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Explicit evaluation of hypersingular boundary integral equations for acoustic sensitivity analysis based on direct differentiation method

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ABSTRACT

This paper presents a new set of boundary integral equations for three dimensional acoustic shape sensitivity analysis based on the direct differentiation method. A linear combination of the derived equations is used to avoid the fictitious eigenfrequency problem associated with the conventional boundary integral equation method when solving exterior acoustic problems. The strongly singular and hypersingular boundary integrals contained in the equations are evaluated as the Cauchy principal values and Hadamard finite parts for constant element discretization without using any regularization technique in this study. The present boundary integral equations are more efficient to use than the usual ones based on any other singularity subtraction technique and can be applied to the fast multipole boundary element method more readily and efficiently. The effectiveness and accuracy of the present equations are demonstrated through some numerical examples.

1. Introduction

Shape design sensitivity analysis is a procedure to calculate gradients of cost functions defined to obtain the optimum shape of a given structure with respect to shape design variables. The obtained gradients can then be used to determine the direction to search the optimum values of the design variables. Accordingly, acoustic shape sensitivity analysis is usually the first and most important step in acoustic shape design and optimization processes.

Many shape sensitivity analysis methods have been proposed so far based on the finite element method (FEM) [1–3] and the boundary element method (BEM) [4–10]. But because of the highly accurate solutions on the boundary, the reduction of dimensionality, and the incomparable superiority in solving infinite or semi-infinite acoustic field problems, the BEM has been widely applied to acoustic shape sensitivity analyses. In particular, the reduction of dimensionality gives the advantage of easier mesh regenerations to the BEM in shape design or optimization processes.

The BEM based on the conventional boundary integral equation (CBIE) fails, however, to yield unique solutions for exterior acoustic problems at the eigenfrequencies of the associated interior problems [11]. These eigenfrequencies are usually called "fictitious eigenfrequencies" because they do not have any physical significance, but just arise from the drawback of the boundary integral representation when solving exterior acoustic problems. In order to tackle this problem, two main methods, appropriate for practical applications, have been proposed over the last several decades. The Combined Helmholtz Integral Equation Formulation (CHIEF) proposed by Schenck [11] can successfully conquer this problem by adding some additional constraints in the interior domain, which leads to an over-determined system of equations, then solved by a least-square procedure. This method is very simple to implement but determining the suitable number and positions of the interior points may become troublesome as the wave number increases. Thereafter, some modified CHIEF methods have been proposed [12,13], but they do not solve the problem completely, especially, in the high frequency range yet.

A more sound and effective alternative to circumvent the fictitious eigenfrequency problem is the Burton–Miller method which uses a linear combination of the CBIE and its normal derivative (NDBIE) [14] as the boundary integral equation to solve. It has been proved that this combined BIE formula can yield unique solutions for all frequencies if the coupling constant of the two equations is chosen properly [14]. The comparison between the CHIEF approach and the Burton–Miller method can be found in [16]. The advantage of the Burton–Miller method is that there is no need for making difficult decisions of interior points. The main difficulty is the evaluation of the hypersingular boundary integrals involving a double normal derivative of the

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