Available online at www.sciencedirect.com

ScienceDirect

Comput. Methods Appl. Mech. Engrg. 276 (2014) 1–19

Computer methods in applied mechanics and engineering

www.elsevier.com/locate/cma

FEM/wideband FMBEM coupling for structural–acoustic design sensitivity analysis

Leilei Chen, Changjun Zheng, Haibo Chen *

Department of Modern Mechanics, University of Science and Technology of China, CAS Key Laboratory of Mechanical Behavior and Design of Materials, Hefei, 230026 Anhui, PR China

Received 25 September 2013; received in revised form 22 March 2014; accepted 26 March 2014
Available online 4 April 2014

Abstract

A coupling algorithm based on the finite element method (FEM) and the wideband fast multipole boundary element method (wideband FMBEM) is proposed for acoustic fluid–structure interaction simulation and structural–acoustic design sensitivity analysis by using the direct differentiation method. The wideband fast multipole method (FMM), which is developed by combining the original FMM and the diagonal form FMM, is used to accelerate the calculation of the matrix–vector products in boundary element analysis. The iterative solver generalized minimal residual method is applied to accelerate the calculation of the solution to the linear system of equations. The FEM/wideband FMBEM algorithm makes it possible to predict the effects of arbitrarily shaped vibrating structures on the sound field numerically. Numerical examples are presented to demonstrate the validity and efficiency of the proposed algorithm.

Keywords: Fluid–structure interaction; FEM; Wideband FMBEM; Design sensitivity analysis; Direct differentiation method

1. Introduction

Analyzing acoustic radiation or scattering from elastic structures in heavy fluids is a classical problem in underwater acoustics. Analytical solutions to acoustic fluid–structure interaction problems are only available when the structure has a simple geometry with simple boundary conditions [1]. For practical problems with complicated geometries, finding analytical solutions is impossible, and thus, developing efficient numerical methods is necessary.

The finite element method (FEM) has been widely used to analyze the dynamic behavior of structures, as well as acoustic and fluid–structure interaction problems. However, the FEM has limitations in modeling infinite domains. The boundary element method (BEM) has been effectively used to solve acoustic problems,

* Corresponding author. Tel.: +86 551 63600345; fax: +81 551 63606459.
E-mail addresses: chenllei@mail.ustc.edu.cn (L. Chen), cjzheng@mail.ustc.edu.cn (C. Zheng), hbchen@ustc.edu.cn (H. Chen).

http://dx.doi.org/10.1016/j.cma.2014.03.016
0045-7825/

because it provides excellent accuracy and easy mesh generation. In particular, the Sommerfeld radiation condition [2] at infinity is automatically satisfied in exterior acoustic problems. The Galerkin method has been widely applied to the numerical solution of boundary integral equations in BEM implementation [3,4]. This process provides a powerful theoretical background to this method. Traditionally, however, the collocation method has been widely used in the engineering community, and thus is adopted in this research. Hence, a suitable approach for analyzing fluid–structure interaction problems is coupled FEM/BEM [5–9]. However, the coupling analysis of underwater structural–acoustic problems based on the FEM/conventional BEM (CBEM) algorithm still represents the bottleneck of large computation costs, because the CBEM produces a dense and non-symmetrical coefficient matrix that induces $O(N^3)$ arithmetic operations to solve the system of equations directly, such as by using the Gauss elimination method. Many fast methods, such as the fast multipole method (FMM), the fast direct solver, and the adaptive cross approximation technique, have been applied to accelerate the solution of the integral equation. The fast direct solver that directly constructs a compressed factorization of the inverse of the matrix was presented by Martinsson and Rokhlin; this method is suitable for problems that involve ill-conditioned matrices [10–12]. The adaptive cross approximation technique introduced by Bebendorf and Rjasanow generates blockwise low-rank approximants from BEM matrices; this method is well-suited for problems with a large number of iteration steps [13,14]. The FMM [15–21] has been presented to accelerate the calculation of the solution to the CBEM system of equations and to decrease memory requirement. Two FMM forms are available for the Helmholtz equation. The first is the original FMM and the second is the diagonal form. Both forms fail in some cases outside their preferred frequency ranges. However, wideband FMM formed by combining the original FMM and the diagonal form FMM can overcome the aforementioned problems [22–26]. Thus, the coupling algorithm based on FEM/fast multipole BEM (FEM/FMBEM) can be effectively applied to solve large-scale fluid–structure interaction problems [27,28]. In the present study the coupling algorithm FEM/wideband FMBEM is proposed to solve large-scale fluid–structure interaction problems.

Passive noise control by modifying structural geometry is moving toward the field of vision for designers. This structural–acoustic optimization exhibits high potential in minimizing radiated noise, particularly for thin shell geometries [29]. Acoustic design sensitivity analysis can provide information on how changes in geometry affects the acoustic performance of a given structure, and thus, this step is important in acoustic design and optimization processes. An overview of developments in structural–acoustic optimization for passive noise control was presented by Marburg [30]. The global finite difference method (FDM) has been widely applied to structural–acoustic optimization because it is easy to implement, as shown in [31–33]. However, this method is inefficient, particularly when many design variables are considered concurrently. Adjoint variable methods, such as those presented in [34] or Wang [35], or direct differentiation methods [25,26,36] can be used to overcome the aforementioned challenge. Sensitivity analysis for fluid–structure interaction problems is the most time-consuming part of gradient-based optimization procedures. To accelerate analysis, this study applies the coupling algorithm FEM/wideband FMBEM to structural–acoustic sensitivity analysis based on the direct differentiation method.

Therefore, this work is novel because the wideband FMBEM is introduced to the coupled structural–acoustic sensitivity analysis. The sensitivity formulation for the coupled FEM/BEM analysis is then obtained. This work promotes the application of coupling the FEM/wideband FMBEM for fluid–structure interaction problems and structural–acoustic sensitivity analysis. The original FMM, diagonal form FMM and wideband FMM are presented in this study. Examples of scattering from underwater thin shell structures are presented to demonstrate the accuracy and efficiency of the proposed method.

2. Structural–acoustic analysis

2.1. Modeling the FEM

Fritze et al. [6] presented the detailed procedure of structural–acoustic simulation, and similar expressions are presented in this subsection. A harmonic load with the excitation frequency ω is assumed to be applied to the structure. The steady-state response of the structure can be calculated from the frequency–response analysis. The linear system of equations for computing the nodal displacement u is derived by