 1% vs. 0.1% by default.

2.2 New method

In a first stage the third-party FE implicit solver is replaced by a new explicit solver in the flowchart of Figure 2. The stable time step is found to be lower than with the classical approach. A new strategy is proposed, which consists in integrating a FE solver as a subroutine in the MBS code VOCO, which suppresses the exchange of data through external files. This FE solver only performs the numerical solution, which means that the numerical problem (element stiffness matrices and boundary conditions) is defined in the external FE code. In practice, two new subroutines have been introduced in the MBS code, one to import the matrices from an external FE code, and the other to solve the FE problem. The process is shown in Figure 2.

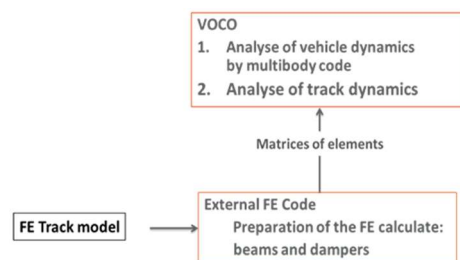


Figure 2. Integration of FE solver in VOCO

In the new method, besides the two coordinate parameters and the coordinates of rail nodes, the characteristic information of track model is extracted from the mesh and the element attributes are additionally written in the track model. The beam elements have two nodes, the interpolation function in the element is Hermit function. Almost FE

software provide an application programming interface (API) of element matrices. Meanwhile for a sake of standardization, the authors developed a translator to excecrate element matrices from FE track model.

The solver is composed of a FE track model module and a track dynamics module. The track model module oversees the lecture of track model. Once the lecture is done, the track dynamics is responsible for the computation of track dynamics response under the contact force and data change between with the main VOCO program.

The time integration scheme is the Euler explicit scheme. The algorithm is:

- a). Initialize the speed \dot{x}_0 speed and the displacement x_0 as null
- b). Integrate the speed \dot{x}_t and the displacement x_t

$$\dot{x}_t = \dot{x}_{t-\Delta t} + \Delta t \ddot{x}_t \quad (4)$$

$$x_t = x_{t-\Delta t} + \Delta t \dot{x}_t \quad (5)$$

where \ddot{x}_t is deduced from the equation of track dynamics:

$$\mathbf{M}\ddot{x} + \mathbf{C}\dot{x} + \mathbf{K}x = \mathbf{F} \quad (6)$$

In the case where some freedom degrees are blocked, the integrations of these freedom degrees are skipped. So, the motions of these freedom degrees rest null.

- c). Calculate the acceleration \ddot{x}_t

Rather than solve the global system, this solver does a loop over the elements. \mathbf{M} , \mathbf{C} and \mathbf{K} represent respectively the mass matrix, the damping matrix and the stiffness matrix. The \mathbf{F} is the external force of the element. The force \mathbf{F} is applied to the closet nodes of contact location, and then distributed by the Hermit interpolation function. As mentioned in the section 2.1, the moment is no longer the moment in the contact zone. The lever arm must be considered. The acceleration \ddot{x}_t can be obtained by placing all other the terms in the right side of equation (6),

$$\ddot{x}_t = \ddot{x}_t = \mathbf{M}^{-1} (\mathbf{F}_{t-\Delta t} - \mathbf{C}\dot{x}_{t-\Delta t} - \mathbf{K}x_{t-\Delta t}) \quad (7)$$

A modification of the mass matrices is made for the convenience of calculation of the integrated FE algorithm. For a beam element of six degrees of freedom and a spring element, the matrix is of dimension of 12*12. But the mass matrices are off diagonal, their inversions and calculation of the acceleration for an explicit scheme require more time than a diagonal matrix. Thus, the mass matrices are diagonalized guaranteeing every node has the same mass. As far as only the free nodes need to be calculated their motions, the matrices of mass are only given to the free nodes. Then the diagonals of mass matrices are saved in the track model for each free node. Besides the stiffness matrices and the damping matrices are saves in the track model indicating the node number of each element.

Some elements have same nodes but are considered as different elements. According to the philosophy of calculating over the elements, the decrease of elements will economize the calculation time. Moreover, for the elements who have blocked nodes,

it's not necessary to calculate an equation of 12*12. The equation (8) is a general case that an element contains a free node and a blocked node.

$$\begin{bmatrix} K11 & K12 \\ K21 & K22 \end{bmatrix} \begin{bmatrix} X_{free} \\ X_{blocked} \end{bmatrix} = \begin{bmatrix} F_{free} \\ F_{blocked} \end{bmatrix} \quad (8)$$

If $X_{blocked} = 0$, $F_{free} = K11 * X_{free}$. It means even the damping matrix and the stiffness of an element with a blocked node can be saved as the term only concerning the free node.

At each time, the acceleration \ddot{x}_t is fit as null.

The stable time step is proportional to $\sqrt{\frac{K}{M}}$ if the influence of the damping is neglected. However, in a case of S&C, when the switch rail and the stock rail are relatively close, some little beam elements arise on the sleepers. These little elements significantly decrease the stable time step. To solve this problem, the so-called 'mass scaling (MS)' technic is used. The extra mass is added on some nodes who influence largely the stable time step. Nonetheless it need find the compromise between the time step and the physics. Because when the mass is changed, the physics is also changed at the same time.

3 Study cases

3.1 Normal rail on through route with four voided sleepers

The FE track model is a through route with a lack of connection between a sleeper and the rails. The rails are modelled par Timoshenko beam supported by discrete sleepers which are modelled as well as Timoshenko beam. 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 as the boundary conditions. The rail used in this study is UIC60, the taper is 1/20. The track is of finite length and its length is about 80m. It begins at -20m and ends at 60m. The sleeper unsupported is positioned at 40 m. The gaps equal 3 mm. The vertical contact force will highly increase at the lack of connection of sleeper because of the increasing flexibility of track. The character can help validate whether the new method has a good dynamics response. The train circuits from 0m in VOCO with a constant speed 87.5 m/s.

The final scope of FE track model is demonstrated in Table 1.

Table 1. Notions of numbering of the FE track model of normal rail.

Notion	Definition	Value
NNOEMAS	Number of nodes with mass (free)	3377
NNOEMAX	Number of nodes in total	9005
NELMAX	Number of elements in total	28764

The vehicle model (Figure 3) in the test simulation is TGV (French: Train à Grande Vitesse, "high-speed train") motor with two wheelsets. Its characteristic parameters are in Table 2.

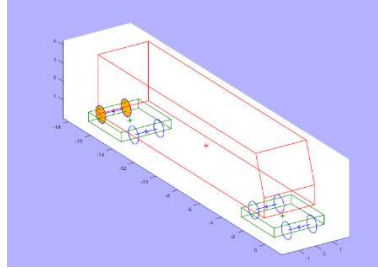


Figure 3. TGV Motor

Table 2. Characteristics parameters of vehicle

	Mass (Kg)	Inertia Ixx (kg.m ²)	Inertia Iyy (kg.m ²)	Inertia Izz (kg.m ²)
Carriage	54244	58783	1118055	1098441
Bogie	2382	1449	1486	3545
Wheelset	2048	892	99	892

3.2 Swedish S&C model from the international S&C Benchmark with four voided sleepers at the level of the nose

The Swedish S&C model is used here. The common description is in another cooperative article by the university of Birmingham, Southwest Jiaotong University, University Gustave Eiffel, and Chalmers University of Technology. The classical dynamic vehicle/track interaction method in VOCO is used to solve the same problem. Here, the new method is applied aiming to have the same result and consume less time. The finite element track model of Swedish S&C is presented in Figure 4. The original is also the beginning of the switch rail. Before the original, the track has supplementary 47 m, among which 22 m to put the vehicle on the track and 25 m to permit that the track is in quasi-static state when the vehicle entre on the switch rail. The rail nodes on both ends of the track model are coupled to create a cyclic condition. The operation allows to avoid the instability when the vehicle is on the extremity of the track.

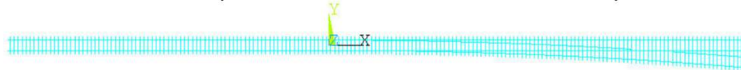


Figure 4. Finite element track model of Swedish S&C

As the section 3.1, the values of notions concerning the size of finite element size both on through route and on diverging route are given in Table 3. The values on through route and on diverging route are lightly different, that's because different rail nodes are used as the route path. As the nominal rail, the Swedish S&C has also four voided sleepers. The gaps equal 3 mm. They are located at the level of the nose.

Table 3. Notions of numbering of the finite element track model of Swedish S&C

Notion	Value on through route	Value on diverging route
NNOEMAS	6457	6455
NNOEMAX	10551	10549
NELMAX	16225	16225

The study case on through route is the set of Run 3 and Run 7 of the S&C Benchmark, while the study case on diverging route is the set of Run 4 and Run 8 [8]. The vehicle is the Manchester Benchmark Vehicle [8]. The other methods used by VOCO in the S&C Benchmark are in [9]. A good compromise between the time step and the physics is found with a limit mass per node equals 10 kg.

4 Numerical Results

4.1 Normal rail model

The vertical contact force (Figure 5, up) is considered. This displacement will be added to the wheel's movement, so it will influence the stability of train.

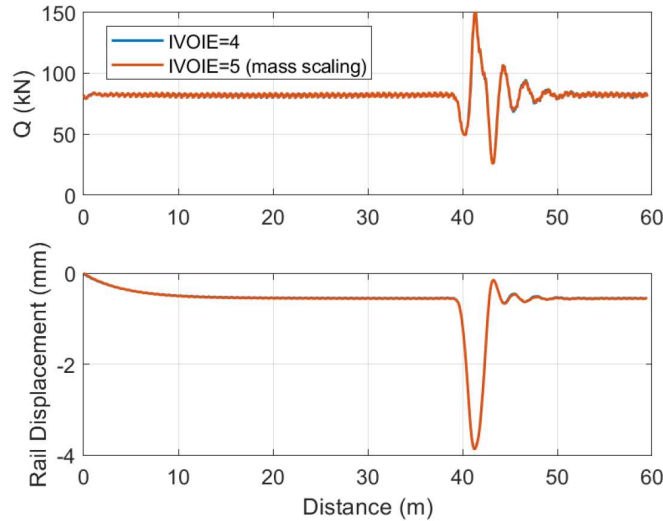


Figure 5. vertical contact force (up); displacement under rail the wheel of first train's axle (down)

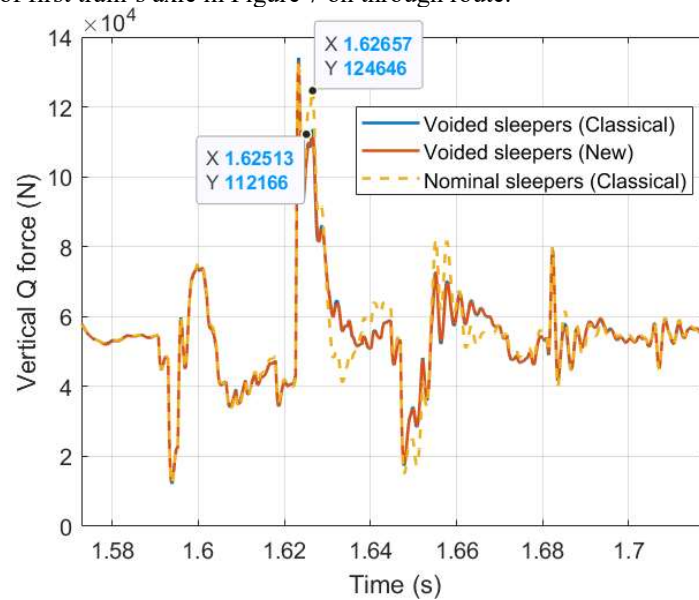
The calculating time of two methods are compared in Table 4, the new method is 64 times faster than the classical method in this case.

Table 4. Comparison of calculating time

Method	Time step (ms)	Time of simulation(s)	Time of calculation (s) without MS	Time of simulation(s) with MS
Classical	0.02	0.68	36771	No data
New	0.003	0.68	810	149

4.2 Swedish S&C model

The vertical contact force of different rails with variable sections are presented in Figure 6 on through route. The displacement under different rails with variable sections the wheel of first train's axle in Figure 7 on through route.

**Figure 6.** Vertical contact force on through route

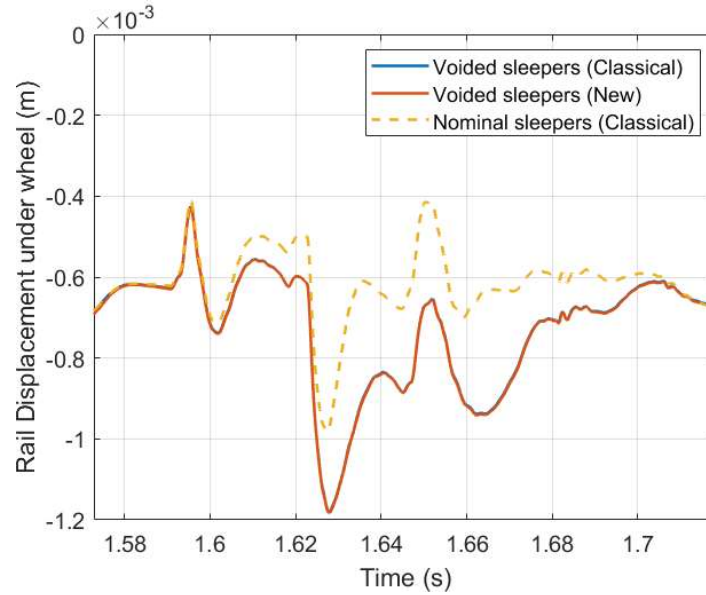


Figure 7. Vertical Displacement of rails under wheel on through route

The Classical method and the new method agree well in the case of the voided sleepers. The model with nominal sleepers has more important force peaks and less important deflection of rail. The calculating time of two methods are compared in Table 4, the new method is 13 times faster than the classical method in this case.

Table 5. Comparison of calculating time

Method	Time step (ms)	Time of simulation(s)	Time of calculation (s) without MS	Time of simulation(s) with MS
Classical	0.02	1.85	157137	No data
New	0.003	1.85	Not tested	16896

5 Conclusions

A new method is proposed enabling 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 time is obtained thanks to an explicit scheme. In order to avoid input/output, this method has to be directly implemented in the MBS software. The third-party FE software is used only to provide elementary FE matrices to the explicit solver. First test cases show a good agreement between both approaches. They are capable to treat the models with

the non-linear links. The first test cases show a good agreement between both approaches in the case of normal rails, switch, and crossing.

Acknowledgements

The work presented in this paper has been carried out with the generous support of ESI GROUP (Paris, France).

References

1. Y. Bezin, S. Iwnicki, M. Cavalletti, E. de Vries, F. Shahzad and G. Evans.: An investigation of sleeper voids using a flexible track model integrated with railway multi-body dynamics. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. vol. 223, pp. 597-607 (2009).
2. Alfi S. and Bruni S.: Mathematical modelling of train-turnout interaction. Vehicle System Dynamics. Vol. 47, No.5, pp. 551-574 (2009)
3. M. Sebès, H. Chollet, E. Monteiro, M. Laurent and C. Muller.: Adaptation of the semi-Hertzian method to wheel/rail contact in turnouts. Proceedings of the 24th Symposium of the International Association for Vehicle System Dynamics, IAVSD, Graz (Austria), (2015)
4. B. Eickhoff, L. Mazzola, Y. Bezin, G. Tucker, H. Stradtman, A. Haigermoser, H. Chollet and J. Landais: Track loading limits and cross-acceptance of vehicle approvals. Proc IMechE Part F: J Rail and Rapid Transit. Vol. 229, No.6, pp. 710–728. (2015)
5. J-B.Ayasse and H. Chollet Determination of the wheel rail contact patch in semi-Hertzian conditions. Vehicle System Dynamics. 43(3). pp.161–172. (2005)
6. Kalker, J. J.: A fast algorithm for the Simplified Theory of rolling contact. Vehicle System Dynamics. Vo.11. pp. 1-13. (1982)
7. Z. Y. Shen, J. K. Hedrick, and J. A. Elkins, A comparison of alternative creep force models for rail vehicle dynamic analysis. The Dynamics of Vehicles on Roads and Tracks, Proc. of the 8th IAVSD Symposium. pp. 591-605. Cambridge (MA): Swets and Zeitlinger. Lisse. (1983)
8. Y. Bezin and B.Pålsson.: Multibody simulation benchmark for dynamic vehicle-track interaction in switches and crossings: Modelling description and simulation tasks. (2019)
9. M. Sebès, D. Fan, A. Qazi, H. Chollet, E. Bourgeois and C. Pozzolini. : VOCO statement of methods. (2020)