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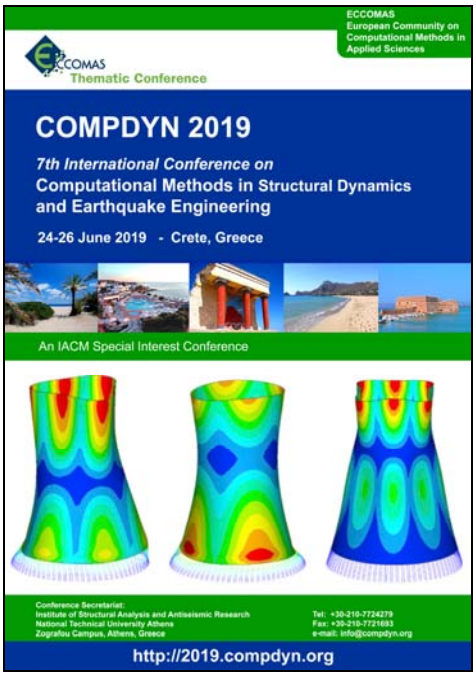

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A VEHICLE/TRACK CO-SIMULATION MODEL USING EASYDYN

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Abstract. *In the railway domain, studies have been undertaken on the attenuation of vibrations transmitted to the vehicle in order to improve the comfort of the passengers. However, a slight variation in the stiffness and damping characteristics of the train constitutive parts can considerably change the amount of energy transmitted to the soil in terms of vibrations. To predict those ground-borne vibrations generated by the vehicle moving along the track that could affect or disturb the surrounding environment, a relevant option would be to build a numerical model that simulates the passage of a vehicle on a track by coupling a multibody modeling of the train with a finite element modeling of the soil using co-simulation techniques. However the location where the model has to be split remains uncertain and then the border between the multibody and the finite element parts must be determined. The aim of this paper is to emphasize the possibility to perform co-simulation between two or more subsystems using an in-house C++ library package called EasyDyn. Using its co-simulation capabilities, the recoupling of a vehicle, that can be modeled using the minimal coordinates approach in multibody systems and a track modeled using a finite element representation of the rail and sleepers, will be discussed.*

1 INTRODUCTION

Nowadays virtual prototyping constitutes a truly useful tool that can provide decisive information about a specific problem. Indeed, in the railway domain, a modeling of a train passing over a soil can be used in order to estimate the ground-borne vibrations generated. Although single simulation were firstly adopted to predict the effect of a running train on the generated ground wave propagation [1, 2], recent research suggested to split the problem in order to take into account specific complex phenomena [3]. Theferore, Kouroussis et al. designed and validated a two-step model [4, 5, 6] that furnishes a sufficiently accurate prediction of the vibrations generated on the ground for different types of soil. This model uses a first step to estimate the forces applied on the soil through a fully coupled model of the vehicle, the track and a reduced coupled lumped masses (CLM) model of the soil [7]. While the first step uses a multibody representation of the vehicle and a finite element definition of the track, both two-dimensional, the second step involves a three-dimensional modeling of the soil including different layers if required. This soil modeling is performed into a dedicated finite element software which provides the different levels of vibrations for different distances from the track and also for different soil configurations.

In order to go further in the modeling of this vehicle/track/soil problem, it is interesting to investigate the possibilities offered by the co-simulation techniques that couple the problem during the time integration process. However this re-coupling involves a discussion on two different issues: the way the time integration of both subsystems is performed (co-simulation scheme) and the type of data (force or displacement) that are exchanged between each subsystem (co-simulation type). In order to compare efficiently the different co-simulated models, different types of tracks including a fixed soil will be studied. Indeed, depending on the split location and the co-simulation scheme chosen, the simulations can lead to drastically different results. Furthermore, depending on the split location, the number of coupling points and the stiffness and damping characteristics of the coupling link between both subsystems can significantly change the results obtained.

The aim of this work is to investigate the benefits and also the drawbacks of co-simulation techniques through a railway example using an in-house C++ library package called EasyDyn. After a brief description of the model used, the different split locations and coupling approaches will be discussed through the rail deflection results obtained.

2 EASYDYN FRAMEWORK

The EasyDyn framework [8] is an in-house set of tools initially dedicated to the time-integration of differential equations for teaching and research purposes. The framework programmed in C++ evolved in a library package able to simulate the behavior of multibody systems through the minimal coordinates approach. The workflow of the framework, illustrated in Figure 1, consists in:

- Defining the kinematics of bodies of the multibody system through their homogeneous transformation matrices $\mathbf{T_{0,i}}$ and their mass and inertial properties. This step is performed in a python environment that will, thanks to a python library called CaGEM (Computer Aided Generation of Motion), compute the different equations of motion symbolically. At the end of this step, a C++ file containing the kinematics is written.

- Defining applied forces and torques, through their wrench form $\mathbf{R_i}$ and $\mathbf{M_{G_i}}$, into the C++ file such that the multibody library (mbs) of EasyDyn can compute the equations of

motion into their residual form $\vec{\mathbf{f}}$.

- Time-integrating the equations of motion using the simulation (sim) library of EasyDyn.

Recently, co-simulation features were added to EasyDyn to allow it to communicate with other subsystems included in the same program or even with subsystems implemented in other software packages.

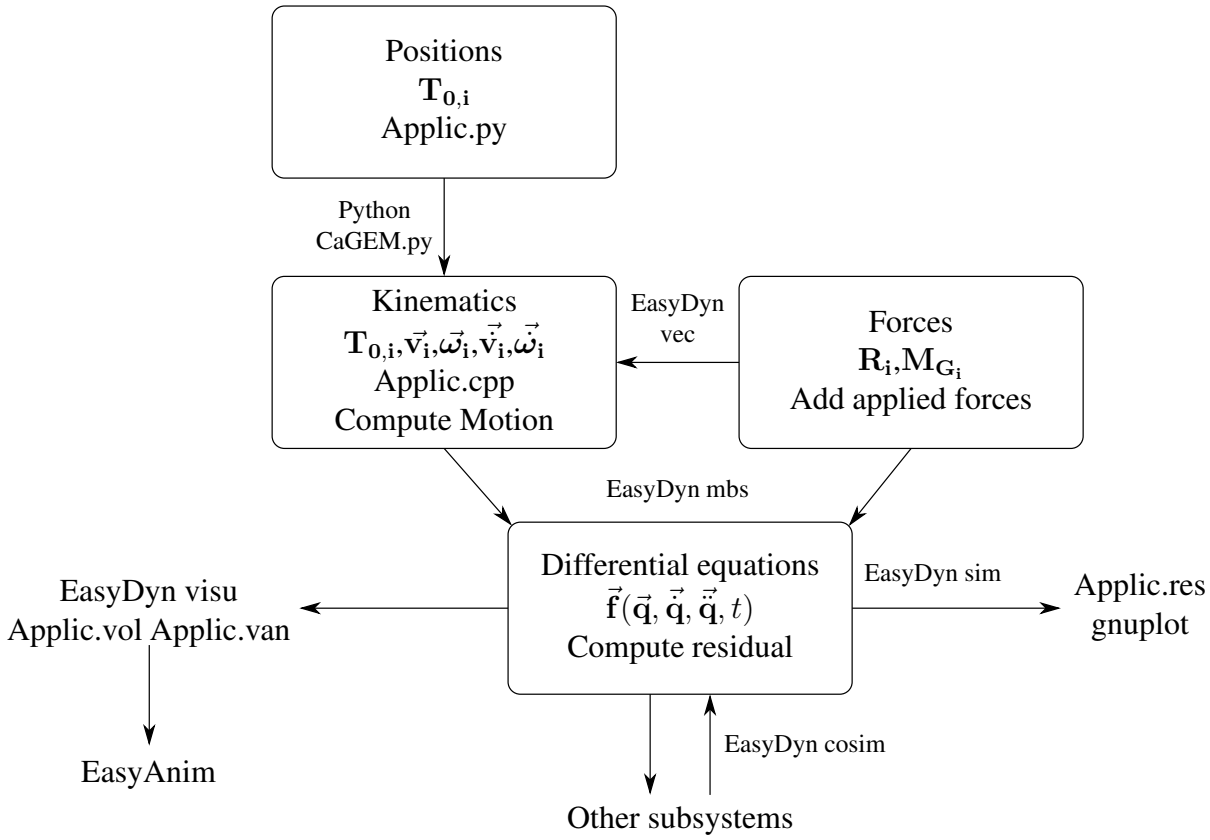

Figure 1: EasyDyn workflow

3 MODEL COMPOSITION

The model studied here (inspired by [9]) to test the co-simulation possibilities offered by EasyDyn is illustrated in Figure 2. It consists of a two-dimensional monolithic modeling of a wheel, on which a constant force $m_{tot}g$, equivalent to the static force applied by the whole vehicle, is applied. The wheel mass is tuned such that the maximal mass per wheelset is reached. The wheel is moving on a track at a v_0 speed and has a vertical degree of freedom q_0. Its contact with the rail is defined by a purely stiff and non-linear Hertz contact of stiffness K_{Hz}.

The track is composed of the rail which is described by its degrees of freedom $q_{r,j}$ related to the motions allowed by the Euler-Bernoulli definition of the rail beam elements. Each rail element possesses two nodes with two degrees of freedom each: one for the vertical translation and one for the rotation about the axis perpendicular to the plane containing the model.

The sleepers are described by their degrees of freedom $q_{s,i}$ that are only vertical. The soil is considered as a fixed reference.

The three parts that forms the monolithic model (vehicle, track and soil) are linked by different elastic elements. Besides the Hertz contact that links the vehicle and the rail, the railpads

(denoted by the subscript p) provides an elastic and damped link between the rail and the sleepers while the ballast (defined by subscript b) links the sleepers with the fixed soil.

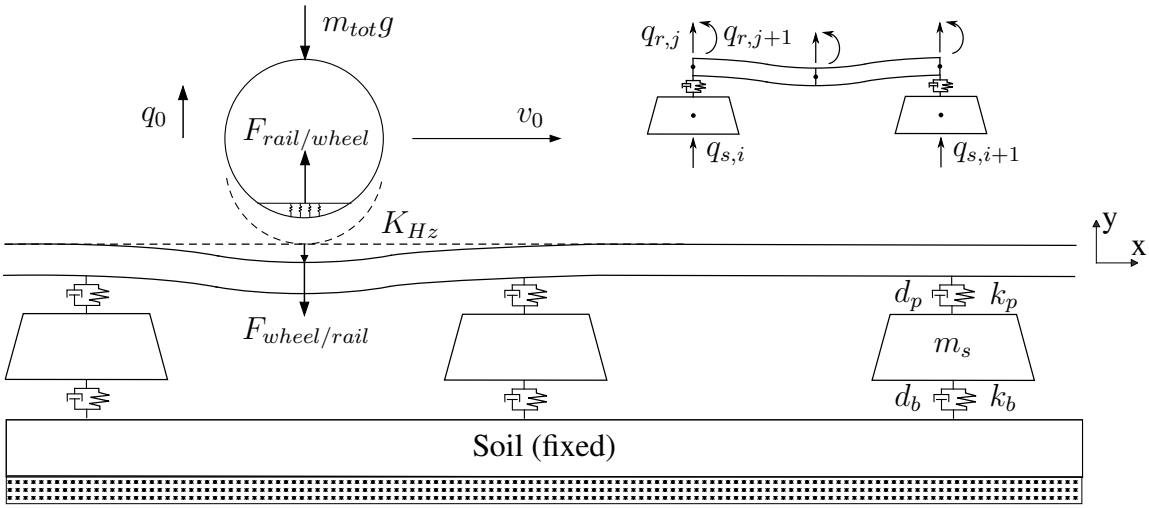

Figure 2: Monolithic modeling of a wheel passing over a flexible track.

The aforementioned monolithic modeling will be taken as a reference to compare the co-simulated results with. Furthermore, the co-simulated models will be very similar to the monolithic one since the only variable element will be the place in which the model will be split, all other parameters remaining identical.

4 SUBSYSTEMS DEFINITION AND INTERACTION

To define the subsystems from the monolithic reference, the only point that requires to be discussed is the split location. Once the subsystems are defined, it has to be decided the type of the data that each subsystem will send to the other one. Moreover, the order in which both subsystems are integrated must be defined.

4.1 Split locations

The co-simulation technique studied in this work consists of an applied-force coupling (see [10, 11]) of both subsystems. This means that the coupling will involve a force (computed or not in each subsystem) applied on both subsystems. Other co-simulation schemes exists such as the constraints coupling [12, 13, 14] but they involve algebraic equations that require specific time-integration schemes. Similar applied-force studies have been undertaken by Antunes et al. [15]. Nevertheless, the present work investigates the case of a flexible track and studies also different split locations and different types of data exchange.

Considering the applied-force methodology, the only way to split the monolithic modeling is through an elastic element that can be used to compute the applied force. The two possible locations are, for this example:

- **The wheel/rail contact:** it involves a relative asymmetry in the degrees of freedom distribution between the subsystems. Moreover, the contact is unique and purely stiff. The contact point is also moving horizontally when observed by the rail.

- **The rail/sleepers:** the asymmetry in the degrees of freedom distribution is minimized with respect to the previous case. Moreover, there exist as many exchange points as the

number of sleepers but in opposition to the wheel/rail case, those points do not move horizontally. Finally, the rail pads are stiff and also damped elements while the Hertz contact is only stiff.

Figure 3 and 4 show the wheel/rail split and rail/sleepers split respectively. The main variables are not changed between those Figures and Figure 2. In both Figures, the subsystem that contains the vehicle is always called Subsystem 1 (S_1) and the one that contains the sleepers, Subsystem 2 (S_2).

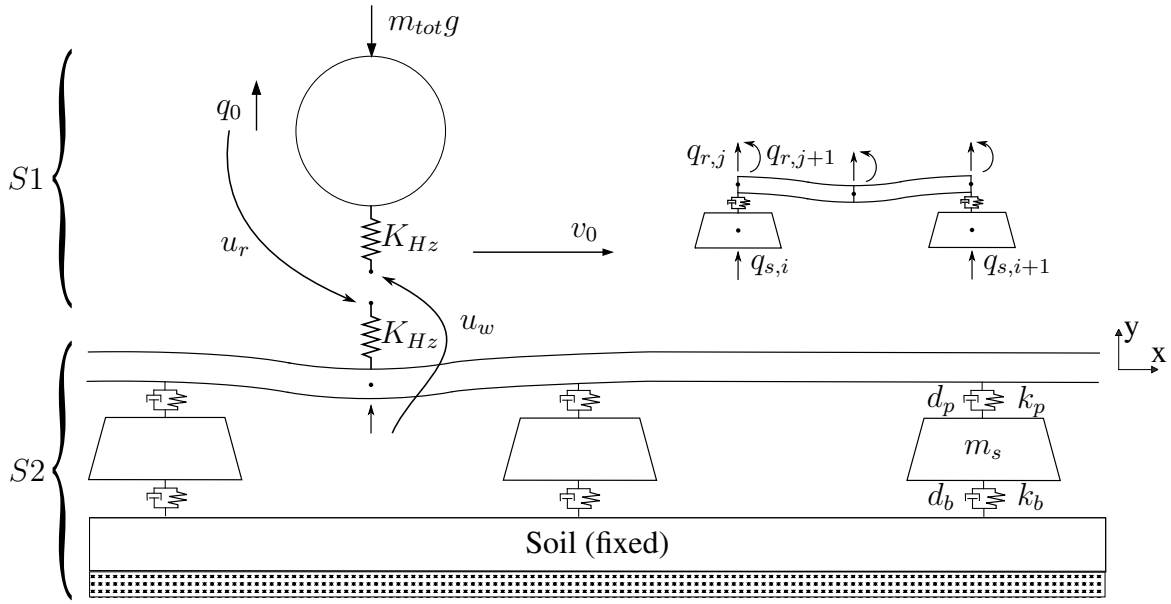

Figure 3: Coupling of wheel and track subsystems through a displacement/displacement method.

4.2 Type of data exchanged

Besides the cutting location, the type of data received by each subsystem (inputs u) must be defined. Indeed, the information going from one subsystem to the other one can take two forms: the displacement of the coupling point or a force applied on the coupling point. In the case of a displacement receiving, the velocity is also required if the element at which the cut is realized presents damping.

In the present work, two different cases will be investigated:

- Both subsystems S_1 and S_2 receive a displacement (called X-X case). Specifically in the case of the Rail/Sleepers cut, the velocity of the coupling points has also to be exchanged since the rail pads present damping characteristics. The X-X Wheel/Rail situation is illustrated in Figure 3.

- Subsystem S_1 receives a displacement and Subsystem S_2 receives a force (called X-T case). Again, a velocity must be sent by S_2 to S_1 in the case of the Rail/Sleepers cut due to the damping properties of the rail pads. The X-T coupling type for a Rail/Sleepers cut is illustrated in Figure 4.

It must be specified that, in the end, a force is always used (being re-computed or not) in the each subsystem. The major difference between the displacement and the force exchange is that

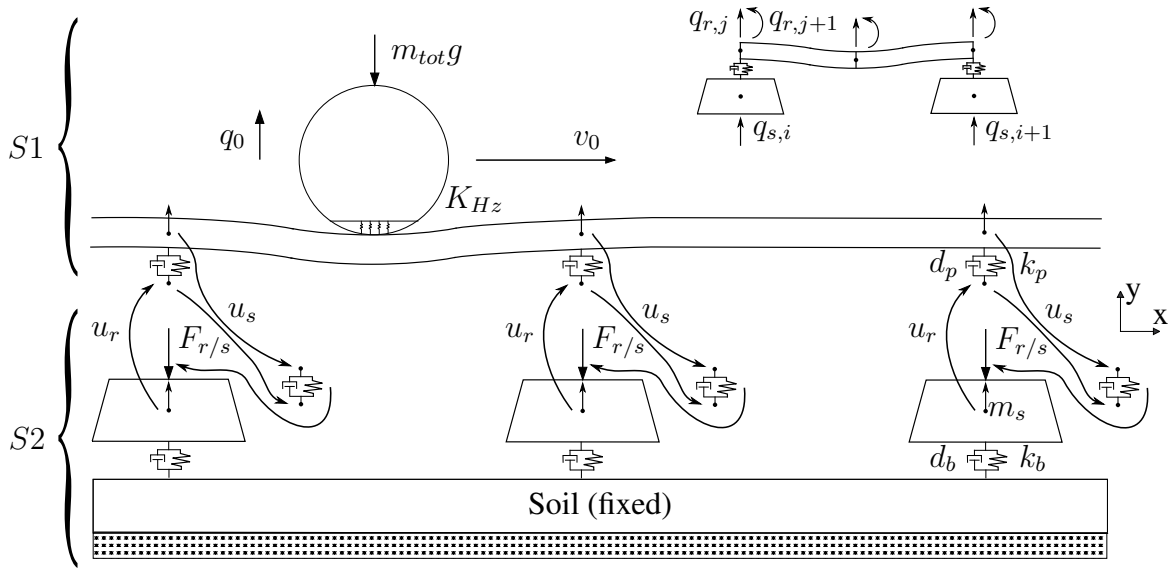

Figure 4: Coupling of wheel-rail and sleepers subsystems through a displacement/force method.

in the force case, the force is a constant until the next time step while this force is a function of the state variables of the subsystem in the displacement exchange.

4.3 Co-simulation schemes used

The co-simulation scheme defines the order in which both subsystems are time-integrated and then how the data are exchanged between them. There exist several types of co-simulation schemes such as explicit, semi-implicit and implicit schemes [10] but this work will focus on two explicit schemes [11]:

- A parallel scheme for which the inputs (coupling variables coming from the other subsystem) of each subsystem are extracted from the state variables of the other subsystem at the beginning of the time step. This means that each subsystem can be time-integrated without waiting for the other one to be integrated. This is called Jacobi scheme.

- A sequential scheme for which both subsystems are integrated sequentially since the inputs of the second subsystem will be computed using the states variables of the first subsystem integration. As for the Jacobi scheme, the inputs for first subsystem integration are computed from the state variables of the other subsystem but at the beginning of the timestep (then the values obtained at the previous time step integration). This is called the Gauß-Seidel scheme.

It has to be mentioned that the data are exchanged following a specific timestep called the macrotimestep while each subsystem can have its own timestep for its time-integration during a macrotimestep. Furthermore, this microtimestep can be different between both subsystems as far as the macrotimestep is common for both of them in order to have a consistent data exchange.

5 RESULTS

In order to demonstrate the co-simulation capabilities of EasyDyn and also the effect of co-simulation techniques on a railway problem, the different aforementioned methods were im-

plemented including the monolithic modeling. The different parameters, whose values are not changed between all the model representations, are expressed in Table 1. It must be mentioned that if the macrotimestep is specified in this table, the microtimestep of each subsystem is not given. This comes from the time integration scheme used that possesses an adaptive time-step. This scheme is identical for both subsystems and is a Newmark-β scheme tuned such that it does not produces numerical damping on the results ($\beta = 0.25$ and $\gamma = 0.5$).

Parameter	Symbol	Value	Unit
Total mass of the wheel	m_{tot}	11250	kg
Hertz contact stiffness	K_{Hz}	92.86	GN/m$^{\frac{3}{2}}$
Rail Young modulus	E	210	GPa
Rail geometrical moment of inertia	I	1987	cm^4
Mass of a sleeper	m_s	90.84	kg
Spacing between two sleepers	l	0.6	m
Area of rail cross section	A_r	63.8	cm^2
Rail density	ρ	7850	kg/m^3
Stiffness of rail pads	k_p	180	MN/m
Stiffness of the ballast	k_b	25.5	MN/m
Damping of rail pads	d_p	28	kNs/m
Damping of the ballast	d_b	40	kNs/m
Number of sleepers	N	50	-
Number of rail elements between sleepers	N_r	2	-
Vehicle speed	v_0	300	km/h
Vehicle initial position	x_0	2	m
Simulation macrotimestep	H	10^{-4}	s

Table 1: Values of the parameters involved in the model simulated.

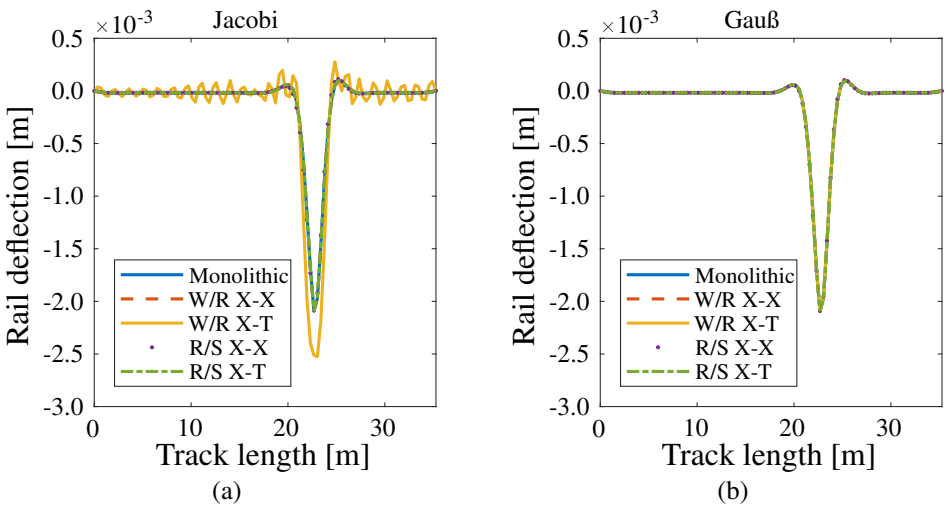

Figure 5: Rail deflexion at $t = 0.25$ s for Wheel/Rail and Rail/Sleepers coupling locations.

Generally speaking, the results obtained are compared through the rail deflection. Figures 5a and 5b illustrates the results obtained for the different coupling locations (W/R and R/S)

and also the different coupling types (X-X and X-T). It can be remarked that a large part of the solutions are slightly different from the monolithic reference. However, one solution involves an abnormal amplification of some specific modes: the Jacobi scheme with an X-T coupling at the wheel/rail contact level.

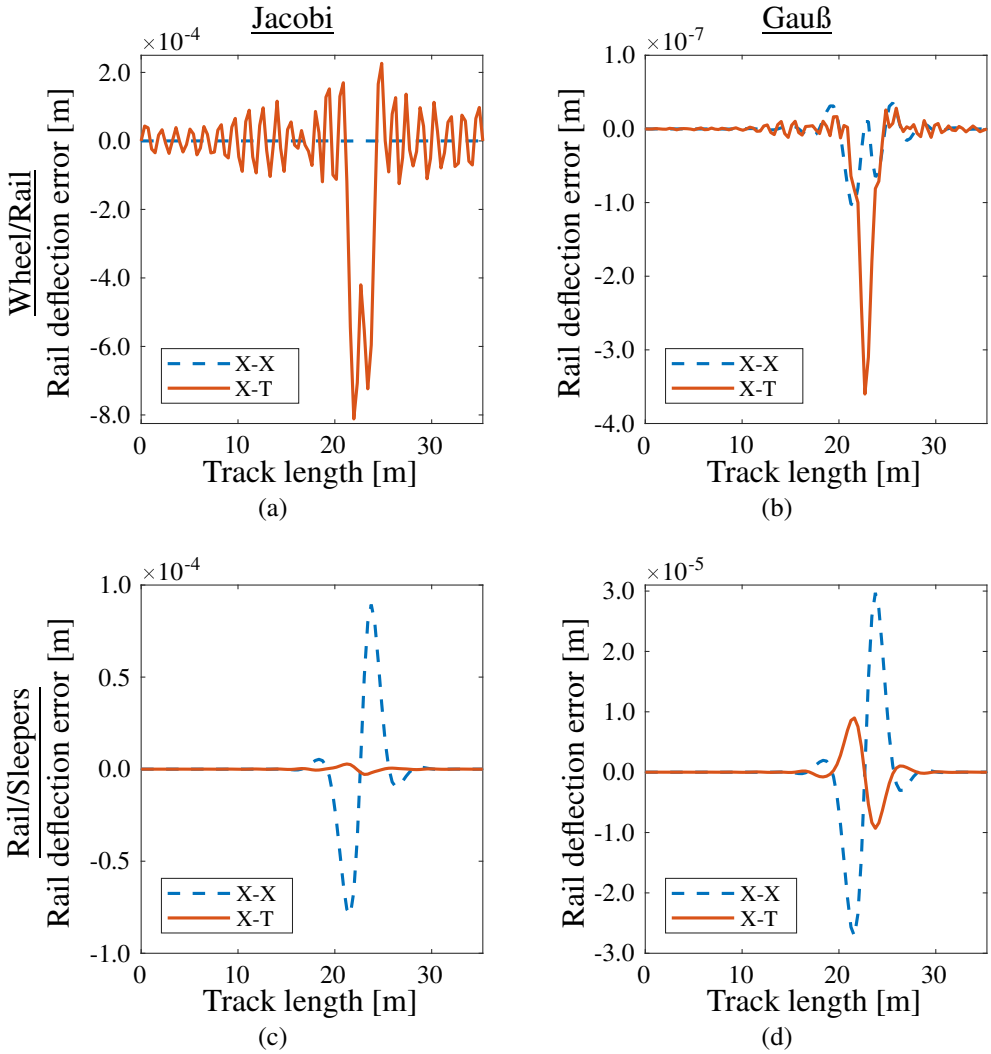

Figure 6: Rail deflexion error at $t = 0.25$ s for Wheel/Rail (top) and Rail/Sleepers (bottom) coupling locations, for Jacobi (left) and Gauß-Seidel (right) coupling approaches and X-X and X-T coupling types.

In order to distinguish the more accurate methods, Figure 6 proposes the rail deflection error defined as the subtraction of the rail deflection given by the monolithic modeling to the considered co-simulated solution. While the instability of the Jacobi X-T W/R is again clearly visible in Figure 6a, a similar but less amplified tendency is present in the corresponding Gauß-Seidel deflection curve in Figure 6b.

Furthermore, due to the classification between the different cases, the error encountered using a specific scheme can easily be observed between different cases. For example, since the Jacobi X-T W/R presents a huge amplification, the generated error remains the biggest found in all the cases. Also, it seems that changing to Gauß-Seidel from Jacobi in the X-X R/S case divides the error by almost 10.

6 CONCLUSIONS

Through a two-dimensional railway example, the capabilities of EasyDyn in co-simulation was highlighted and the effect of co-simulation techniques was studied and compared to the corresponding monolithic modeling. Several cases were developed in terms of coupling location (wheel/rail contact cut and rail pads cut), coupling type (displacement/displacement and displacement/force) and coupling approach (Jacobi and Gauß-Seidel).

Generally speaking, the parallel scheme (Jacobi) provides a less accurate rail deflection than the sequential Gauß-Seidel scheme for this specific railway example. This can be explained by the loss of accuracy in the parallel integration of both subsystems during a macrotimestep while the time-integration of the second subsystem in Gauß-Seidel scheme uses a more accurate version of its input variables thanks to the already performed integration of the first subsystem.

Furthermore, if the displacement/displacement coupling type seems to be more accurate in the wheel/rail coupling location case, the tendency is reversed in the rail/sleepers case. Meanwhile, even if the rail deflection seems more accurate in the wheel/rail coupling case (except for the Jacobi X-T case), the rail/sleepers case remains more stable. Additional studies could be carried out in order to detect if it comes from the lack of physical damping in the coupling element or if it comes from the fact that the coupling point is moving in the wheel/rail case.

Finally, this example was developed in order to determine the best coupling method that could be used to perform co-simulation on a more comprehensive model in order to evaluate the ground-borne vibrations in a 3D modeling of a soil. Indeed, it is currently possible to perform co-simulation between EasyDyn an another software containing a three-dimensional modeling of a soil. Based on the results obtained with the model treated in this work and thanks to the EasyDyn capabilities of co-simulation through network, actual co-simulation between a multibody modeling of a full vehicle and a finite element modeling of a soil will be investigated in further research.

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