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A study on the application of material selection optimization approach for structural-acoustic optimization ☆

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ABSTRACT

Issues of application of the material selection optimization approach for structural-acoustic optimization is investigated herein. By introducing the stacking sequence hypothesis of metal material, the mechanical properties parameters and plies' numbers of the metal material or composite material are defined as design variables; the mathematical formulation about material selection optimization approach is established. Finally, a hexahedral box structure is taken as an example, and the material selection optimization is conducted. By introducing genetic algorithm (GA), the optimization problem is solved. The numerical example shows the effectiveness of the proposed stacking sequence hypothesis of metal material.

1. Introduction

Noise and vibration control becomes more and more important in engineering design and manufacturing. The optimization analysis of acoustic radiation properties is considered with the objective of minimizing the total acoustic power radiated from the vibrating structure surface into a surrounding acoustic medium. On the other hand, many new materials are used in dynamic environment, vibration control and noise reduction which have great technical significance. The material properties and material selection method are very important in product design and manufacturing. Composite materials begin to play important roles in vibration and noise reduction in recent years. Meanwhile, a lot of researches have been conducted on composite material structure for acoustic radiation problem. The discrete material optimization formulation has been applied to achieve the design optimization of fiber orientation angles, plies number and material selection of for composite laminated plates [1]. The optimization study on cylindrical sandwich shell to minimize the transmitted sound which is into the interior induced by the exterior acoustic excitation was analyzed [2]. By introducing solid isotropic material with penalization (SIMP) model, the topology optimization of laminated composite structures for the minimization of the acoustic power radiation has been studied [3]. The acoustic radiation power is defined as the objective function, in which the influence of fiber orientations angle and plies number were compared [4]. To reduce the acoustic pressure in the acoustic domain, the thickness distribution optimization problem of a multilayered structure was analyzed, in which, continuous approximation of thickness distribution is assumed [5]. To minimize the acoustic radiation which transmits into the interior induced by the exterior acoustic excitations, the thickness of skins and core were defined as the design variables, and the sandwich structure optimization has been studied [6].

The structural-acoustic optimization approach includes sizing optimization, shape optimization, topology optimization, and so on. With the development of technology, material selection method becomes a new optimization tool in manufacturing process and life cycle. In structure design, the right selection of available material is critical for the success and competitiveness of the manufacturing organization. Main superiority of reliable materials selection is to take advantage of best mechanical behavior of each material candidate of a structure under given load and boundary conditions. The material selection optimization (MSO) is the method for material conversion in optimization process, which includes conversion between composite material and metal materials; conversion between different kinds of composite material; conversion between different kinds of metal material, and so on. Numerous studies have been published on this topic during the last decade. This MSO problem is solved by using the so-called discrete material optimization approach, in which the structure constituents are chosen among a given set of different candidate materials [7]. Different glass/carbon ratios and stacking sequences of a static loading problem were investigated in a hybrid composite laminated structure [8]. An integrated approach was used to optimize

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the multi-objectives problem by material selection, concerning material characteristics and sustainable strategies [9]. With a design index, the discrete problem in material selection can be defined as a continuous optimization problem, and the gradient-based optimization algorithm is used in numerical analysis [10]. A novel multi-material selection method for lightweight design is discussed, which incorporates recyclability for an automotive body assembly [11]. The material section optimization issue was analyzed in the car's structure design; minimization weight of the entire bottom structure defining as objective function, constraints including stiffness, strength and buckling parameter [12]. The environmental impact was considered as a constraint, the MSO approach were applied a pressure vessel design, in which, four pressure vessel steels and three aluminum alloys can be selected [13]. In the automotive design, it is widely accepted that using material selection theory can reduced weight without increasing cost [14]. The acoustic pressure on a prescribed reference plane/domain in the acoustic field that is generated by the vibrating structure is minimized by two-phase damping material distribution optimization over the structure domain [15]. Materials selection optimization formulations for hybrid steel-composite with 0–1 topological design variables were presented, and the method of continuation with variables and mapping function transformation was discussed in optimization formulations [16]. A mapping transformation function approach is presented to convert the mixed variable formulation to the one with only continuous variables, and the vibration problem of a hybrid steel-composite floating raft is discussed for example [17]. The multi-objective optimization on the basis of ratio analysis (MOORA) method was applied to solve common material selection problems, in which, three mathematical approaches are applied [18].

The objective of present study is the minimization of structural-acoustic radiated power from a hexahedral box structure under broadband excitation by using material selection optimization approach. Based on the structural optimization theory and metal stacking sequence hypothesis, the acoustic radiation power is taken as the optimization objective function, the material mechanical properties (density, Young's modulus, shear modulus, loss factor, etc.) and plies number of hybrid metal-composite structure are taken as design variables, the genetic algorithm (GA) is employed to solve the relationship between acoustic radiation performances and design variables, the materials selection optimization function is analyzed in present paper.

This paper is organized as follows: a brief literature review of structural-acoustic radiation and material selection optimization is given in Section 1; the basic structural-acoustic radiation formulation is reviewed in Section 2; the basic concept of composite laminated structure is performed in Section 3; the metal material stacking sequence hypothesis is introduced in Section 4; the material selection optimization mathematical formulation for acoustic optimization is established in Section 5; the numerical result and the comparison of material selection optimization are presented in Section 6; finally, the conclusion is drawn in Section 7.

2. Structural-acoustic radiation formulations

In this section, structural-acoustic radiation formulations are discussed. Finite element method (FEM) is used to obtain the structural frequency response analysis and boundary element method (BEM) is applied to deal with the exterior acoustic radiation problem. Taking the structural response (harmonic normal velocity) as boundary condition, the boundary element method is used to calculate the acoustic radiation behavior (acoustic pressure and acoustic radiation power).

2.1. Structural vibration formulations

The structural vibration analysis is the premise and basis of structure optimization analysis. Considering a continuum structure with an external harmonic loading $\mathbf{F}(x,t)$, it is assumed that the material damping can be regarded as a proportional damping and the fluid–structural coupling is weak coupling that can be neglected, especially for air and wide open spaces. In the structure domain Ω^S, the differential equation governs the behavior of this structural dynamic system can be expressed as:

$$[\mathbf{M}]\{\ddot{\mathbf{U}}\} + [\mathbf{C}]\{\ddot{\mathbf{U}}\} + [\mathbf{K}]\{\mathbf{U}\} = \mathbf{F}(x,t), \quad x \in \mathbf{\Omega^S}, t > 0. \tag{1}$$

where Ω^S indicates the structural domain, $\{\mathbf{U}\}$ indicates the nodal displacement vector matrix, $[\mathbf{M}]$ is the structural mass matrix, $[\mathbf{K}]$ is the structural stiffness matrix, and $[\mathbf{C}]$ is the viscous damping matrix. Considering the excitation force $\mathbf{F}(x,t)$ is a harmonic time dependence load, it can be expressed as:

$$\mathbf{F}(x,t) = f(\omega)e^{\mathbf{i}\omega t}, \tag{2}$$

where $f(\omega)$ is the magnitude of the harmonic load, ω the circular frequency, and it is considered as a constant. Using the complex variable method, the nodal displacement vector can be expressed as: $\mathbf{U}(x,t) = \mathbf{u}(\omega)e^{\mathbf{i}\omega t}$, where, $[\mathbf{u}(\omega)]$ is a column matrix of the nodal displacement vectors, and $\mathbf{i} = \sqrt{-1}$.

Substituting the displacement vector equation and harmonic loading equation into Eq. (1), and there is obtaining the spatial state operator equation:

$$\{-\omega^2[\mathbf{M}] + \mathbf{i}\omega[\mathbf{C}] + [\mathbf{K}]\}[\mathbf{u}(\omega)] = f(\omega). \tag{3}$$

In addition, the frequency response equation can be written as shorthand $[\mathbf{A}(\omega)][\mathbf{u}(\omega)] = f(\omega)$, where $[\mathbf{A}(\omega)] = -\omega^2[\mathbf{M}] + \mathbf{i}\omega[\mathbf{C}] + [\mathbf{K}]$, and the nodal displacement vector matrix $[\mathbf{u}(\omega)] = [\mathbf{A}(\omega)]^{-1}f(\omega)$.

Defining the nodal velocity vector $\mathbf{v}(\omega)$, it can be expressed as: $\mathbf{v}(\omega) = \mathbf{i}\omega\mathbf{u}(\omega)$. At the interface between the structure and the fluid, the nodal particle normal velocity vector can be written as:

$$\mathbf{v}_n(\omega) = \mathbf{i}\omega\mathbf{N}\mathbf{A}^{-1}(\omega)f(\omega). \tag{4}$$

where $[\mathbf{N}]$ is the nodal normal vector matrix; it associates to structural surface shape. The nodal particle normal velocity is used as boundary condition in acoustic boundary element method analysis.

2.2. Acoustic power formulations

In solving the acoustic radiation problem, the boundary element method (BEM) has many advantages. It is unnecessary to generate a complicated three-dimensional acoustic model. Only the low-middle frequency domains exterior acoustic radiation problem of the continuum structure was analyzed present paper. The standard acoustic wave equation is reduced to the Helmholtz equation in the harmonic response problem. For an arbitrary shape structure, the governing differential equation in steady-state linear acoustics is the classical Helmholtz equation as follows:

$$\nabla^2\mathbf{p} + k^2\mathbf{p} = 0. \tag{5}$$

where $\mathbf{p}$ is the acoustic pressure of the acoustic field point, $k(=\omega/c)$ denotes the wave number, ω and c are the angular frequency and speed of sound, respectively. ∇^2 is the Laplace operator. The acoustic wave has assumed harmonic time variations throughout with $\mathbf{e}^{-i\omega t}$ dependence suppressed for simplicity.

At the interface of the structure-fluid Ω, the acoustic pressure must satisfy the Neumann boundary condition: $\frac{\partial \mathbf{p}}{\partial \mathbf{n}} = -\mathbf{i}\omega\rho\mathbf{v}_n$, where $\mathbf{v}_n$ is the nodal normal velocity of structure, ρ is the density of fluid medium and $\mathbf{n}$ is the outer-normal units vector of the structure surface. Moreover, the acoustic pressure $\mathbf{p}$ satisfies