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Dynamic analysis of large-scale SSI systems for layered unbounded media via a parallelized coupled finite-element/boundary-element/scaled boundary finite-element model

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ABSTRACT

An algorithm for a parallelized coupled model based on finite element method (FEM), boundary element method (BEM), and scaled boundary FEM (SBFEM) for harmonic and transient dynamic response of large-scale 2D structures embedded in or on layered soil media is presented. The BEM and SBFEM are used for modelling the dynamic response of the unbounded media. The standard FEM is used for modelling the finite region and the embedded structure. The objective of the development of this parallelized coupled model is to use the power of high performance computing, and to take into account the advantages and evade the disadvantages of the above mentioned numerical methods for modelling of the unbounded media in soil-structure interaction (SSI) systems. The development of the parallel algorithm for this model is essential for solving arbitrarily shaped large-scale SSI problems, which cannot be solved within reasonable elapsed times by a serial algorithm. The efficiency of the proposed parallel algorithm and the validity of the coupled model are shown by means of three numerical examples, indicating the excellent accuracy and applicability of the parallel algorithm with considerable time-savings in large-scale problems.

1. Introduction

The dynamic response of massive, stiff, and embedded structures in relatively soft soil conditions such as nuclear reactors, tunnels, liquid-storage tanks, gravity dams, and high-rise buildings are affected by solid-structure interactions (SSI) as well as the dynamic characteristics of the exciting loads (i.e. earthquake, wind, explosion, machinery vibrations) and the structures. The effect of the SSI may alter the dynamic characteristics of the stiff, rigid and massive structures resting on or embedded in relatively soft and/or layered media significantly. Several analytical and numerical methods have been developed and investigated to analyse the SSI problems by the well-known authors Wolf and Song [1], Wolf [2], Luco and Barros [3], Lysmer and Kuhlemeyer [4], Gazetas [5], etc. It is known that analytical methods are applicable only for simple structures that rest on linear and uniform soil media. For a complex or arbitrary shaped body subjected to dynamic loads requires the use of discrete numerical methods such as the finite element method (FEM) or the boundary element method (BEM). These two methods can be formulated in time or frequency spaces, and each has relative advantages and disadvantages. The properties of the system to be analysed, such as geometry, material properties, boundary conditions, and type of loading are the dominant effects to make a decision of which methods should be used. The FEM is well-suited for linear and non-linear behaviour of complex or arbitrary shaped structures with non-homogeneous and anisotropic material properties. For systems with infinite or semi-infinite extension, however, the use of the BEM is more effective than FEM. The scaled boundary-finite element method (SBFEM) is an alternative and effective method for modelling systems with finite and infinite extension having non-homogeneous and incompressible material properties. The SBFEM is developed and applied to SSI problems both in time and frequency domains by Wolf and Song [1], and Wolf [2]. Recently, it is applied to the structural elastodynamics [6,7], crack [8–10] and fracture mechanics [11,12] problems.

In order to profit from advantages and evade disadvantages of these methods, many authors have developed combined formulations for SSI problems which are composed of finite and infinite media. Numerous studies on coupled models are available in the literature. The coupled finite element and boundary element method (FE-BEM) is the most widely used combined model in both time and frequency domains [13–15]. The main developments regarding FE-BEM combinations are not discussed in this paper, but comprehensive reviews can be found, for instance, in Beer and Watson [16] and Stamos and Beskos [17]. The progress of the BEM for numerical solutions for elastodynamic problems

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and major developments are reported in details in the important reviews made by Beskos [18,19]. For this work, it is also convenient to point out some recent publications: Luco and Barros [3], where a 3D BEM/FEM coupling dedicated to frequency domain problems is presented; Antes and Steinfield [20], dealing with 3D BEM/BEM coupling in time domain; Guan and Novak [21], to analyse 2D transient problems using a BEM formulation combined with rigid strips; Von Estorff and Firuziaan [22], dealing with a coupled BEM/FEM approach for nonlinear soil-structure interaction in time domain; and Von Estorff and Hagen [23], to analyse 3D transient elastodynamic problems by an iterative coupled BEM/FEM Model in time domain. In addition to these studies, a BEM based formulation and a computer programme is proposed by Tanrikulu et al. [24] for 2D and 3D SSI problems with layered domains. Another combined model is coupled finite element and scaled boundary-finite element method (FE-SBFEM) in frequency domain for large-scale SSI systems [25]. It can be emphasised that, if BEM is used for modelling a non-homogeneous (layered) soil media extending to infinity (Fig. 1), the interface between the soil layers and the free surface of the soil must be discretized, which increases the computational load considerably. In addition, on the boundaries extending to infinity, discretization needs to be truncated, and this leads to errors. In the study of Tanrikulu et al. [24], the BEM formulation for infinite non-homogeneous media was improved for three different layers. However, SBFEM can easily model non-homogeneous soil media with many layers extending to infinity. In the SBFEM, the boundary conditions at the interfaces and at the free surface can be satisfied closely and automatically without any further discretization. In addition, SBFEM satisfies the radiation condition and calculates the dynamic response of the media extending to infinity at a truncated media without requiring fundamental solution as in BEM. These are the main advantages of the SBFEM. Modelling non-homogeneous soil media with layers by SBFEM requires the soil media to be discretized until rigid bedrock or homogeneous half space is reached. If the surface of the rigid bedrock is horizontal, this problem can be handled by using a special case of SBFEM which sets the similarity centre at infinity [1]. For the layered mediums on homogeneous half-space the satisfaction of the similarity is handled by using the structure medium interface outwards as mentioned in Wolf and Song [1]. The SBFEM results in a system of first-order non-linear ordinary differential equations (ODE) for the dynamic stiffness matrix of the soil extending to infinity at the boundary with the independent variable frequency. Through the SBFEM, dynamic stiffness matrix calculations of the infinite media are performed through an integration algorithm in a pre-defined frequency interval. But in the SBFEM formulations, the radiation condition is satisfied at high frequency values. Therefore, it requires some extra calculations until the desired frequency level is reached. Hence, for large-scale problems (i.e. structures resting on a layered soil and three-dimensional problems) the computational load increases significantly. The time measurements made showed that the vast majority of the time is spent for the solution of ODE resulting from SBFEM. In the studies of Genes and Kocak [25,26], the shortcoming of the SBFEM for large-scale SSI problems was considerably eliminated by introducing a parallelized algorithm for the solution of first-order non-linear ODEs. More recent studies are found in Cunha et al. [27], Bird et al. [28], and Park and Heister [29]. Cunha and et al. [27] applied the standard and portable libraries for the parallelization of BEM codes; Bird et al. [28] used a coupled BEM/SBFEM formulation to analyses linear elastic fracture mechanic problems; Park and Heister [29] proposed a parallelization procedure for the analysis of unsteady BEM problems. Most of these studies have worked on a structural problem or parallel implementation itself.

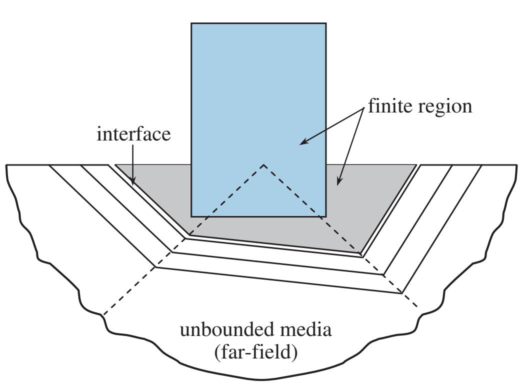

Fig. 1. A Soil-Structure Interaction problem.

The proposed model in this paper is first developed by Genes and Kocak [30] for the 2D structures rested on or embedded in layered unbounded media. In the present contribution, the model presented by Genes and Kocak [30] is further improved for large-scale structures under harmonic and transient exciting by implementing the FEM and BEM to the recently improved parallel computation algorithm which was presented in the studies of Genes and Kocak [25,26] in the first format. The improvement of the parallel algorithm is performed by major modifications in communication algorithm between the slave and master processors. This study is discussed in a journal paper which is currently under review. In addition, the solution of the system equations from the FEM and BEM are solved by a separate parallel algorithm at discrete frequencies to speedup the solution. For the analysis of large-scale computationally intensive problems, for which one analysis with a serial programme on a PC with Intel(R), Core(TM), 2 Quad CPU, 2.66 GHz takes several days, elapsed times of several coupled models are compared and a considerable time savings are obtained.

The boundary at the bottom of the finite media, which is extending to infinity in vertical direction, is modelled by the BEM. In addition, the vertical boundary of the layers, which extends to infinity in the horizontal direction, is modelled by the improved computation algorithm for the parallelized SBFEM.

In the proposed model, the transient load is applied in frequency space by using Fast Fourier Transformation (FFT) [31]. The dynamic stiffness matrices of the boundaries are combined with the dynamic stiffness matrix of the finite media by using the substructure method (SM).

The main aim of this paper is to propose a coupled model which is referred to as Parallelized Coupled FE-BE-SBFEM. One can see that, in this coupled model, good features of these three methods are combined to obtain a SSI model, and the high performance of the parallel computers is applied to solve large-scale problems in a short time. This method is verified by studying one example, which was analysed by Genes and Kocak [30], and Kim and Yun [32] under harmonic loading, and two examples which were analysed by Estorff [33] and [32] under transient loading. It is found that the results agree well with the literature. Also, the efficiency of the proposed parallel programs for the coupled model is tested by comparing the elapsed time of the processors during the analysis of the studied examples.

2. Physical models and numerical approaches

2.1. Finite element formulation

The characteristics of visco-elastic plane-strain structures such as strip foundations, tunnels, gravity dams, retaining walls etc.