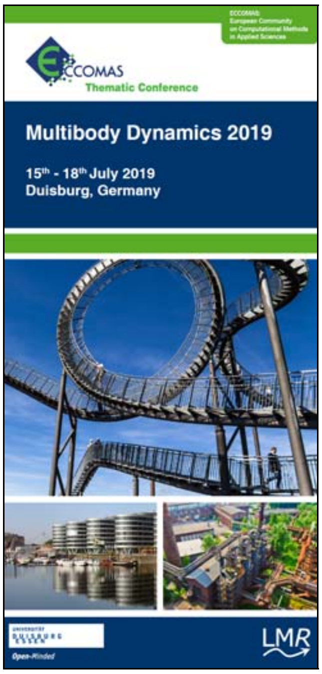
Université de Mons
Faculté Polytechnique – Service de Mécanique Rationnelle, Dynamique et Vibrations
31, Bld Dolez - B-7000 MONS (Belgique)
065/37 42 15 – georges.kouroussis@umons.ac.be



Bryan Olivier, Olivier Verlinden and Georges Kouroussis, Effect of applied force co-simulation schemes on recoupled vehicle/track problem, *Proceedings of the ECCOMAS Multibody Dynamics Conference 2019*, Duisburg (Germany), July 15–18, 2019.

Effect of applied force co-simulation schemes on recoupled vehicle/track problem

Bryan Olivier, Olivier Verlinden and Georges Kouroussis

Abstract The aim of this paper is to discuss the effect of two co-simulation approaches: a parallel approach, called Jacobi, and a sequential approach, called Gauß-Seidel, on a railway vehicle/track/soil model. In a first time, only the vehicle and the track are considered, and coupled inside an in-house multibody dedicated software. The definition of the subsystems, thus the place at which the entire system is split (between wheel and rail or between rail and sleepers), is an important point in the co-simulation process. It is discussed as well as the type of data exchanged between both subsystems. Moreover, it is shown that the output of each subsystem, either a displacement or a force, has a significant impact on the results. Furthermore, the time step at which both subsystems exchange these data is investigated. In a second time, the soil elasticity and the vehicle influence are considered with a vehicle/track/soil model involving two different software environments: the same in-house software as previously for the vehicle and the track and a finite element analysis software for the soil.

1 Introduction

The ground-borne vibrations generated by a train moving along a track on a flexible soil can cause discomfort or environmental nuisances in surrounding buildings. Therefore it becomes useful to estimate those vibrations in order to take relevant measures to prevent those nuisances [1]. To predict those vibrations, two-step numerical models were developed [2, 3] to get the best of different simulation environments. However, the problem decoupling can be unadapted in certain cases as for soft soils [4]. Therefore, this paper investigates some co-simulation implementations for the vehicle/track/soil system.

Bryan Olivier
Department of Theoretical Mechanics, Dynamics and Vibrations, Faculty of Engineering, University of Mons, Place du Parc 20, B-7000 Mons, Belgium, e-mail: bryan.olivier@umons.ac.be

Firstly, the soil is discarded and a model is built to simulate the passage of a vehicle on a track laying on a rigid foundation. The vehicle model is constructed according to the multibody approach (minimal coordinates) while the track is represented by a two-dimensional finite element model. This model is used to analyze the influence of co-simulation approaches (Jacobi or Gauß-Seidel, coupling types (displacement-displacement X-X or displacement-force X-T) and split location (wheel/rail W/R and rail/sleepers R/S).

Secondly, the soil elasticity is introduced and the whole system is co-simulated by using on one hand, the same multibody software dealing with the vehicle/track subsystem and, on the other hand, a finite element code implementing the soil. In this case, the split takes place between the sleepers and the soil with a displacement/force coupling type, and for different types of soil (soft, medium and stiff). Finally, the influence of the vehicle, either a simple wheel or a quarter of a car is observed.

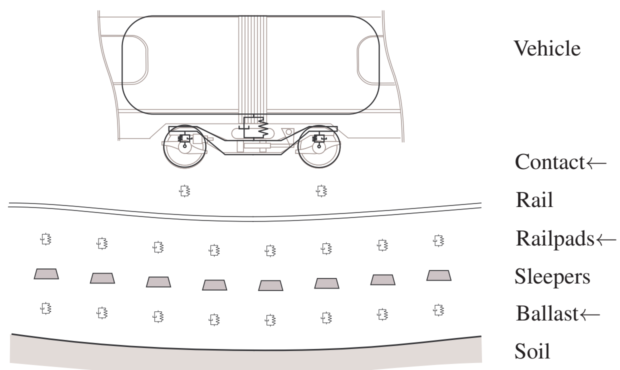


Fig. 1: Different places where the monolithic modeling vehicle/track/soil can be separated.

2 Model construction

The studied system is illustrated in Figure 1. It consists of a railway vehicle moving on a flexible track. Two different parts will be presented in the paper depending on the nature of the soil:

- Part 1: A study of the influence of the co-simulation approach, the data exchange time step and the type of coupling. For this part, the soil will not be considered.
- Part 2: A study of the impact of the vehicle type and the soil flexibility on a more comprehensive model including a 3D finite element representation of the soil.

2.1 Subsystems definition

When the split location is known in a system, the composition of each subsystem is also known. However, in the present case, the split location is a studied point. Therefore, two subsystems are established as follows:

- The upper subsystem: it always contains the vehicle (either the wheel or the quarter of a car). Depending on the split location, this subsystem will contain one or more elements of the track (rail and sleepers).
- The lower subsystem: it consists of the soil and the parts of the track not included in the upper subsystem. When the soil is considered as rigid, it contains the sleepers only or the sleepers and the rail. When the soil is considered as flexible, it contains only the soil and the track is completely included in the vehicle subsystem.

The vehicle is modeled in two dimensions using the minimal coordinates approach in multibody dynamics in an in-house software called EasyDyn [5]. It consists, in a first time, of a single wheel whose weight is equivalent to a regular wheel/rail static contact force. In a second time, the vehicle studied is considered as the quarter of a car that has 4 bodies (two wheels, a bogie and a part of the car) and whose motion is described by 5 degrees of freedom (the vertical motion of both wheels, the bogie and the car and the pitch of the bogie). Typical values of the springs and dampers are retained [6]. Moreover, the weight of the car was tuned so that the static force exerted between both wheels and the rail remains identical to the same force in the wheel case.

The rail is flexible and modeled by Euler-Bernoulli beam elements while the sleepers are modeled as lumped masses with a single vertical degree of freedom. When the soil is considered as flexible, a two-part finite element modeling of an homogeneous soil is used (similar to the soil used in [7]). The first part is an hemispherical kernel meshed with tetrahedral elements on which two tracks lay symmetrically with respect to the diameter of the hemisphere. The second part is an hemispherical wrapping meshed with semi-infinite elements so as to avoid undesirable wave reflection at the boundary between the kernel and the wrapping. Both parts are tied so that the soil kernel is not rigidly fixed to the bedrock.

2.2 Coupling approaches

Applied-force coupling schemes are used to perform co-simulation in the present case. Therefore, the split has to be realized at the level of an elastic element. The main advantage of this technique is to avoid algebraic constraints in the equations. The eligible coupling elements at which the system can be cut are indicated by an arrow in Figure 1. Furthermore, once the split location is known (the subsystems are defined), two main characteristics of the coupling must be detailed:

- the coupling approach, that relates to the order of integration of the subsystems and also to the data management in between;

- the coupling type, that defines the nature of the data exchanged between the subsystems (force or displacement).

The two studied co-simulation approaches [8, 9] are illustrated in Figure 2. Gauß-Seidel scheme (left) consists of a sequential integration of both subsystems during a macrotimestep (timestep at which both subsystems exchange data) while Jacobi is completely parallel.

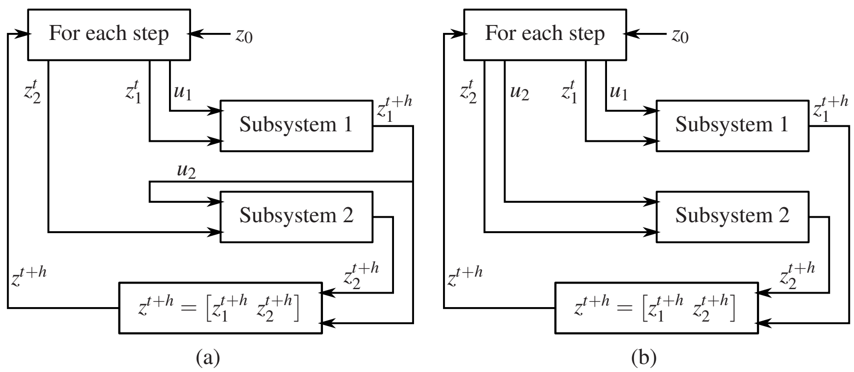


Fig. 2: Gauß-Seidel (left) and Jacobi (right) co-simulation schemes: step procedure with initial conditions z_0, subsystem i state variables z_i and subsystem i inputs u_i. Figure from[10].

The coupling types used in this paper are the displacement/displacement and the displacement/force types denoted, in this paper, by X-X and X-T respectively. In the X-X case, both subsystems receive a displacement from the other subsystem that corresponds to the displacement of the end of the elastic coupling element which is not included in the considered subsystem. Therefore, the coupling element is explicitly represented in both subsystems. In the X-T case, the first subsystem receives a displacement and the second one receives the force applied by the other subsystem through the elastic element. It has to be mentioned that the inputs stay constant in each subsystem over a complete macrotimestep. Moreover, when the elastic element also presents damping, the velocity must be exchanged as well as the displacement.

3 Results

This section presents the results obtained for the two parts considered:

- Firstly, the influence of the coupling approach, of the macrotimestep and of the coupling type through a simulation of a wheel rolling on a flexible track laid on a rigid soil.

- Secondly, the influence of the soil elasticity and of the vehicle type is investigated using X-T co-simulation between a vehicle/track subsystem and a three-dimensional soil subsystem.

3.1 Coupling approach, coupling type and macrotimestep influence

In this section, the results, obtained for a single wheel by various co-simulation implementations, are compared with the monolithic modeling which is taken as a reference.

Figure 3 shows the rail deflection with respect to the track position at the specific time 0.2 s and with a macrotimestep of 10^{-4} s. The two coupling approaches are compared for a wheel/rail split location and for both X-X and X-T coupling types. It is clearly visible that for a same macrotimestep and a same coupling type, the Jacobi scheme can lead to abnormally amplified displacements while Gauß-Seidel does not. Moreover, in the Jacobi case, those abnormal oscillations appear only in the X-T case.

Figure 4 compares the coupling type as well as the split location through the error in the rail deflection with respect to the monolithic case. The observed time is identical to Figure 3, the macrotimestep is taken as 10^{-6} s and the coupling approach is only taken as Jacobi. In terms of the split location, it appears that the wheel/rail split stays more accurate than the rail/sleepers split for both coupling types. Moreover, the X-T case seems to be the most accurate coupling type.

Figure 5 illustrates the macrotimestep influence for different split locations and coupling types for the Jacobi coupling approach only. It clearly appears that the error converges to zero when the macrotimestep decreases.

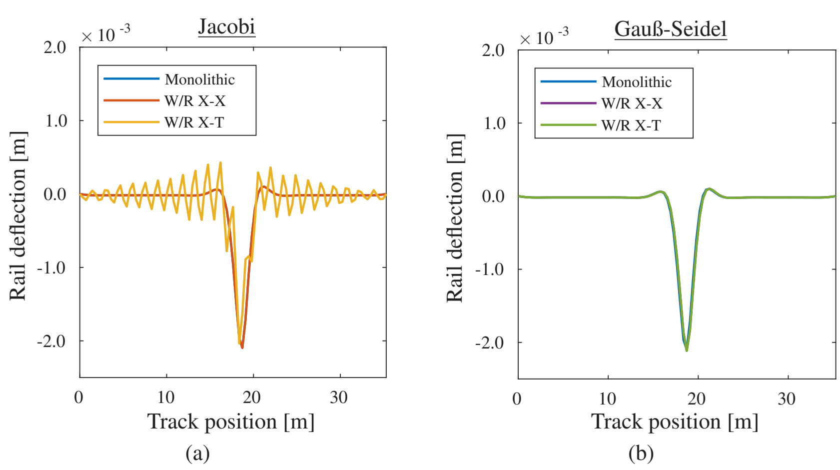
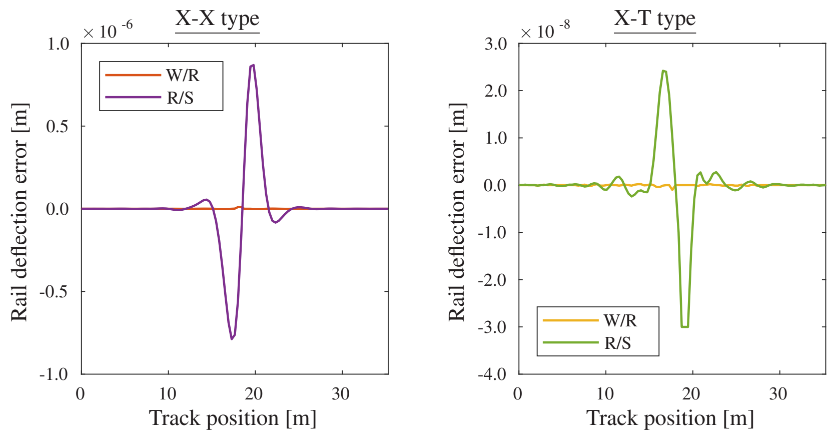
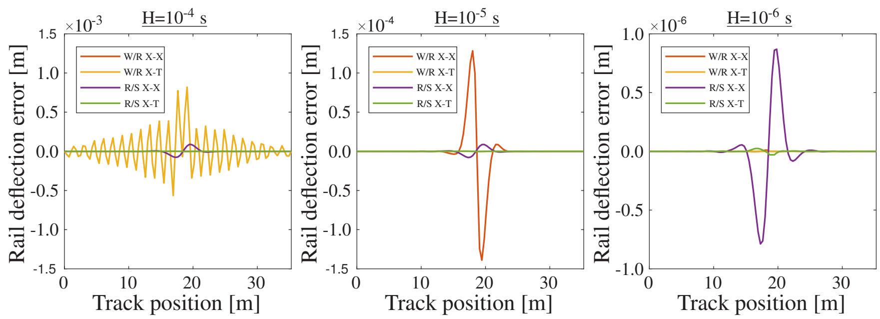


Fig. 3: Coupling approaches comparison



(a) (b)

Fig. 4: Coupling type and split location comparison.

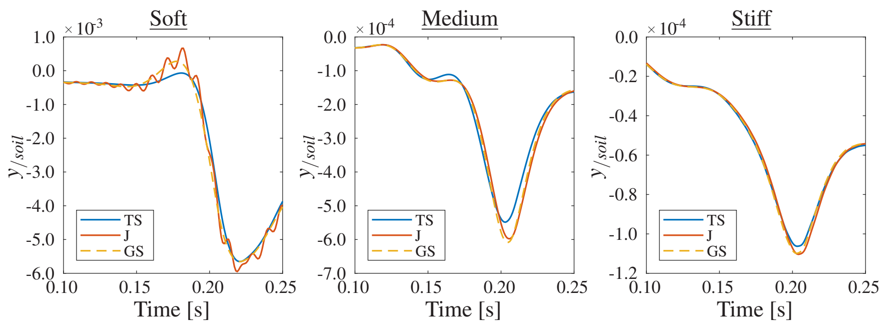


(a) (b) (c)

Fig. 5: Macrotimestep comparison.

3.2 Soil elasticity and vehicle type influence

Since the ballast is modeled as spring and damper elements, each sleeper is connected to a rigid surface on the soil whose motion is reduced to the motion of a point. Figure 6 shows the vertical displacement of a point of the flexible soil corresponding to the 20th sleeper of a track of 81 sleepers. Three different homogeneous soils are compared: soft (E=10 MPa), medium (E=155 MPa) and stiff (E=750 MPa), every other parameter being identical. The macrotimestep is taken as 10^{-3} s. In each graph, the Jacobi (J) and Gauß-Seidel (GS) approaches are compared with a two-step (TS) and experimentally validated model [7, 3]. Generally speaking, it can be observed that the stiffer the soil, the closer the co-simulation results are to the two-step model. Moreover, in Figure 6a, it can be seen that the Jacobi scheme presents abnormal oscillations while Gauß-Seidel does not.



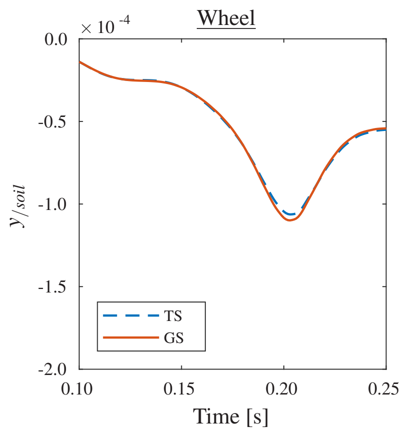
(a) (b) (c)

Fig. 6: Soil flexibility influence.

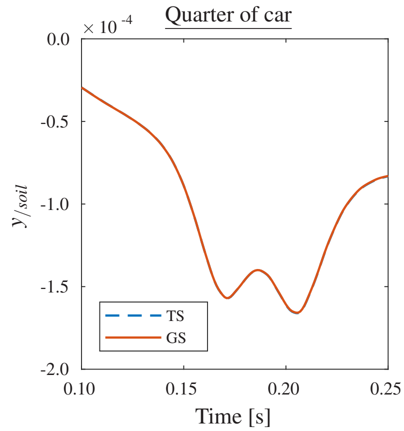
Figure 7 compares two different types of vehicle: a single wheel and a quarter of a car, the rest of the model remaining identical. The vertical displacement of the same part of the soil as in Figure 6 is observed and the same macrotimestep is taken. In each Figure, the Gauß-Seidel approach is compared with the two-step model. For the quarter of a car simulation, the maximal microtimestep (internal integration time step of subsystem) was voluntarily taken much smaller than in the wheel simulation for convergence purposes. Therefore, it is normal that the difference is smaller in the quarter of a car case. However, the main drawback is a bigger simulation time.

4 Conclusions

In case of multiphysics problems such as the vehicle/track/soil model, co-simulation constitutes a powerful technique to perform a simulation in which each subsystem is modeled in a convenient environment and time-integrated using an adapted solver. After having briefly defined the co-simulated models used, this paper discussed the results obtained. Two different parts were discussed. The first part was a discussion on specific co-simulation options through a model including a rigid soil. The second part studied the soil elasticity and the vehicle influence with a more comprehensive model including a deformable soil. It was shown, through those comparisons, that the stability and the accuracy of co-simulated models depend on the co-simulation approach, the co-simulation type, the macrotimestep chosen and also the parameters of the system modeled.



(a)



(b)

Fig. 7: Influence of the vehicle type.

References

1. J. Yang, S. Zhu, W. Zhai, G. Kouroussis, Y. Wang, K. Wang, K. Lan, and F. Xu. Prediction and mitigation of train-induced vibrations of large-scale building constructed on subway tunnel. *Science of the Total Environment*, 668:485–499, 2019.
2. E. Kece, V. Reikalas, R. DeBold, C.L. Ho, and M.C. Forde. Evaluating ground vibrations induced by high-speed trains. *Transportation Geotechnics*, 2019.
3. B. Olivier, D. P. Connolly, P. Alves Costa, and G. Kouroussis. The effect of embankment on high speed rail ground vibrations. *International Journal of Rail Transportation*, 4(4):229–246, 2016.
4. G. Kouroussis, O. Verlinden, and C. Conti. On the interest of integrating vehicle dynamics for the ground propagation of vibrations: the case of urban railway traffic. *Vehicle System Dynamics*, 48(12):1553–1571, 2010.
5. O. Verlinden, L. B. Fékih, and G. Kouroussis. Symbolic generation of the kinematics of multibody systems in EasyDyn: from MuPAD to Xcas/Giac. *Theoretical and Applied Mechanics Letters*, 3(1):013012, 2013.
6. G. Kouroussis, O. Verlinden, and C. Conti. Influence of some vehicle and track parameters on the environmental vibrations induced by railway traffic. *Vehicle System Dynamics*, 50(4):619–639, 2012.
7. G. Kouroussis, L. Van Parys, C. Conti, and O. Verlinden. Using three-dimensional finite element analysis in time domain to model railway-induced ground vibrations. *Advances in Engineering Software*, 70:63–76, 2014.
8. M. Busch. *Zur effizienten Kopplung von Simulationsprogrammen*. PhD thesis, Kassel University, 2012.
9. C. Gomes, C. Thule, D. Broman, P. Larsen, and H. Vangheluwe. Co-simulation: a survey. *ACM Computing Surveys (CSUR)*, 51(3):49, 2018.
10. B. Olivier, O. Verlinden, and G. Kouroussis. Stability and error analysis of applied-force co-simulation methods using mixed one-step integration schemes. In *IUTAM Symposium on co-simulation and solver coupling*, Darmstadt (Germany), 2017.