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MBS/FEM CO-SIMULATION FOR HYBRID MODELING OF RAILWAY DYNAMICS

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Abstract. Nowadays in railway traffic, specific speed limitations exist depending on the train charge, due to a fragile subsoil or even an old building that has to be preserved. Depending on the type of vehicle, the type of soil or even the vehicle speed, the ground-borne vibration characteristics can significantly vary. It becomes thus important to predict the vibrations generated by a train passing on a track in the surrounding soil. In order to achieve this prediction, a hybrid modeling approach, consisting in a vehicle modeled using the minimal coordinates approach in multibody systems theory and a soil modeled using a finite element method, is developed. The recoupling of this hybrid system is performed using co-simulation between two different software packages with their own solvers. The first software is EasyDyn, an in-house C++ library package dedicated to multibody dynamics and the second software is ABAQUS that is dedicated to finite element analysis. The aim of this paper is to illustrate the results given by this hybrid model. Then two different co-simulation schemes (the sequential Gauß-Seidel scheme and the parallel Jacobi scheme) will be used and compared in terms of accuracy for this specific railway application.

1 INTRODUCTION

Whether for a commercial or a personal purpose, railway transportation is currently a popular mean of transportation. Moreover, due to the permanently growing population, railway could follow an important development in the next decades. Simultaneously, homes and buildings are built close to stations and railway tracks. Depending on the type of tracks, the speed of the vehicle and a large range of different parameters, the passing of a train on a track usually generate significant ground-borne vibrations.

The effect of soil dynamics on the train dynamics and on the ground-borne vibrations was already studied in the literature. Yang recently depicted the effect of a train passing under an hotel in order to determine if the level of vibrations during day and night shifts do not exceed the levels imposed in China [1]. Like many models [2, 3, 4] in this field, Yang used a two-step model to determine the ground-borne vibrations generated by a running train on specific tracks.

The first step of two-step models is usually the estimation of the force applied by the vehicle or the track on the soil depending in which part the track is modeled. The second step is the computation of the vibrations generated on the soil due to the application of the estimated forces. In order to produce the best estimation of forces applied on the soil, a reduction of the soil can be included in the first step (containing the vehicle dynamics). There exist different models of soil reduction such as the Winkler or the coupled lumped mass (CLM) model [5].

Through two-step models, it is possible to decouple substantial monolithic modelings to integrate the two different parts (vehicle dynamics and soil dynamics) separately. However, even if the efficiency of this kind of model was proven many times in the literature, the step-decoupling is limited for soft soil cases since the coupling between the track and the soil is weaker when the soil is stiffer than the ballast [6]. Therefore this work will focus on the simulation of a coupled vehicle/track/soil model using co-simulation techniques between two-different software packages. The vehicle/track subsystem will be time-integrated in EasyDyn [7], an in-house C++ library package dedicated to multibody modeling using the minimal coordinates approach. The soil subsystem will be modeled and simulated in a commercial finite element software called ABAQUS. Through different comparisons between the vibrations predicted by co-simulated models and a two-step model, it will be demonstrated that both types of simulations are efficient in their specific domain.

2 MODEL CONSTRUCTION

The vehicle/track/soil model used to investigate the possibilities offered by co-simulation techniques is illustrated in Figure 1. It is based directly on the two-step model proposed by Kouroussis [8] that consists in the following steps:

- The vehicle and the track are modeled with a reduced CLM model of the soil in order to compute the forces acting on the ground applied by the sleepers through the ballast. The CLM model of the soil includes five different parameters that are tuned so that the frequency response of the reduced model overlaps sufficiently with the response of the 3D finite element modeling of the soil.
- The forces computed in the first step are applied on the soil that is modeled as a finite element meshed hemisphere. The contact surface between the ballast and the soil is reduced at the surface generated by the orthogonal projection of the sleeper on the ground as depicted in Figure 1.

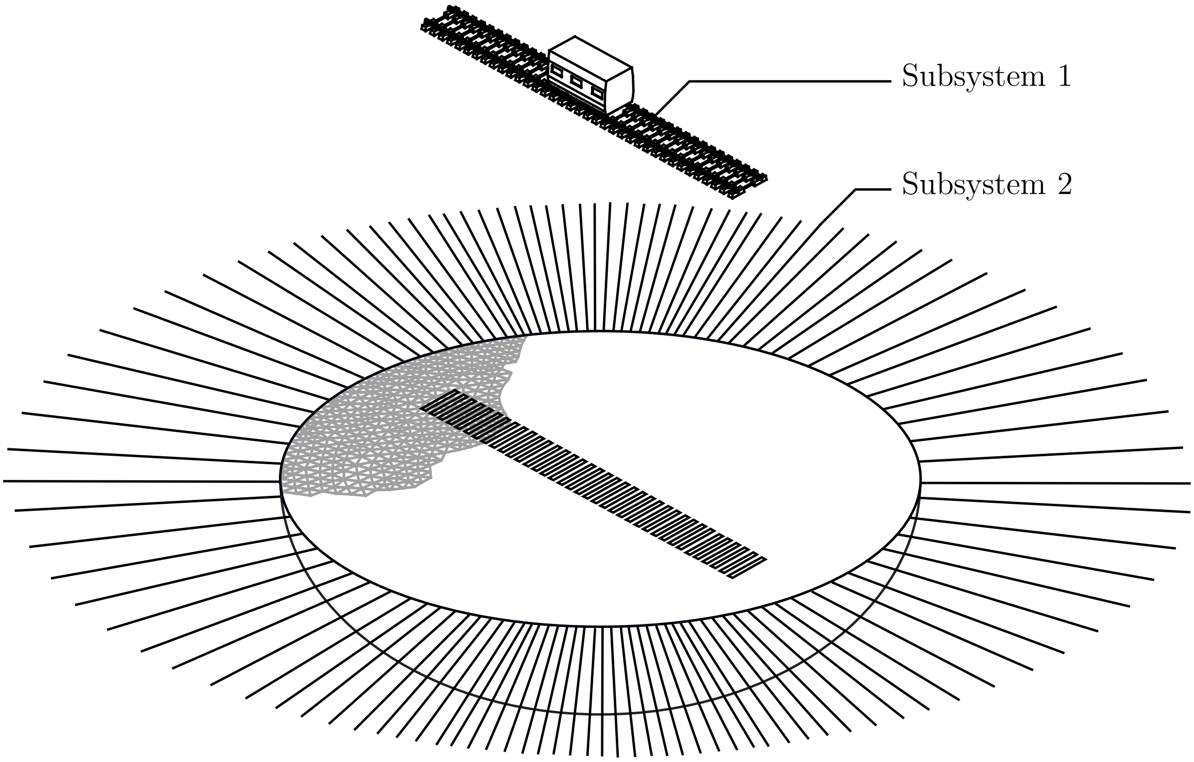


Figure 1: Railway model — illustration of the subsystems

The co-simulated model is cut following the same logic as the one used in the two-step model. Therefore, the first subsystem will contain the vehicle and the track and the second subsystem will contain the soil only. The following sections will describe both subsystems and the method used to couple them during the time-integration process.

2.1 Subsystem 1: Vehicle and track subdomains

The vehicle/track subsystem is modeled in an in-house C++ software dedicated to multibody dynamics. It contains three different parts:

1. A multibody modeling of the vehicle. From a simple wheel to a complete car, the vehicle is composed of bodies that are defined by their mass and inertial properties and the position of their center of mass depending on the different degrees of freedom. These degrees of freedom are included in homogeneous transformation matrices that express the position and orientation of the frame of a body with respect to the main frame. The choice of a unique wheel for the vehicle definition was made in order to test the co-simulation effect on a simple case.

2. A finite element representation of the rail. The rail is split into Euler-Bernoulli beam elements so that the whole rail system is represented by its global mass and stiffness matrices.

3. A discrete representation of the sleepers. Each sleeper only has one degree of freedom (vertically oriented) and is considered as a moving mass.

The coupling between the different elements is performed through a non-linear Hertz contact between the wheel and the rail while the railpads (rail/sleepers coupling) and the ballast (sleepers/soil coupling) are represented by linear spring and dashpot elements.

2.2 Subsystem 2: Soil subdomain

The soil subsystem is modeled in a commercial finite element software called ABAQUS. It is mainly composed of two different parts:

1. A meshed soil kernel. The soil on which the track lays is defined as an hemisphere meshed with tetrahedral elements including a variable mesh seed. This soil can be divided into different layers to model as well as possible the soil composition but in the simulations performed, the hypothesis of an homogeneous soil composition is made for the sake of simplicity.

2. A semi-infinite shell. The soil kernel is surrounded by an hemispherical shell composed of semi-infinite elements. The internal surface of the semi-infinite shell and the external surface of the soil are tied together. The purpose of the semi-infinite elements is to prevent undesirable wave reflections on the external surface of the soil kernel if fixed boundary conditions were specified.

2.3 Coupling technique

The coupling technique is here divided into two different aspects:

- The coupling approach that defines the data exchange management as well as the time-integration management of each subsystem.

- The coupling type that defines the type of the input and output variables of each subsystem used to re-couple them during the integration process.

As depicted in Figure 2, the coupling approaches can be either completely sequential or parallel. This Figure illustrates the two co-simulation approaches used in this work over a macrotimestep h that is defined as the common timestep at which both subsystems exchange data. The sequential approach (called Gauß-Seidel) consists in a first integration of the vehicle/track subsystem then the integration of the second subsystem whose input variables u_{GS} directly comes from the first subsystem integration. The parallel approach (called Jacobi), performs both subsystems integration over a macrotimestep simultaneously. This means that no communication exists between both subsystems during a macrotimestep and that the input variables of each subsystem are taken from the results of the previous timestep perfomed.

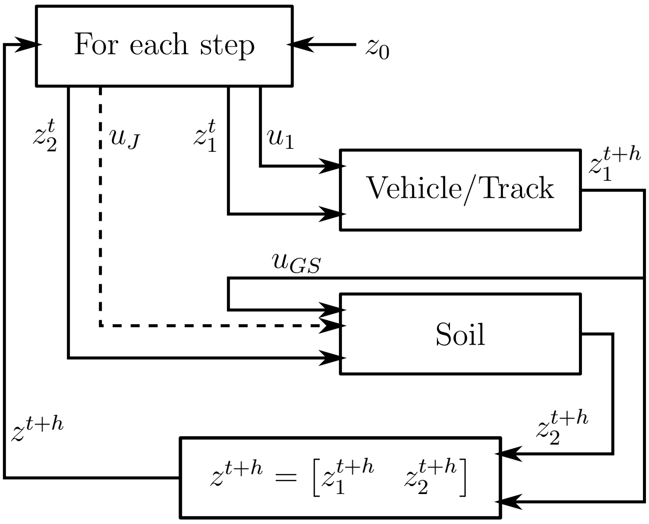


Figure 2: Gauß-Seidel scheme (plain) - Jacobi scheme (dashed). The symbols u and z define the input and state variables respectively.

Figure 3 illustrates the type of input and output variables of each subsystem to complete the coupling. The input variables of the vehicle/track subsystem (also the output variables of the soil subsystem) are defined as the displacement and velocities of the coupling surfaces (sleeper print on the soil). Using the vertical displacement and velocities of all the coupling surfaces, the vehicle/track subsystem can be integrated over a macro-timestep and the force developed by by the sleepers to the soil through the ballast are computed. Therefore, those forces that are the output variables of the vehicle/track subsystem (also the input of the soil subsystem) are applied on the coupling surfaces after being transformed into pressures. This way, the soil can be time-integrated and the coupling surface positions and velocities can be updated for the next vehicle/track subsystem integration.

3 RESULTS

Using typical values of the track parameters [9], simulations were undertook using three different type of soil: a stiff (E=750 MPa), a medium (E=155 MPa) and a soft (E=10 MPa) soils. Moreover, both Gauß-Seidel (denoted GS) and Jacobi (denoted J) coupling approaches were tested. The reference model, to which the co-simulated ones will be compared, is the two-step model (denoted TS) detailed in the previous sections.

Figure 4 compares the Peak Particle Velocity (PPV) in the vertical direction of the vibration signals generated by the running wheel with respect to the distance from the track. The PPV is defined as the maximum absolute value of a signal over a given period of time. This indicator is often employed to compare vibratory signals and evaluate the vibrations effect on people's comfort and structures [10]. It can be seen in the Figures that the stiffer the soil is, the closer the co-simulated and the two-step models results

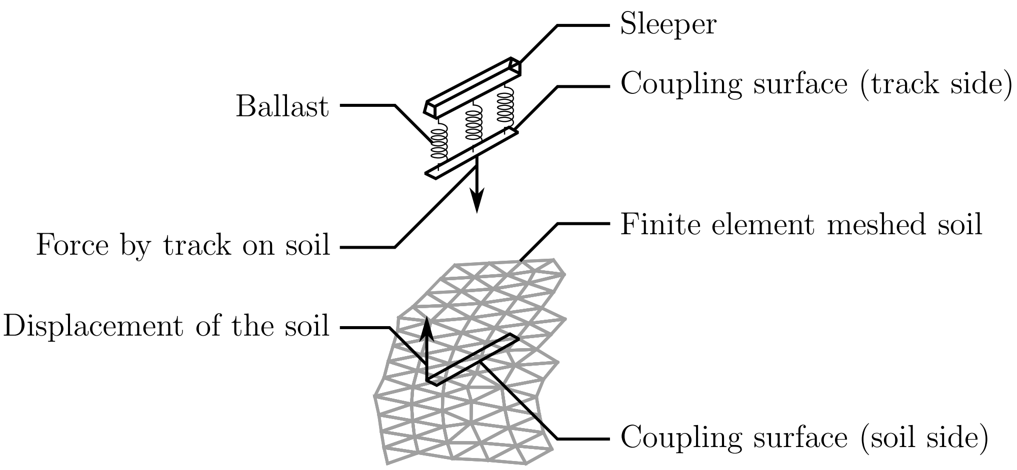
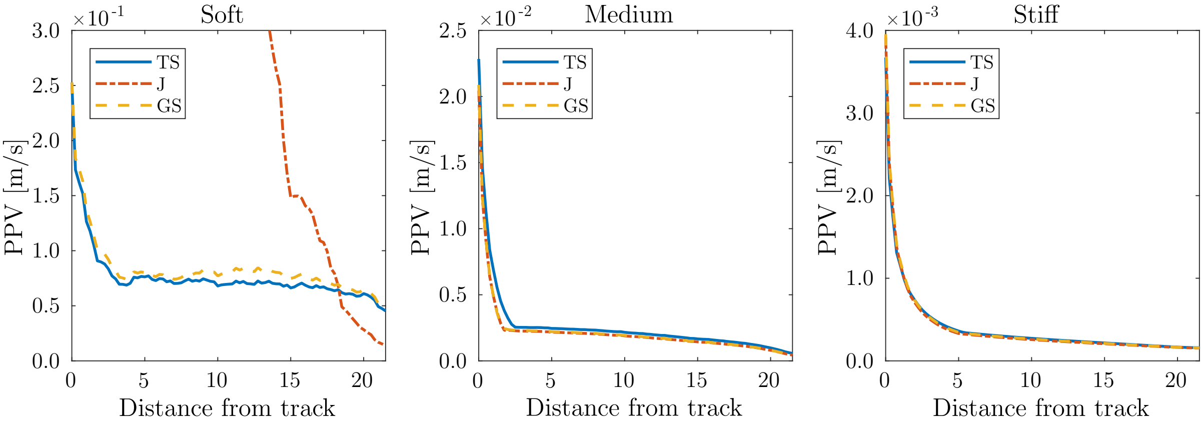


Figure 3: Coupling type used to exchange data between subsystems

are. Moreover, in the soft soil case, even if the divergence is clearly noticeable, the PPV obtained using the Gauß-Seidel co-simulated scheme remains close to the PPV obtained using the two-step model already validated by Kouroussis in his research [11]. However, the PPV obtained using the Jacobi coupling approach diverges completely from the regular shape because the simulation becomes unstable due to the loss of information implied by the data exchange management [12].



(a) (b) (c)

Figure 4: Vertical Peak Particle Velocity with respect to the distance from track for the soft (E=10 MPa), medium (E=155 MPa) and stiff (E=750 MPa) soil types. The macrotimestep is 1 ms.

The loss of information due to the Jacobi co-simulation approach can be diminished if the data are exchanged more often. This can be possible if the macrotimestep decreases. Figure 5 illustrates the PPV with respect to the distance from the track for the soft soil only. However, two different macrotimesteps are compared: 1 ms in Figure 5a and 0.1 ms in Figure 5b. Those two Figures clearly shows that using a smaller macrotimestep increases the convergence of the solutions obtained using the different models.

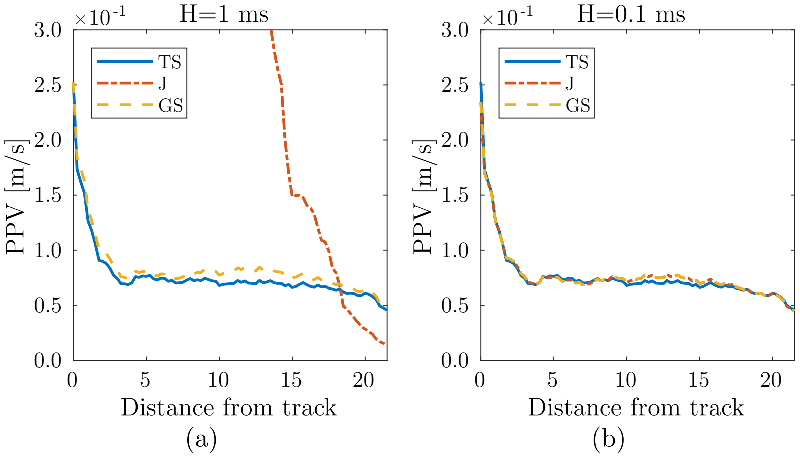


Figure 5: Vertical Peak Particle Velocity with respect to the distance from track for the soft (E=10 MPa) soil type. Comparison of 1 ms (left) and 0.1 ms (right) macrotimesteps.

The results obtained can also be compared in in terms of frequency content. The frequency content with respect to time is computed using the wavelet transform of the vertical velocity of specific points at 2.5 and 5 meters from the track. The Continuous Wavelet Transform (CWT) [13] is a time-frequency analysis method which does not present the drawback of the time-frequency limitation, unlike the Fourier Transform, allowing for a fine-scale analysis. It is therefore well adapted to transient phenomenon such as railway-induced ground vibrations [14].

The results comparison between the two-step model and the two different co-simulation approaches for the three types of soil are depicted in Figures 6 and 7 respectively. The macrotimestep for those simulations is 1 ms. Generally speaking, the wheel rolling on the track can clearly be noticed by the increase of the frequency content from a certain time. As for the PPV comparison in the soft soil case (Figure 5a), it can be seen that the Jacobi coupling leads to unstable results while the Gauß-Seidel coupling stays stable. Moreover, it seems that the tendency of the wavelet coefficients are more similar if the stiffness of the soil increases.

4 CONCLUSIONS

After the definition of a reference two-step model that was experimentally validated, a vehicle/track/soil model using co-simulation techniques was detailed. The co-simulation link was performed using two different software packages: a multibody software in which the vehicle/track subsystem was modeled and a finite element software for the soil. Three different types of soil were considered and two co-simulation techniques were compared to the two-step reference: a parallel and a sequential approaches.

In order to efficiently compare the results obtained using the different modelings, the

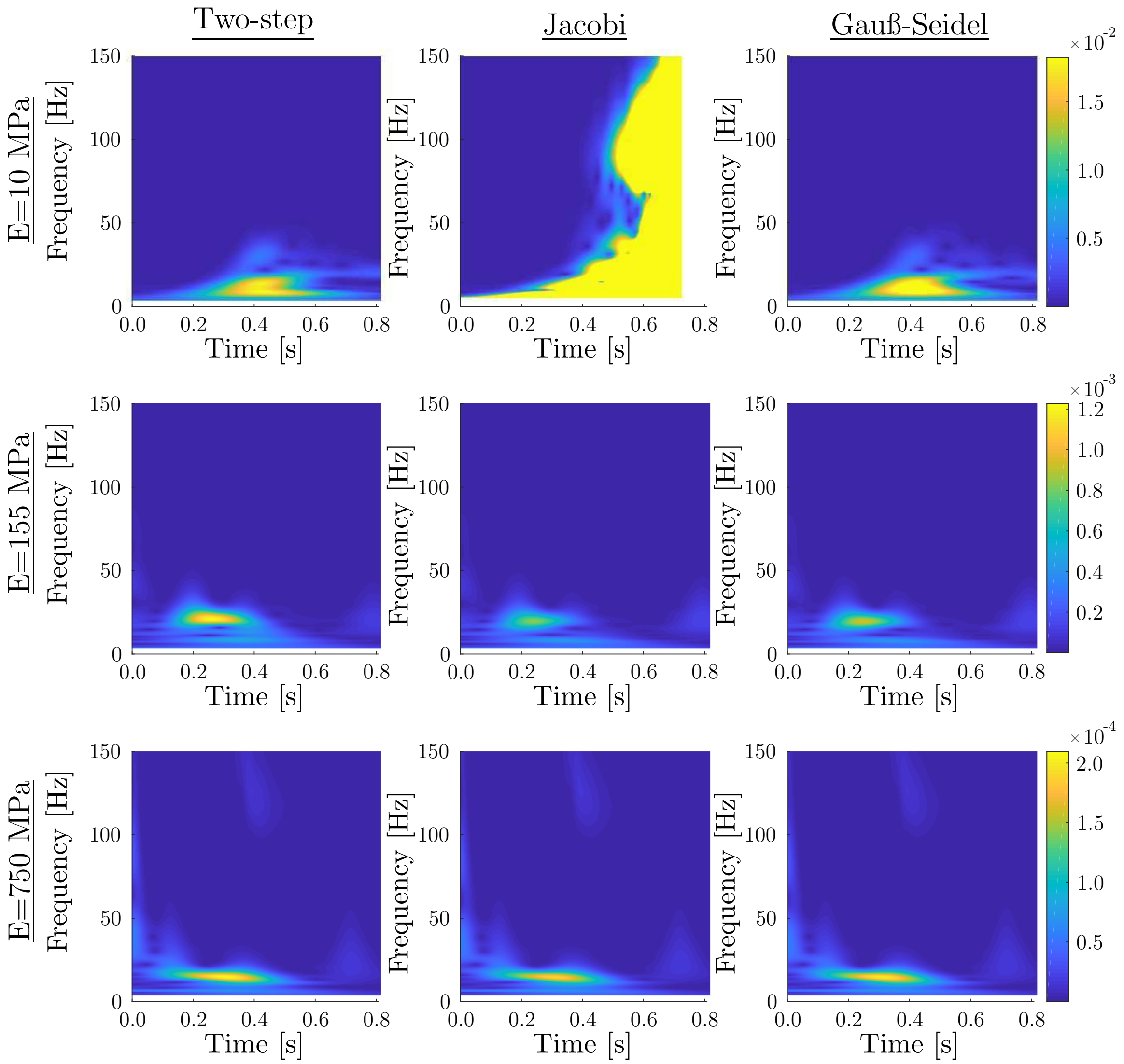


Figure 6: Wavelet transform of the vertical velocity at 2.5 meters from the track

peak particle velocity depending on the distance from the track were compared as well as the frequency content of the vibratory signals at two different distances from the track through their wavelet transform.

Finally it was noticed that a soft soil with a Jacobi coupling approach can leads to unstable results if the macrotimestep becomes too large. Meanwhile, changing the coupling approach to the Gauß-Seidel one or even changing the soil stiffness while keeping the

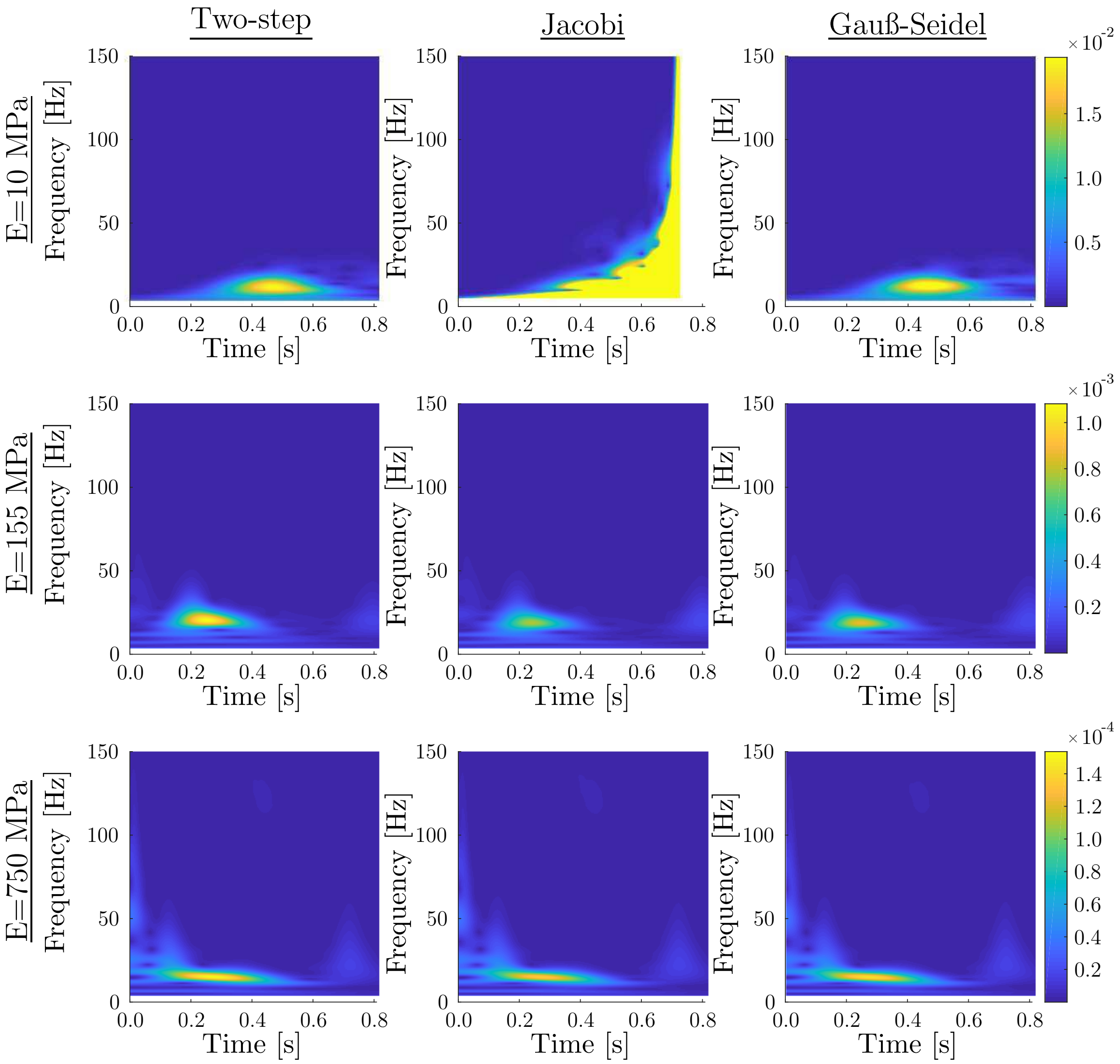


Figure 7: Wavelet transform of the vertical velocity at 5 meters from the track

same macrotimestep (that lead to instabilities) can provide stable results. Moreover, it was also noticed that the convergence of the results given by the co-simulated approaches and the two-step reference are closer if the soil becomes stiffer.

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