Université de Mons
Faculté Polytechnique – Service de Mécanique Rationnelle, Dynamique et Vibrations
31, Bld Dolez - B-7000 MONS (Belgique)
065/37 42 15 – georges.kouroussis@umons.ac.be

G. Kouroussis, B. Olivier, O. Verlinden, A co-simulation strategy in the simulation of vehicle-track-ground subdomains, In W. Zhai, K. C. P. Wang and S. Zhu (ed.), *ICRT2021*, 2022, *ISBN 978-0-7844-8388-6.*

A Co-Simulation Strategy in the Simulation of Vehicle-Track-Ground Subdomains

Georges Kouroussis[1]; Bryan Olivier[2]; and Olivier Verlinden[3]

[1]Dept. of Theoretical Mechanics, Dynamics and Vibrations, Faculty of Engineering, Univ. of Mons, Belgium. E-mail: georges.kouroussis@umons.ac.be
[2]Dept. of Theoretical Mechanics, Dynamics and Vibrations, Faculty of Engineering, Univ. of Mons, Belgium
[3]Dept. of Theoretical Mechanics, Dynamics and Vibrations, Faculty of Engineering, Univ. of Mons, Belgium

ABSTRACT

Modelling a whole vehicle-track-foundation-soil system is complex and usually the problem is split into several subdomains for predicting railway-induced ground vibrations. In this way, a modelling approach (multibody simulation, finite element analysis) dedicated to each subdomain can be adopted without any numerical constraint. A limitation however occurs regarding the interaction between each subsystem which is thus neglected. For some cases, the whole modelling does not allow an accurate simulation. A solution consists on co-simulation that can be applied to re-couple the decoupled model during the time integration process. The purpose of this paper is to analyse various techniques of co-simulation by considering theoretically a monolithic model, split at different location. A TCP/IP client/server binding is used for the data transfer during the numerical integration. An application case is then presented using two different software packages: EasyDyn, an in-house multibody simulation software, for the vehicle subsystem and ABAQUS, a commercial finite element software, for the soil subsystem.

INTRODUCTION

Due to the always growing computational capacity, modelling a whole vehicle/track/foundation/soil has become an indispensable tool to evaluate the dynamic response of a moving rail vehicle and its interaction with the railroad (Connolly et al. 2015). Such prediction models are widely used for various applications, including the assessment of stresses on track components, the stalibity study of vehicle, the noise emission calculation, or the prediction of ground-borne vibrations. In particular, the assessment of annoyance from vibration is of growing interest (Thompson et al. 2019), the existing models being nowadays of a sufficient accuracy to predict some important phenomena (moving load effect, interaction with rail joints, effect of transition zones, ...).

To take into account all the subsystems involved (Figure 1), a full model is required, usually in the time domain. Galvín et al. (2010) proposed a time domain fully coupled multibody/finite element/boundary element model to predict high-speed train vibrations, attempting to combine the advantages of both methods. The finite element approach is however preferred to model a medium such a soil due to its versatility and natural way to be numerically integrated in the time domain. Triepaischajonsak et al. (2011) used a two-stage hybrid approach that couples a time domain finite element model for the track with a simple moving vehicle model. Connolly et al. (2013) developed an ABAQUS model that couples multibody dynamics and finite element techniques in a single program. El Kacimi et al. (2013) studied the train fundamental passing frequency effect on the dynamic railway track response for train speeds belonging to the subcritical, critical and supercritical ranges. Shih et al. (2016) investigates the meshing and boundary conditions of accurately model the effect of high-speed moving load.

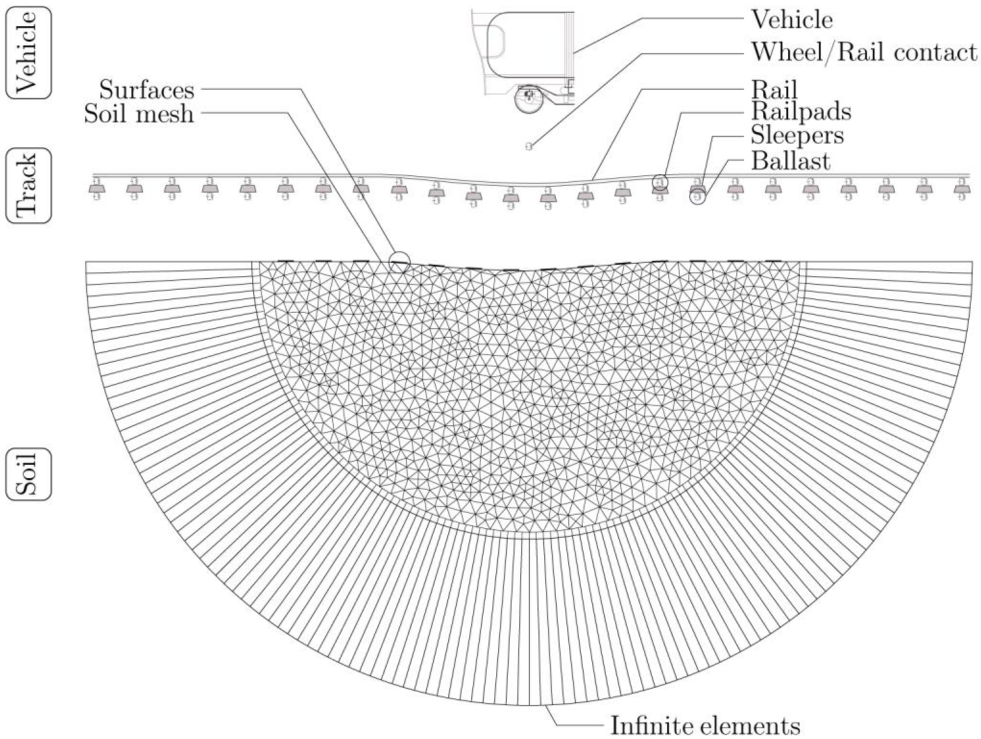
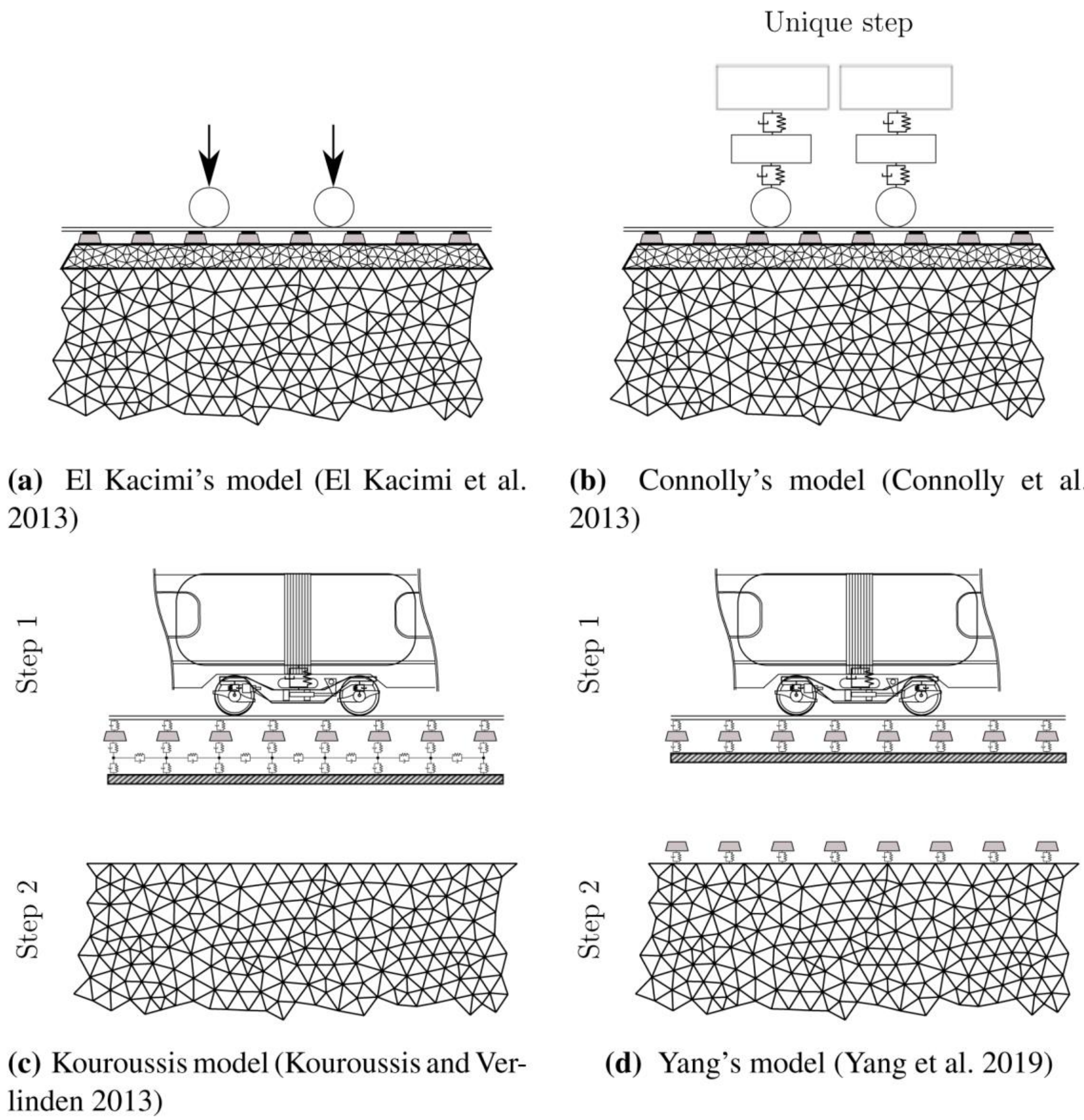


Fig. 1. Representation of the vehicle-track-soil subsystems

The actual goal aimed when establishing a railway modelling can vary significantly (Kouroussis et al. 2014). In an usual way, the vehicle is simplified by several constant or varying axle load moving along the track (El Kacimi et al. 2013). To take into account the vehicle dynamics, Connolly et al. (2013) proposed to consider the vehicle modelled using a multibody approach and its equations are derived considering that it can be split into a series of simplified systems including three bodies and three degrees of freedom (Figure 2b). This model requires the implementation of a specific time-integration algorithm dedicated to the vehicle equations of motion. This approach could be characterized of "embedded function" in the coupling classification that will be presented in the next section. To tackle the specificity of each subsystem (large rigid body motion for the vehicle, deformation for the track and soil), multi-step approaches are preferred, introducing some assumption at the interfaces. Two of them are illustrated in Figure 2. The model (illustrated in Figure 2d) used by Yang et al. (2019) is, like the model proposed by Kouroussis and Verlinden (2013), a two-step model whose first step focuses on vehicle/track interaction and second step focuses on ground-borne vibrations. In opposition to Kouroussis model (Figure 2c), it neglects the soil in the first step. A major advantage of these models is that they provide, through its overlapping two steps, relevant information regarding both vehicle/track interaction and ground-borne vibration. The main drawback is the decoupling at one interface of the whole system.

To overcome this limitation, co-simulated vehicle/track/soil model in which the vehicle and the track are simulated in an in-house software dealing with multibody dynamics while the soil is simulated in a finite element software can be a promising solution. Basically, it corresponds to the two-step model aforementioned but the recoupling is directly performed during the integration process. Various co-simulation models exist in the literature such as the model of the vehicle/track dynamics proposed by Dietz et al. (2002). Usually those models do not include a complete soil modelling and the track is limited to the ballast and sub-ballast elements. The purpose of the present paper is to establish the principles and the rules using co-simulation techniques to build a vehicle/track/soil model allows using dedicated solvers and software for the modelling of each subsystem.



(a) El Kacimi's model (El Kacimi et al. 2013)

(b) Connolly's model (Connolly et al. 2013)

(c) Kouroussis model (Kouroussis and Verlinden 2013)

(d) Yang's model (Yang et al. 2019)

Fig. 2. Vehicle/track/soil models dedicated to ground-borne vibration assessment: different ways to model a finite element approach

BASICS OF CO-SIMULATION TECHNIQUES

As explained, co-simulation consists of coupling two or more schemes that are integrated simultaneously using possibly different numerical solvers. Busch (2012) classified the coupling methods according to different criteria (Figure 3): the modular modelling which defines the nature of the coupling performed; the interfaces that define whether there is a strong coupling (also called monolithic modelling in which all the models are time integrated using the same unique solver) or a weak coupling; the numerical approaches that define if the coupling is explicit or implicit.

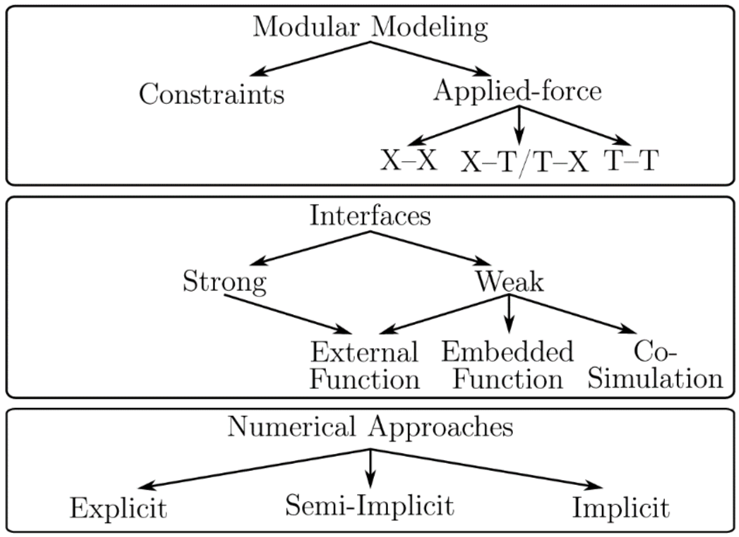


Fig. 3. Classification of the different coupling methods

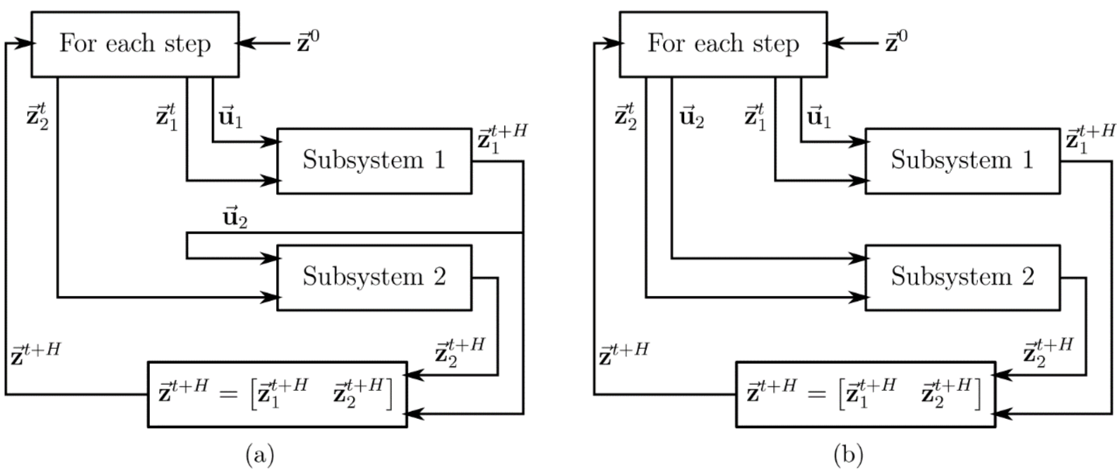


Fig. 4. Gauß-Seidel (left) and Jacobi (right) co-simulation approaches

In addition to this classification, additional features are of great interest (Figure 3):

- In the weak case (interface), if the discretised equations of one subsystem are included in the second, it is called "embedded function approach".
- The "external function" approach being either in the weak and strong coupling sections: this qualifies an external function that contains a model of a subsystem (mainly the equations of motion) but does not time-integrate it in this external function. That kind of function is used when a master environment deals with the integration of both subsystems. This obviously allows a monolithic modelling (strong coupling) to be built but it also allows the use of two independent solvers in the main integrating environment. Therefore this external function is located between the strong and weak interfaces.

- The X–X, X–T/T–X and T–T options called the co-simulation type in this work. The T actually defines a force quantity while the X symbolizes a kinematic quantity. In the literature, X is often called displacement for the sake of simplicity although the velocity can be exchanged as well (when the coupling presents damping).

The main numerical approaches used in co-simulation are Jacobi and Gauß-Seidel explicit approaches (Figure 4). $\vec{\mathbf{Z}}_i^t$ symbolizes the vector of state variables of subsystem *i* at time *t*, $\vec{\mathbf{z}}^t$ is the concatenation of state variables of both subsystems and $\vec{\mathbf{u}}_i$ symbolizes the vector of inputs in subsystem *i* coming either from the state variables of the other subsystem or its coupling force. The way both subsystems interact (exchange data) and the way they are time-integrated will be defined as the co-simulation approach and consists of integrating a subsystem from *t* to *t* + *H* where *H* is the macrotimestep (common exchange time step).

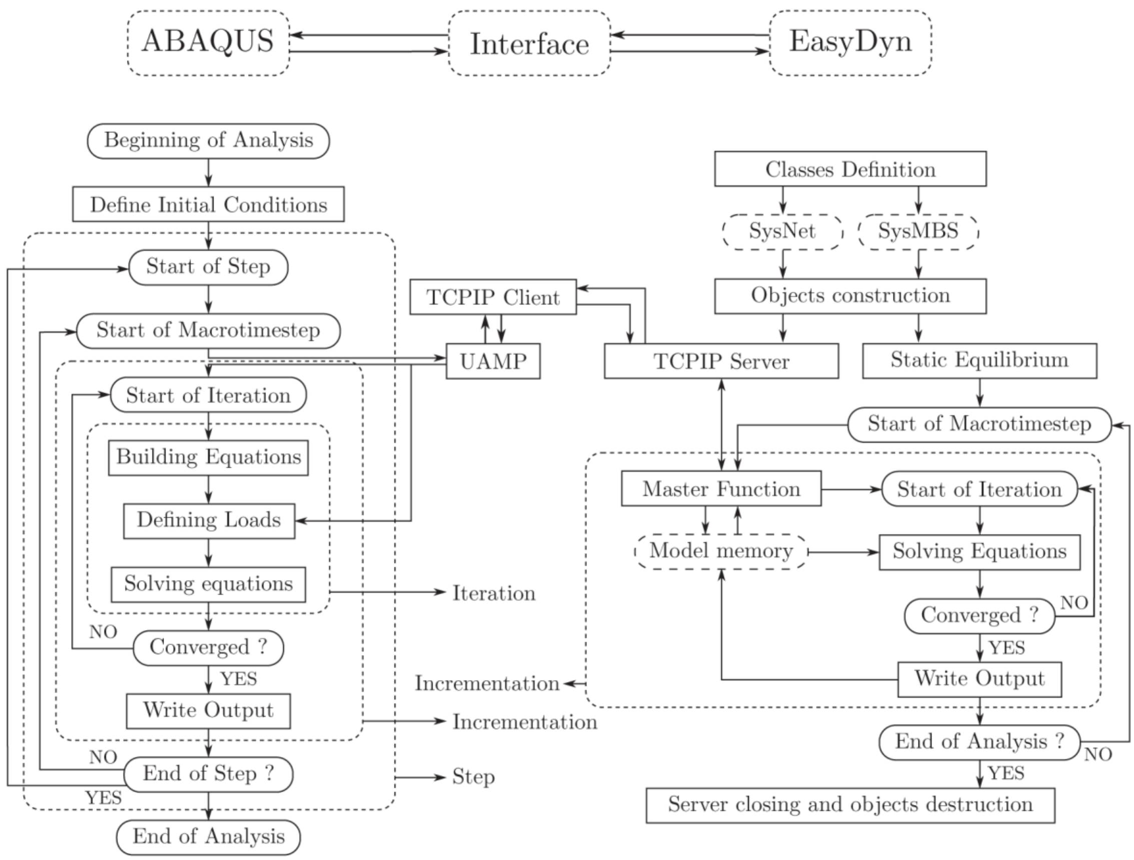


Fig. 5. Interfacing and co-simulation workflow between Abaqus and EasyDyn (Olivier et al. 2020b)

CO-SIMULATION METHODS APPLIED ON A VEHICLE/TRACK/SOIL MODEL

The two-step model developed by Kouroussis and Verlinden (2013) is used to implement the co-simulation technique. Two solvers are used: an in-house software called EasyDyn for multibody simulation and the finite element commercial software Abaqus. Both coupling types (X–T, X–X) and both coupling approaches (Jacobi and Gauß-Seidel) are analysed. The vehicle/track subdomain is built as a multibody system using the minimal coordinates approach, developed by Hiller (1993). The wheel/rail forces are defined using non-linear Hertz's theory and allows the coupling between the vehicle model and the track. The track is defined as a flexible beam discretely supported by the regularly spaced sleepers, including viscoelastic elements for the ballast and the railpads. The second stage concerns the soil whose free-field response is computed using the finite element method. A specific attention is paid on the use of both infinite elements and viscous boundaries as non-reflecting boundaries in order to mimic the infinite dimensions of the soil.

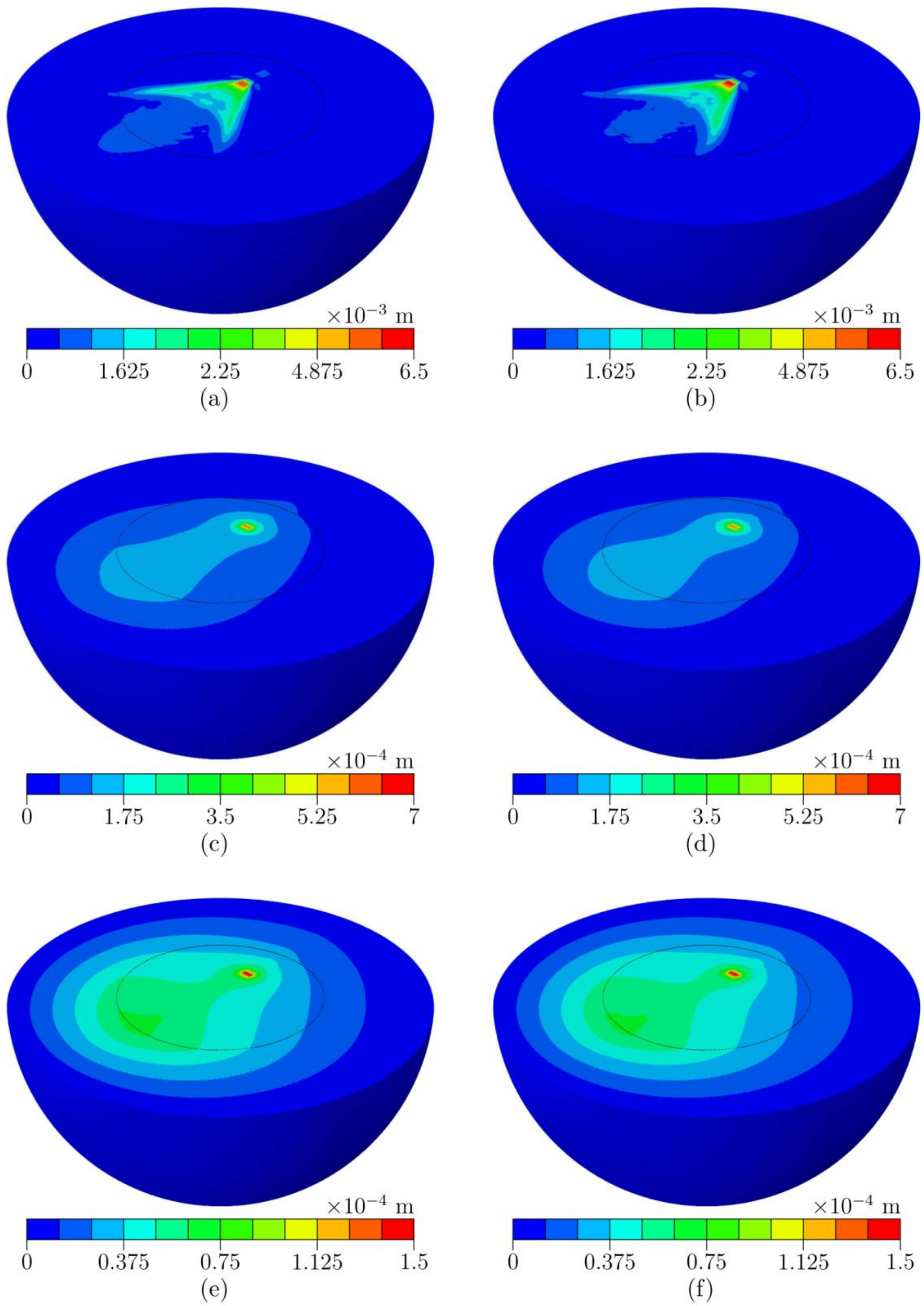


Fig. 6. Magnitude of the soil displacements between the two-step model (left) and Gauß-Seidel co-simulation (right) approach: soft (top), medium (middle) and stiff (bottom) soils

Figure 5 depicts how EasyDyn and Abaqus interact during the time integration process using the network functions through a subroutine. The exchange between EasyDyn and Abaqus is completely articulated around the TCP/IP client-server link. Basically, at the beginning of a macrotimestep, the Abaqus subroutine is called ans starts a TCP/IP client which is linked with its corresponding server contained in EasyDyn. Additional information about the interfacing and workflows is provided in (Olivier et al. 2019; Olivier et al. 2020a; Olivier et al. 2020b).

Figure 6 shows the field view of the soil displacements at a specific time of the simulation process. The two-step model and Gauß-Seidel approach for a ballast level split with an X–T coupling type are compared for the three considered soils (soft, medium, stiff). The macrotimestep in the co-simulated cases is fixed to of H = 1.10^{-3} s for both configurations. Generally speaking, the order of magnitude of the results remains the same between the two-step model and the proposed co-simulation approach. The slip location and coupling type is choice according to the two-step model nature. Additional results (not presented here) provided the following finding. The following remarks can be made:

- Jacobi is worse than Gauß-Seidel in terms of performance.
- The X–T coupling type is better than the X–X type in terms of accuracy but the its stability domain is smaller.
- Cutting at the ballast level provides better results in terms of accuracy and stability.
- The stiffer the soil, the more consistent are the results obtained using the different co-simulation techniques. This phenomenon is reinforced by decreasing the macrotimestep.
- Decreasing the macrotimestep will generally provide more accurate results.

CONCLUSIONS

This work studied the development of a co-simulated vehicle/track/soil model dedicated to ground-borne vibration assessment. The proposed model couples a multibody software that simulates the upper subsystem including the vehicle and a finite element software forthe lowersubsystem simulation including thesoil. Different co-simulation techniques have been studied in order to point out the appropriate co-simulation scheme for railway analysis. The co-simulated model built in this work is compared with an already validated two-step model. It turns out that the co-simulation models proposed and the two-step model provide similar results. The reduced model of soil, initially developed for the two-step model, is thus efficient. However, unlike the two-step modelling technique, co-simulation does not require the computation of a reduced modeling of the soil.

REFERENCES

Busch, M. (2012). “Zur effizienten Kopplung von Simulationsprogrammen.” Ph.D. thesis, Kassel University, Germany.

Connolly, D., Giannopoulos, A., and Forde, M. C. (2013). “Numerical modelling of ground borne vibrations from high speed rail lines on embankments.” *Soil Dynamics and Earthquake Engineering*, 46, 13–19.

Connolly, D. P., Kouroussis, G., Laghrouche, O., Ho, C., and Forde, M. C. (2015). “Benchmarking railway vibrations — track, vehicle, ground and building effects.” *Construction and Building Materials*, 92, 64–81.

Dietz, S., Hippmann, G., and Schupp, G. (2002). “Interaction of vehicles and flexible tracks by co-simulation of multibody vehicle systems and finite element track models.” *Vehicle System*

Dynamics Supplement (The Dynamics of Vehicles on Roads and on Tracks), 37, 372–384.

El Kacimi, A., Woodward, P., Laghrouche, O., and Medero, G. (2013). “Time domain 3d finite element modelling of train-induced vibration at high speed.” *Computers & Structures*, 118, 66–73.

Galvín, P., Romero, A., and Domínguez, J. (2010). “Fully three-dimensional analysis of high-speed train–track–soil–structure dynamic interaction.” *Journal of Sound and Vibration*, 329(24), 5147–5163.

Hiller, M. (1993). “Dynamics of multibody system with minimal coordinates.” *Computer-Aided Analysis of Rigid and Flexible Mechanical Systems, Proceedings of the NATO Advanced Study Institute*, M. Pereira and J. Ambrosio, eds., Tróia, (Portugal), 119–163.

Kouroussis, G., Connolly, D. P., and Verlinden, O. (2014). “Railway induced ground vibrations — a review of vehicle effects.” *International Journal of Rail Transportation*, 2(2), 69–110.

Kouroussis, G. and Verlinden, O. (2013). “Prediction of railway induced ground vibration through multibody and finite element modelling.” *Mechanical Sciences*, 4(1), 167–183.

Olivier, B., Verlinden, O., and Kouroussis, G. (2019). *Stability and error analysis of applied-force co-simulation methods using mixed one-step integration schemes*. IUTAM Symposium on Solver-Coupling and Co-Simulation, Springer International Publishing, 243–254.

Olivier, B., Verlinden, O., and Kouroussis, G. (2020a). “Effect of applied force cosimulation schemes on recoupled vehicle/track problems.”*Multibody System Dynamics*, 50(4), 337–353.

Olivier, B., Verlinden, O., and Kouroussis, G. (2020b). “A vehicle/track/soil model using co-simulation between multibody dynamics and finite element analysis.” *International Journal of Rail Transportation*, 8(2), 135–158.

Shih, J., Thompson, D., and Zervos, A. (2016). “The effect of boundary conditions, model size and damping models in the finite element modelling of a moving load on a track/ground system.” *Soil Dynamics and Earthquake Engineering*, 89, 12–27.

Thompson, D. J., Kouroussis, G., and Ntotsios, E. (2019). “Modelling, simulation and evaluation of ground vibration caused by rail vehicles.” *Vehicle System Dynamics*, 57(7), 936–983.

Triepaischajonsak, N., Thompson, D. J., Jones, C. J. C., Ryue, J., and Priest, J. A. (2011). “Ground vibration from trains: Experimental parameter characterization and validation of a numerical model.” *Journal of Rail and Rapid Transit*, 225(2), 140–153.

Yang, J., Zhu, S., Zhai, W., Kouroussis, G., Wang, Y., Wang, K., Lan, K., and Xu, F. (2019). “Prediction and mitigation of train-induced vibrations of large-scale building constructed on subway tunnel.” *Science of the Total Environment*, 668, 485–499.