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Co-simulation coupling spectral/finite elements for 3D soil/structure interaction problems

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ABSTRACT

The coupling between an implicit finite elements (FE) code and an explicit spectral elements (SE) code has been explored for solving the elastic wave propagation in the case of soil/structure interaction problem. The coupling approach is based on domain decomposition methods in transient dynamics. The spatial coupling at the interface is managed by a standard coupling mortar approach, whereas the time integration is dealt with an hybrid asynchronous time integrator. An external coupling software, handling the interface problem, has been set up in order to couple the FE software Code_Aster with the SE software EFISPEC3D.

1. Introduction

Among the different numerical approaches for solving the wave propagation problem, the spectral element method (SEM) with explicit time integration offers the flexibility of the classical finite element method (FEM) for dealing with quite complex geometries, anisotropy and free-surface condition, while minimizing the computational cost thanks to its efficient quadrature formulation and its high-order polynomial accuracy to approximate smooth solutions. The SEM was first developed in computational fluid dynamics [1] and applied in the late nineties for wave propagation in 3D earth media by Komatitsch and co-authors [2,3]. The application of a SEM on soil/structure interaction problems has not been investigated yet because the zone of interest of the soil/structure interaction is geometrically complex and may experience non-linear soil/structure behaviors that are hardly handled by the explicit integration scheme of a SEM. Indeed, the SEM is desirable for modeling the wave propagation at large scale, while the FEM deals with the soil/structure interaction problem at smaller scale. Thus, the SEM and FEM approaches have their own advantages for simulating a soil/structure interaction problem, advocating for an hybrid approach enabling to use both methods in the same simulation. More precisely, the goal of this work is to propose a co-simulation strategy, in which SEM and FEM numerical codes are coupled.

The coupling is based on domain decomposition method with non-overlapping subdomains, using a dual approach with the introduction of Lagrange multipliers in order to connect the different meshes. Multi-time step explicit/implicit co-simulations have been proposed by the authors in previous papers in the case of structure/structure coupling in non-linear dynamics (earthquake and blast loading, [4–6]), fluid structure interaction problem [7], and contact mechanics [8]. Coupling methods have been developed in [9] and [10] based on energy considerations, ensuring the stability and accuracy of the cou-

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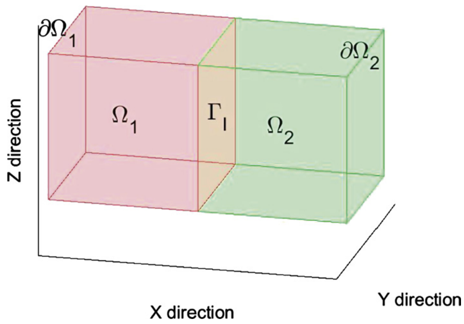

Fig. 1. Ω_1 and Ω_2 3D subdomains with a flat interface Γ_I.

pling scheme. In the case of non-matching interface and different spatial discretizations in subdomains, the mortar coupling approach was proposed by Bernardi et al. [11] for connecting finite element meshes to spectral element meshes in solid mechanics. Casadei et al. [12] proposed an hybrid approach using the mortar coupling method to deal with soil/structure interaction problem, demonstrating the accuracy, robustness and flexibility of the SEM/FEM coupling approach. However, the coupling approach is not a co-simulation, because it is implemented in only one explicit FEM code, Europlexus, with a unique time step. The aim of this paper is to set up a coupling strategy enabling to use an explicit SEM code, EFISPEC3D [13], with an implicit FEM code, Code_Aster [14], while considering different time scales for the time integration. The paper is organized as follows: Section 2 presents the general statement of the soil/structure interaction problem of interest as well as the weak form of the domain decomposition problem that contains the common formalism of the following spatial discretizations; Section 3 provides a brief review of the spatial FEM and SEM discretizations and gives the mortar coupling terms in the weak form of the global problem, related to the interface between the subdomains; Section 4 is devoted to the hybrid (explicit/implicit) asynchronous (different time steps) time integration adopted for the EFISPEC3D/Code_Aster co-simulation; finally, in Section 5, 3D numerical tests employing hexahedral elements in both SEM and FEM partitions are presented in order to demonstrate the accuracy and flexibility of the proposed approach.

2. Problem statement

2.1. Domain decomposition for SEM/FEM coupling

The purpose of this work is to set up a FEM/SEM coupling approach in order to deal efficiently with soil/structure interaction problems. Let Ω a bounded domain belonging to $\mathbb{R}^d$ with a regular boundary, d being the number of space dimensions assumed to be equal to 3 in the following. $J = [0, T]$ is the time interval of interest. As illustrated in Fig. 1, we assume that the domain Ω is divided into two parts Ω_1 and Ω_2 such as: $\Omega_1 \cap \Omega_2 = \emptyset$ and $\partial\Omega_1 \cap \partial\Omega_2 = \Gamma_I$. Γ_I represents the interface between the two subdomains. For both subdomains, we assume the classical partition of the boundary $\partial\Omega_i$ between the Dirichlet boundary, the Neumann boundary and the interface boundary, denoted by Γ_i^{D}, Γ_i^{N} and Γ_I, respectively: $\partial\Omega_i = \Gamma_i^{\mathrm{D}} \cup \Gamma_i^{\mathrm{N}} \cup \Gamma_I$.

It is assumed that both subdomains Ω_1 and Ω_2 are characterized by the density ρ_1, ρ_2 and the Lamé coefficients λ_{L_1}, μ_{L_1} and λ_{L_2}, μ_{L_2}. E_1, ν_1 and E_2, ν_2 are Young's modulus and Poisson's ratio. The purpose of this section is to set up the formulation of the coupling between the two subdomains related to different numerical approaches:

- Ω_1 solved by the Finite Element Method (FEM) dealing with the structure and its surrounding soil, corresponding to the zone of interest,
- Ω_2 solved by the Spectral Element Method (SEM) dealing with the soil regions sufficiently far away from the zone of interest.

The SEM partition is assumed to remain linear elastic (small-displacement behavior and elastic linear materials) because the SEM takes full profit of the linear assumption, enabling to drastically reduce the computation time. The FEM partition is also assumed to be linear elastic in the following presentation. However, in practical soil/structure interaction, both structure and surrounding soil are prone to exhibit strong site effects, characterized by material non linearities such as damage and plasticity, large displacements, large strains or contact/friction phenomena. As a result, it is suitable to include such non-linearities in the FEM subdomain, whereas the SEM regions should remain linear elastic or viscoelastic. The extension of the proposed FEM/SEM co-simulation strategy to non-linear behavior in the FEM partition is planned in future works.