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Shape sensitivity analysis of sequential structural–acoustic problems using FEM and BEM

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Abstract

A shape design sensitivity formulation for structural–acoustic problems using sequential finite element and boundary element methods is presented. Frequency-response analysis is used to obtain the dynamic behavior of the structure, while boundary element analysis is used to solve for the pressure response of the acoustic domain. It is shown that the adjoint method, which takes the reverse direction to response analysis, provides a very efficient way of sensitivity calculation. In addition, it has been shown that the adjoint equation for the shape design problem is the same as that of the sizing design problem. The only difference is the numerical integration that evaluates the sensitivity coefficient. The combination of the semi-analytical method for the structure and the analytical differentiation method for the acoustic cavity yields a very practical approach for the shape design sensitivity formulation. The accuracy of the sensitivity information is compared with the analytical sensitivity as well as the sensitivity calculated using the finite difference method.

1. Introduction

This paper is the continuation of our previous publication [1] that treated the *sizing* design sensitivity formulation for sequential structural–acoustic problems. Here *shape* design sensitivity analysis of sequential structural–acoustic problems is presented in which the structural and

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acoustic behaviors are decoupled. When a harmonic excitation is applied, the dynamic behavior of the structure is described using frequency-response analysis. Boundary element analysis is then employed to calculate the radiated noise (pressure) from the structural response (harmonic velocity). This paper describes how to calculate the rate of change of the radiated noise effectively when the geometry of the structure is changed. The calculated sensitivity information can be used either in the interactive design process or in the automated optimization process. As sensitivity calculation is the most expensive process in optimization, the focus of the paper is on how to calculate it efficiently and accurately.

Traditionally, the sensitivity formulation can be classified into two approaches: the *direct method* and the *adjoint method*. The former calculates the sensitivity of the state response by differentiating the governing equation and then, using the chain rule of differentiation to calculate the performance sensitivity. The latter, however, calculates the performance sensitivity without recourse to the sensitivity of the state response. Rather, it utilizes the adjoint problem in calculating the implicitly dependent terms [2]. When the number of design variables is greater than that of performance functions, the adjoint method is more efficient than the direct method.

In the literature, many shape sensitivity formulations of structural–acoustic problems have been presented using the boundary element method. Most shape sensitivity formulations in the literature use the direct method. For example, Smith and Bernhard [3] presented the semi-analytical sensitivity formulation using the direct method. Koo et al. [4,5], Kane et al. [6], and Matsumoto et al. [7] derived the acoustic sensitivity expression with respect to the shape design variable. When only boundary element analysis is used [3–7], it is necessary that the velocity on the boundary and its shape sensitivity be prescribed.

Since the velocity on the boundary is determined through structural analysis, a finite element method and a boundary element method have been used sequentially in calculating the radiated noise [8]. The fundamental assumption is that the vibration of the structure is not affected by the bounding acoustic domain. Englestad et al. [9] optimized the interior noise problem using the direct method of sensitivity calculation. They considered sizing design variables; i.e., the thickness of the plate. Hahn and Ferri [10] used the perturbation technique to derive the sensitivity expression with respect to sizing design variables. Since the acoustic domain is independent of sizing design, they only perturbed the finite element matrix. Mallardo and Aliabadi [11] used the shape sensitivity information in order to identify the location of flaws by minimizing the error between the numerical and experimental data. As far as authors' knowledge extends, there is no publication available on the adjoint method in the shape sensitivity formulation of sequential structural–acoustic problems, which is the main purpose of this paper. The shape design sensitivity formulation is derived using the adjoint method that takes the reverse order of response analysis. It has been shown that the adjoint equation is identical for sizing and shape design problems. The proposed approach can also be applied to the acoustic problem that uses boundary element analysis only, if the surface velocity and its sensitivity are assumed to be available.

The composition of the paper is as follows. After a brief review of structural–acoustic analysis using the finite element and boundary element methods in Section 2, the shape sensitivity formulation is developed in Section 3 using direct and adjoint methods. Numerical examples are shown in Section 4 in order to show the accuracy and efficiency of the proposed sensitivity calculation method, followed by conclusions in Section 5. In order to simplify the presentation,