Available online at www.sciencedirect.com
SCIENCE DIRECT
ACADEMIC PRESS
Journal of Sound and Vibration 263 (2003) 569–591
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

Design sensitivity analysis for sequential structural–acoustic problems

Nam H. Kim[a], Jun Dong[b], Kyung K. Choi[b,*], N. Vlahopoulos[c], Z.-D. Ma[d], M.P. Castanier[d], C. Pierre[d]

[a] *Department of Mechanical and Aerospace Engineering, College of Engineering, University of Florida, Gainesville, FL 32611, USA*
[b] *Center for Computer-Aided Design, Department of Mechanical Engineering, College of Engineering, The University of Iowa, Iowa City, IA 52242-1000, USA*
[c] *Department of Naval Architecture and Marine Engineering, The University of Michigan, Ann Arbor, MI 48109, USA*
[d] *Department of Mechanical Engineering, The University of Michigan, Ann Arbor, MI 48109, USA*

Received 29 August 2001; accepted 30 June 2002

Abstract

A design sensitivity analysis of a sequential structural–acoustic problem is presented in which structural and acoustic behaviors are de-coupled. A frequency-response analysis is used to obtain the dynamic behavior of an automotive structure, while the boundary element method is used to solve the pressure response of an interior, acoustic domain. For the purposes of design sensitivity analysis, a direct differentiation method and an adjoint variable method are presented. In the adjoint variable method, an adjoint load is obtained from the acoustic boundary element re-analysis, while the adjoint solution is calculated from the structural dynamic re-analysis. The evaluation of pressure sensitivity only involves a numerical integration process for the structural part. The proposed sensitivity results are compared to finite difference sensitivity results with excellent agreement.

1. Introduction

Structure-induced noise and vibration control at low frequency is an important area of research for reducing the noise level generated by various structural parts. In automotive applications, for example, the noise level of a passenger compartment can be reduced by changing the structural design parameters. Design sensitivity analysis (DSA) is an essential process in the gradient-based

*Corresponding author. Tel.: +1-319-335-3380; fax: +1-319-335-5669.
E-mail address: kkchoi@ccad.uiowa.edu (K.K. Choi).

0022-460X/03/$ - see front matter
PII: S0022-460X(02)01067-2

optimum control technique. Some research results have been reported in DSA of a structural–acoustic problem. Ma and Hagiwara [1, 2], Wang et al. [3], and Choi et al. [4] developed DSA of a coupled structural–acoustic problem using a finite element method (FEM). Either a direct or frequency method is used to solve the system of matrix equations. However, the excessive number of elements to represent the complicated three-dimensional acoustic cavity has been the major bottleneck of the finite element-based approach [5]. To avoid the problems associated with a large number of elements in an acoustic domain, Salagame et al. [6] presented an analytical sensitivity method using a Rayleigh integral [7]. The sensitivity of a surface velocity is obtained by differentiating the frequency-response matrix equation, and the pressure sensitivity is then calculated by differentiating the Rayleigh integral. This approach is limited to a flat plate problem. Recently, Scarpa [8] proposed a parametric sensitivity calculation method using a symmetric Eulerian formulation. The velocity potential is used instead of the pressure to represent the fluid's behavior.

Compared to FEM, the boundary element method (BEM) has an advantage in the modelling of the acoustic cavity: It is unnecessary to generate a complicated, three-dimensional acoustic model. Several research studies have been conducted for DSA using BEM. Assuming that the structure's velocity sensitivity is known, Smith and Bernhard [9] developed a semi-analytical design sensitivity formulation. Cunefare and Koopman [10], Kane et al. [11], Matsumoto et al. [12], and Koo [13] presented an analytical design sensitivity formulation using BEM. For the general structure-induced noise problem, however, the velocity sensitivity has to be calculated from the structural frequency-response analysis [14]. A structural acoustic sensitivity algorithm with respect to sizing design variables based on finite element and boundary element computations has been presented [15]. A structural acoustic sensitivity formulation based on boundary elements has been developed for structures subject to stochastic excitation [16].

In this paper, a design sensitivity analysis of a sequential structural–acoustic problem is presented in which structural and the acoustic behaviors are de-coupled. For the case of a harmonic excitation, the dynamic behavior of the structure is described using a frequency-response analysis. A boundary element method [17] is used to calculate the radiated noise (pressure) from the structural response (harmonic velocity). Instead of differentiating a discrete matrix equation, a continuous variational equation is differentiated with respect to the design parameter. In case of sizing design, the boundary integral equation does not contain any terms that are explicitly dependent on the design; only implicitly dependent terms exist through the state variables.

While the direct differentiation method in DSA follows the same solution process as the response analysis, the adjoint variable method follows a reverse process. One of the challenges of the adjoint variable method in sequential DSA is how to effectively and practically formulate this reverse process. For example, in the transient response DSA developed by Haug et al. [18], the adjoint problem becomes a terminal-value problem, whereas the original problem is an initial-value problem. Such an opposite solution process in the adjoint problem causes a significant amount of inconvenience and ineffectiveness in DSA. To overcome these difficulties, a sequential adjoint variable method is presented in which the adjoint load is obtained from boundary element re-analysis, and the adjoint variable is calculated from structural dynamic re-analysis. So far, no research results have been reported in the development of the adjoint variable method in a sequential problem. In addition, it is shown that the acoustic adjoint problem still uses the same coefficient matrix from the direct problem, even if the coefficient matrix is not symmetric.