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A multi-domain boundary element formulation for acoustic frequency sensitivity analysis

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ABSTRACT

The determination of acoustic sensitivity characteristics for vibrating structures with respect to the design parameters is a necessary and an important step of the acoustic design and optimization process. Acoustic frequency sensitivity analysis, as one kind of the sensitivity analysis, is extremely useful for large models in which only a few discrete frequencies can be analyzed due to high computational cost. Through frequency sensitivity analysis, the acoustic performance can be obtained near the initial frequency for less cost than a second full analysis. However, based on single-domain boundary element method (BEM), acoustic sensitivity analysis also has low computation efficiency. When many forces, with the same frequency, act on one vibrating structure, it is hard to decide which one should be improved. On the contrary, by using multi-domain BEM, the sensitivity figure can clearly show which exciting frequency has the greatest influence on acoustic characteristics with lower computational cost. Adopting multi-domain BEM, the expressions of the change of acoustical characteristic with respect to the change of the frequency are presented for exterior problems. The sensitivities of coefficient matrix are computed by analytical differentiation of the discrete Helmholtz integral equation. Finally, several examples are given to demonstrate the validation and availability of the presented method.

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1. Introduction

Structure-acoustic sensitivity analysis, which used to predict the change of acoustic performance with a change of design variables, is an active research area in recent years [4–27]. It is concerned with the relationship between design variables and acoustical characteristics by the laws quantificationally. Based on it, an engineer can decide on the direction and the amount of design change to improve the objective function [40]. In general, design sensitivity analysis is the first and the most important step in the optimization problems.

In acoustic design sensitivity, the objective function is usually chosen as acoustic pressure or acoustic power. The design variables include material properties, size, shape, surface normal velocity, frequency, etc. So far, many structural–acoustic sensitivity analysis methods have been presented based on boundary element method (BEM) [4–16], finite element method (FEM) [17–22] or both of them [23–26]. Among these methods, the boundary element method is considered to be an important technique in the computational solution of acoustics, due to the reduction of the dimension [1–3], especially for exterior problems.

The shape and the size design variables have been discussed widely in the past acoustic sensitivity analysis. But for some applications, the analysis frequency may be chosen as design variable, this is classified as frequency sensitivity analysis. For large models, only some specified frequencies can be analyzed due to high computational cost. Based on frequency sensitivity analysis, the acoustic performance can be obtained near the initial frequency for less cost than a second full analysis [4]. Generally, for large and complex models, there are many exciting forces acting on them. The frequency of each force may be the same or different, coherent or incoherent. By the sensitivity of acoustic pressure with respect to each frequency, it is easier to find which frequency has the most significant influence on acoustic pressure. Consequently, avoided this frequency, the vibrating structure may radiate lower noise in a specified region.

However, the sensitivity analysis based on single-domain acoustic boundary element method (SBEM) could only obtain the derivative with respect to one frequency. This has two main shortcomings. First, it could not clearly show which force has the greatest influence on acoustic pressure, especially, when the exciting frequencies of the forces are the same or closed to each other, since it differentiates the whole domain with respect to frequency. Second, for a large and complex vibrating structure, it is unnecessary to consider the influence of one frequency on the total system. Only the neighborhood of that exciting frequency need to be computed and the far field can be neglected, due to the weak influence. As we

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know, the required computer memory size and time increase tremendously as much as $O(N^2)$ and $O(N^3)$, respectively, for solving the linear system equation of the SBEM, along with the increase of the number of unknowns N [27]. So it is unpractical that all coefficient matrices are recalculated in sensitivity analysis and optimization. But if only the neighborhood of that frequency was considered, the computational cost can be reduced largely.

Using a multi-domain method [28–39], also known by the names of sub-domain technique, multi-region, poly-region or domain decomposition [29], the system matrix becomes sparse and thus, the necessary amount of memory can be considerably decreased. The basic idea is to divide the vibrating structure into smaller domain elements connected by hypothetical interface planes. The single-domain boundary integral equation (SBIE) is applied to each sub-domain. Based on multi-domain acoustic boundary element method (MBEM) sensitivity analysis, all sub-domains of the vibrating surface can be grouped into two categories: sub-domains mostly affected by the exciting frequency which is under consideration, can be classified as the first kind, and the other kind contains sub-domains which are nearly not influenced by that exciting frequency. By this category, only the sensitivity coefficient matrices in the first kind of sub-domains should be computed. For a large and complex vibrating structure, this kind of sub-domains is small, and the computational cost for sensitivity coefficient matrices will be improved obviously.

Jeong [14] had obtained acoustic sensitivity equations based on MBEM. The design variables were chosen as shape and non-shape. As an effective complement, the MBEM-based expression of sensitivities of the acoustic pressure with respect to the change of frequency is presented in this paper. Instead of finite difference method (FDM) shown in Ref. [14], the computation of the sensitivity coefficient matrices is based on analytical differentiation of the discrete Helmholtz integral equation (HIE) [13]. Compared with the FDM, both the computation cost and the accuracy are improved, because the FDM has some weak points as follows. The precision is dependent on the magnitude of perturbations. And even though a very small perturbation is utilized, numerical noise will become dominant for the too-small step size. In addition, the computational cost might be high for a second full analysis. The validity of the presented formulations is demonstrated through several examples. In the first and the second cases, the exterior acoustic field from a cuboid model is chosen to validate the proposed methods and the results are compared with that of FDM. In the third and last examples, a more complex structure is investigated. By the proposed sensitivity analysis, the force whose frequency has the greatest influence on acoustic pressure can be picked out easily for a specified field point, although several exciting frequency have the same or closed values. And it is hard for SBEM.

2. Acoustic frequency sensitivity equations based on analytical differentiation of the discrete single-domain boundary integral equation

The direct boundary element method can determine the acoustic pressure or velocity generated by a vibrating structure at any position within an acoustic medium. After dividing the radiator surface into N elements, the numerical solution can be achieved. Integration is performed over the area S_j of each element. Fig. 1 shows nomenclatures in the exterior acoustic problem. The discrete Helmholtz integral equation is obtained as

$$C(\mathbf{x})p(\mathbf{x}) - \sum_{j=1}^{N}\left(\int_{S_j} \partial\frac{\partial G(r,k)}{\partial n}\,dS\right)p(\mathbf{y}) = i\rho_0 kc\sum_{j=1}^{N}\left(\int_{S_j} G(r,k)\,dS\right)V(\mathbf{y}), \tag{1}$$

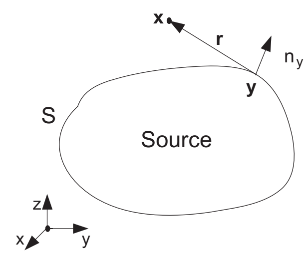

Fig. 1. Nomenclature in the exterior acoustic problem.

where $C(\mathbf{x})$ is the geometry-related coefficient, $\mathbf{y}$ is the source point on the boundary surface S and $\mathbf{x}$ are the field point in the fluid domain, respectively. The unit normal to the surface at source point $\mathbf{y}$, denoted as $\mathbf{n}$, points into the fluid domain. $\mathbf{r} = |\mathbf{x}-\mathbf{y}|$ is the vector directed from the source point $\mathbf{y}$ to the field point $\mathbf{x}$, and r is the length of it. $G(r,k) = e^{-ikr}/4\pi r$ is the Green's function in an unbounded fluid domain without reflecting objects. $k = 2\pi f/c$ is the wave number, f is the frequency, c is the acoustic velocity, $i = \sqrt{-1}$. For the exterior problem, the coefficient $C(\mathbf{x})$ in Eq. (1) is given by [42]

$$C(x) = \begin{cases} 0, & \text{for points } x \text{ outside the acoustic medium,} \\ \frac{1}{2}, & \text{for points } x \text{ on the boundary smooth surface,} \\ 1 + \left(\frac{1}{4\pi}\right)\oint_S \frac{\partial}{\partial n(y)}\left(\frac{1}{r}\right) ds, & \text{for points } x \text{ on the boundary nonsmooth surface,} \\ 1, & \text{for points } x \text{ in the acoustic medium.} \end{cases} \tag{2}$$

For acoustic sensitivity analysis based on the direct boundary element method, there are still two steps similar to the direct boundary element method [13]. The sensitivity of surface acoustic pressure is computed first. Then, field pressure sensitivity within the acoustic medium is evaluated [13].

The acoustic sensitivity is the partial derivative of the objective function with respect to some design variables. When frequency is chosen as design variable, it is classified as frequency sensitivity analysis. Although it is named as "frequency sensitivity", the wave number k is adopted, due to the widespread use of k and the linear relationship between wave number and frequency [4,15]

$$k = \frac{2\pi f}{c}. \tag{3}$$

Chosen wave number k as the design variable, the differentiation of Eq. (1) gives

$$\begin{aligned} &C(\mathbf{x})\frac{\partial P(\mathbf{x})}{\partial k} + \frac{\partial C(\mathbf{x})}{\partial k}p(\mathbf{x}) - \sum_{j=1}^{N}\left(\int_{S_j}\partial\left(\frac{\partial G}{\partial n}\right)\Big/\partial k\,dS\right)P(\mathbf{y}) \\ &\quad - \sum_{j=1}^{N}\left(\int_{S_j}\frac{\partial G}{\partial n}\frac{\partial(dS)}{\partial k}\right)P(\mathbf{y}) - \sum_{j=1}^{N}\left(\int_{S_j}\frac{\partial G}{\partial n}\,dS\right)\frac{\partial P(\mathbf{y})}{\partial k} \\ &= i\rho_0 c\sum_{j=1}^{N}\left(\int_{S_j}G\,dS\right)V(\mathbf{y}) + i\rho_0 c\sum_{j=1}^{N}\left(\int_{S_j}G\,dS\right)\frac{\partial V(\mathbf{y})}{\partial k} \\ &\quad + i\rho_0 kc\sum_{j=1}^{N}\left(\int_{S_j}\frac{\partial G}{\partial k}\,dS\right)V(\mathbf{y}) + i\rho_0 kc\sum_{j=1}^{N}\left(\int_{S_j}G\frac{\partial(dS)}{\partial k}\right)V(\mathbf{y}). \end{aligned} \tag{4}$$

The variable $C(\mathbf{x})$ and the area S_j of the element j have no relation to the wave number k. Consequently, the derivatives of these variables with respect to k equal zeros

$$\frac{\partial C(\mathbf{x})}{\partial k} = 0, \tag{5a}$$

$$\frac{\partial(dS)}{\partial k} = 0. \tag{5b}$$

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