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Numerical simulation of soil-structure elastodynamic interaction using iterative-adaptive BEM-FEM coupled strategies

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ABSTRACT

The study of solid–solid interaction problems is of significant interest in many engineering areas, such as structural dynamics or soil–structure interaction problems. In many of these cases, a localized and well-defined structure is embedded or connected to an infinite or semi-infinite domain, and thus the best option is to use different numerical techniques to model each part of the problem. In this paper, the authors propose two iterative coupling strategies to tackle this type of problem, considering the structure to be modelled by the FEM and the soil by the BEM. In both approaches, optimized relaxation parameters are employed, improving the efficiency of the analyses. Within the proposed iterative coupling algorithms, adaptive refinement of the FEM mesh may also be performed, in order to increase the accuracy of the calculations. Numerical examples are presented in the end of the manuscript, illustrating the main features of the proposed methods, assessing their applicability and effectiveness.

1. Introduction

The analysis of dynamic phenomena in elastic media and the interaction between possible heterogeneities and a host elastic space have been extensively researched in the last decades. Problems in fields such as soil–structure interaction, ground-borne noise and vibration induced by transportation systems, surface geophysics, non-destructive evaluation or wave scattering by inclusions in elastic media have mostly motivated this research. A wide range of analytical and numerical strategies is available for the solution of wave propagation and vibration problems of different complexities, and these tools are of significant importance for a detailed and accurate analysis in engineering applications [1–4].

The most accurate strategies for the solution of specific problems in elastodynamics correspond to closed-form solutions, although they have a very limited scope of application, as they can only be defined for very simple geometries and physical configurations (see, for example, [5]). In spite of their limited applicability, these solutions are quite useful as reference responses in the verification of more complex and general methods. Complementing these solutions, there is a large variety of numerical methods that are applicable in the study of elastodynamic problems, including domain discretization methods, such as the Finite Difference Method (FDM) [6] or the Finite Element Method (FEM) [7, 8], and boundary discretization methods, such as the Boundary Element Method (BEM) [9–11]. Several review works (such as [12, 13]) are available in the literature summarizing available strategies.

The selection between domain or boundary discretization methods often depends on the type of problem to be solved, with the FDM and FEM being usually adopted for modelling bounded or finite domains, inhomogeneous and anisotropic solids, and for dealing with non-linear behaviour, while for discretizing domains with infinite extension, the BEM is a commonly accepted method. In the former case, the FDM and the FEM require special computational procedures where the mesh is truncated, such as the use of artificial boundary conditions, absorbing boundary conditions or perfectly matched layers (PML) [14], and their computational cost becomes prohibitive for 3D unbounded and large scale problems. The BEM is recognized to be an interesting technique since the far-field radiation conditions can be automatically satisfied by the Green's functions in infinite, semi-infinite (halfspace) or layered media and it can handle irregular geometries, without the discretization of the propagating media. Since only the domain interfaces need to be discretized with boundary elements, this enables the reduction (by one) of the problem's dimension, leading to reduced meshes, simpler mesh generation processes and very accurate results [15–17].

Given the specific advantages and disadvantages of the different numerical methods, their combined use in coupled models has been addressed in many scientific publications, trying to explore the individual advantages of each technique. For example, in solid–fluid and soil–structure interaction problems, the particular case of coupling the FEM

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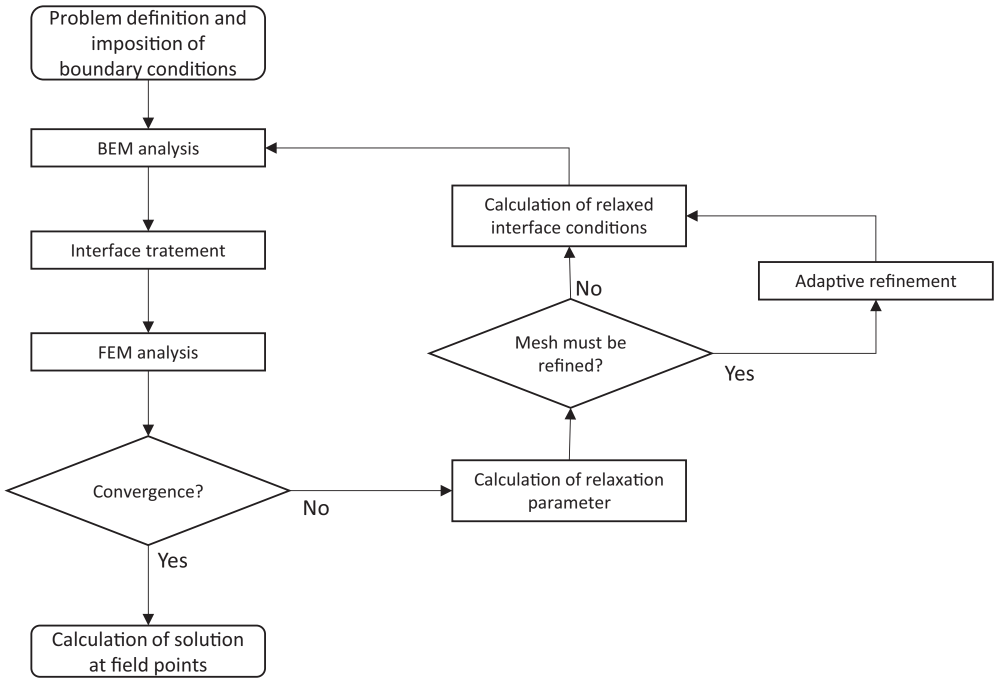

Fig. 1. Workflow of the proposed adaptive-iterative coupling approach.

and the BEM has been investigated by many authors, proposing different coupling techniques for this purpose [18–23]. Usually, the FEM is chosen to model the structure, while the BEM is used to model the infinite or semi-infinite fluid or soil hosting the structure. In many of the published works, the proposed algorithms are based on direct coupling methodologies, but a number of works also propose the use of iterative strategies to perform the coupling between the BEM and FEM subdomains. Indeed, this alternative is quite appealing, since it allows the use of independent discretizations for each method, as well as the separate analysis of the interacting subdomains. In addition, by separating the different parts of the problem, the systems of equations usually become better conditioned, allowing enhanced solutions. Several works have been published concerning the use of iterative strategies, such as [24–30], and they are summarized in a recent review paper by the authors [31]. In most of these works, fluid–solid interaction is addressed using iterative procedures and coupling not only the BEM and FEM, but a variety of other numerical methods, such as many meshless techniques (for instance, the Method of Fundamental Solutions (MFS) [32] or the Meshless Local Petrov-Galerkin (MLPG) [33]). In the referred papers, the authors report that the use of iterative coupling procedures can be very efficient and can lead to quite accurate results.

A particular advantage of iterative coupling becomes clear whenever modifications of the meshes are required. In this case, if direct coupling is performed, remeshing one of the subdomains will require the recalculation of all the involved matrices, thus rendering the process quite demanding from the computational point of view. On the other hand, by adopting an iterative coupling strategy, the analysis of the interacting subdomains is performed separately and using different methods; thus, in this case, the remeshing process will only affect its respective subdomain, while the matrices related to the other subdomains will remain unchanged. In this work, the authors propose an advanced iterative coupling technique involving the adaptive mesh refinement within the iterative process, making use of the BEM and the FEM to model each of the elastodynamic interacting subdomains. Two variants are proposed and analysed, in which either displacements or tractions can be considered prescribed to the BEM or FEM common interfaces; in both cases, adaptive refinement is incorporated into the process. It is worth noting that adaptive remeshing has already been reported in the context of numerical simulation of coupled BEM-FEM models. For the case of elastoplasticity, remeshing has been applied in BEM-FEM coupled analysis by Elleithy and Grzhibovskis [34, 35], who updated the subdomains modelled by the FEM and the BEM according to the evolution of the plastic zones of the model. Recently Soares and Godinho [36,37] developed a multiple iterative-adaptive coupling procedure for inelastic analysis and for frequency domain analysis of thermal problems, which proved to be very efficient. Regarding dynamic problems, although contributions can be found in the literature on elastodynamics (such as [38–40]), the authors are not aware of many works dealing with such problem using iterative coupling. In existing works, such as [41–42], the BEM-FEM coupling is performed in a direct form, requiring the construction of a fully coupled matrix. The approach proposed here is thus very different: the regions modelled by the BEM do not change during the analysis, and thus the fully populated matrices of the BEM are computed only once, rendering the procedure more efficient; as for the FEM, a rough discretization is used to start the algorithm, and then it is adaptively enriched as the solution evolves. In this context, and since refining only takes place within the FEM subdomains, non-matching nodes must be considered in the BEM-FEM interfaces, otherwise changing the BEM point distributions would require complete recalculation of the corresponding matrices, with a consequent loss of efficiency. The use of an iterative coupling algorithm is thus highly desirable due to its good performance and flexibility.

In the following sections, the governing equations of the elastodynamic problem are firstly presented, in the frequency domain; then, the involved numerical methods are discussed, and the BEM and the FEM formulations are briefly described; the iterative coupling procedures are presented in the sequence, and the proposed algorithms incorporating adaptive refinement are then explained in detail; finally, the effectiveness of the proposed techniques is analysed in the end of the paper, considering four numerical examples.

2. Governing equations

Elastodynamic problems are usually assumed to be governed by the well-known elastic wave equation, which is given by:

$$(c_d^2 - c_s^2)\, u_j(\mathbf{x},\omega)_{,ji} + c_s^2\, u_i(\mathbf{x},\omega)_{,jj} + \omega^2 u_i(\mathbf{x},\omega) + b_i(\mathbf{x},\omega) = 0 \tag{1}$$