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Structural acoustics analysis and optimization of an enclosed box-damped structure based on response surface methodology

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A B S T R A C T

In this paper, the structural acoustics analysis and optimization of an enclosed box-damped structure are investigated by using the response surface methodology (RSM). Acoustic frequency response function analysis, i.e. a unit harmonic force imposing on structure and calculating the sound pressure in cavity, is applied to achieve the critical frequency. The acoustic sensitivity analysis of sound pressure level with respect to the thicknesses of damping layer panels are employed to identify the significant variables. With the help of faced central composite design, an efficient set of sample points are generated, and then the second order polynomial function of the sound pressure response at critical frequency is computed and verified by the adjusted coefficient of multiple determination. After the response surface function is verified, the effect of the thicknesses of damping layer panels on sound pressure is analyzed quantitatively, and the thicknesses of damping layer panels are further optimized to minimize the sound pressure response of the target node. The results indicate that, by using the RSM, the computational time for structural acoustic is saved and the optimization process is simple. The sound pressure of the target node is controlled effectively with less damping material used.

1. Introduction

There are numerous engineering applications of shell structures. The body of vehicle, aircraft and submarine are some examples for which evaluation of a structure-born acoustics in an enclosed cavity is very important. In general, these thin-walled structures are vulnerable to vibrate and radiate noise into the passenger compartment when they are excited by dynamic force, especially when the exciting frequency is close to the natural frequencies of shell structures or the air cavity. Thus, it is an important and meaningful task for engineers to investigate and control the sound radiation of shell structures.

Structure-born acoustics [1] which is a typical coupled vibro-acoustic problem, is characterized by the acoustic noise radiation from the vibrating panel structures into an enclosed cavity. The underlying physics governing of this dynamic behavior can be represented by the acoustic frequency response function (AFRF) [2]. In analyzing the AFRFs, the applications of finite element models (FE models) to both the body structure and cavity acoustics [3,4], and mixed finite-boundary element theory where the cavity acoustics is represented as a boundary element model (BE model) [5–7] are often employed. In order to control the vibration and reduce the noise radiation of thin-walled structures, the damping material is widely used and the literatures on this aspect are surprisingly voluminous. For surface damping treatments, literatures [8,9] analyzed the response of sandwich viscoelastic structures under dynamic loads to describe the behavior of different types of surface damping treatments. Refs [10,11] reduced the sound power radiated from plates by redistribution of the unconstrained damping layers. By using the FE method and panel acoustic contribution analysis, Han [12] pasted an equal thickness of damping layer at optimum locations to refine the interior sound field. The FE method or BE method have been applied to compute the vibro-acoustic problem successfully, which is a highly nonlinear process, while the optimization algorithm for reducing the structural acoustics is complex and time consuming, especially for a large complex structure.

However, the response surface methodology (RSM) in conjunction with FE method can be employed to compute and optimize the vibro-acoustic problem effectively, if the mathematical formulations of RS model close to the physics (being modelled) significantly. The RSM was first proposed by Box and Wilson in 1951 [13], and the article by Box and Hunter [14] provided an outline of the basic principles of RSM, i.e. fitting a response surface function (RS function) related the inputs and outputs using a small number of data sets which are chosen

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in the design space rigorously. Due to these superiorities, the RSM has been applied in many research fields such as the design of experiment (DOE) and analysis for engineering structure to reduce the vibration [15,16], optimal design of rocket injector, a failed clutch fork or viscoelastic damping structures [17–19], and structural safety and reliability analysis for frequency response functions calculation, buckling analysis or vehicle side impact crashworthiness [20–22], etc. Although the RSM has been successfully applied to reduce the structural vibration (e.g. Refs [15,16].) and analyze the acoustic frequency response function (e.g. Refs [6].), literatures about the optimization of damping layers for the control of structural-born acoustics, which is a coupled vibro-acoustic problem, are handful. For example, Refs [19] optimized the geometric parameters and material layout of viscoelastic damping structures to reduce vibration, while it is not a coupled vibro-acoustic problem and the RSM is not used. Literatures [23,24] investigated the function relationship between sound radiation power and three design variables (i.e. the thickness of base panel and damping panel, the material parameter of base panel), and the sound radiation level of the vibrating panel was obtained efficiently, while it only investigated the external acoustic of the structure and the effects of sound radiation on the structure vibration was not considered.

The current paper is partly motivated by these investigations and carries out related research. The RSM is employed to establish the function relationship between sound pressure response and the thicknesses of damping layers. The AFRF analysis and sensitivity analysis of sound pressure level with respect to the thicknesses of damping layers are used to obtain the critical frequency of interest and design factors respectively. The design of experiment (DOE) in conjunction with finite element method are conducted to obtain the data points for building response surface model (RS model).

2. Basic theory of response surface methodology

The RS model is a statistical approximation to the metamodels and it helps, when reasonably applied, to deal possibly with more configurations of the input parameters to be tested and explore deeply the domain of the problem's solutions. The construction process of a RS model for a coupled vibro-acoustic problem is illustrated as follows.

2.1. Construction of response surface function

If the sound pressure in cavity has been established by using the FE method, the relationship between sound pressure response at the critical frequency of interest denoted by y and the thicknesses of damping layer panels, which are screened out by using the acoustic sensitivity analysis, denoted by vector $\boldsymbol{x}$ $(x_1, x_2, \ldots, x_k)$ is

$$y = f(x_1, x_2, \ldots, x_k) + \varepsilon \tag{1}$$

where ε is the random experimental error term and its mean value is zero, $f(x_1, x_2, \ldots, x_k)$ is a function of $\boldsymbol{x}$ whose elements consist of powers and cross products of powers of $x_1, x_2, \ldots, x_k$ up to a certain degree. For many practical engineering applications, the order of polynomial of f $(x_1, x_2, \ldots, x_k)$ is not more than three [15,20,25,26]. In terms of the second-order RS function, the $f(x_1, x_2, \ldots, x_k)$ is expressed as

$$f(\mathbf{x}, \boldsymbol{\alpha}) = \alpha_0 + \sum_{i=1}^{k} \alpha_i x_i + \sum_{i=1}^{k} \alpha_{ii} {x_i}^2 + \sum_{i=1}^{k} \sum_{j<i} \alpha_{ij} x_i x_j \tag{2}$$

in which, $\boldsymbol{\alpha}$ are the regression coefficients to be solved. To estimate the unknown parameters vector $\boldsymbol{\alpha}$, a series of experiments are conducted and the corresponding responses y are measured at specified settings the thicknesses of damping panels. At the mth experimental run, the thickness of the ith damping panel is set to $x_i^{(m)}$ $(i = 1.2, \ldots, k, m = 1.2, \ldots, n)$ and $y^{(m)}$ denotes the corresponding response value. We then have

$$y^{(m)} = f\left(x_1^{(m)}, x_2^{(m)}, \ldots, x_k^{(m)}\right) + \varepsilon^{(m)} = \alpha_0 + \sum_{i=1}^{k} \alpha_i x_i^{(m)} + \sum_{i=1}^{k} \alpha_{ii} \left(x_i^{(m)}\right)^2 + \sum_{i=1}^{k} \sum_{j<i} \alpha_{ij} x_i^{(m)} x_j^{(m)} + \varepsilon^{(m)} \tag{3}$$

Eq. (3) can be rewritten in a matrix form as

$$\mathbf{y} = \mathbf{X}\boldsymbol{\alpha} + \boldsymbol{\varepsilon} \tag{4}$$

$$\mathbf{X} = \begin{bmatrix} 1 \; x_1^{(1)} \cdots x_k^{(1)} & \left(x_1^{(1)}\right)^2 \cdots \left(x_k^{(1)}\right)^2 & x_1^{(1)} x_2^{(1)} \cdots x_{k-1}^{(1)} x_k^{(1)} \\ \vdots \; \vdots \quad \vdots & \vdots \quad \vdots & \vdots \quad \vdots \\ 1 \; x_1^{(m)} \cdots x_k^{(m)} & \left(x_1^{(m)}\right)^2 \cdots \left(x_k^{(m)}\right)^2 & x_1^{(m)} x_2^{(m)} \cdots x_{k-1}^{(m)} x_k^{(m)} \\ \vdots \; \vdots \quad \vdots & \vdots \quad \vdots & \vdots \quad \vdots \\ 1 \; x_1^{(n)} \cdots x_k^{(n)} & \left(x_1^{(n)}\right)^2 \cdots \left(x_k^{(n)}\right)^2 & x_1^{(n)} x_2^{(n)} \cdots x_{k-1}^{(n)} x_k^{(n)} \end{bmatrix} \tag{4.1}$$

in which $\boldsymbol{X}$ is a matrix of order $n \times p$ $(p = (k+1)(k+2)/2)$, $\boldsymbol{y} = (y_1, y_2, \ldots, y_n)^{\mathrm{T}}$, $\boldsymbol{\varepsilon} = (\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_n)^{\mathrm{T}}$, and $\boldsymbol{\alpha} = (\alpha_0, \alpha_1, \ldots, \alpha_{ij})^{\mathrm{T}}$. From Eqs. (4) and (4.1), it should be noted that the number of unknown coefficients $\boldsymbol{\alpha}$ is $(k+1)(k+2)/2$,thus, to estimate these parameters, an equal or more number of experiment runs (i.e. $n \geq p$) are needed. The coefficient vector $\boldsymbol{\alpha}$ is estimated by the ordinary least-squares estimator [18,20] which are given by

$$\boldsymbol{\alpha} = \left(\mathbf{X}^{\mathrm{T}}\mathbf{X}\right)^{-1} \mathbf{X}^{\mathrm{T}}\mathbf{y}. \tag{5}$$

2.2. Faced central composite design

DOE is a collection and arrangement of experimental runs designed to gain the information most relevant to the project goals with a minimum of resource and time, and a poor distribution of data points in the design space will decrease the fidelity of the fitting response surface observably. Thus the faced central composite design (FCCD), which has two advantages, is employed in this paper to choose data points for obtaining high fidelity acoustics response surfaces. The first one is that, compared with the central composite design (CCD) [15,18,24], the axis points of the FCCD are set to the levels 1 or −1 to make all data points limited strictly in the design region (see Fig. 1), and more details referring to the literature [16]. The second one is that, compared with the full factorial design (FFD), the number of experiment runs of the FCCD is less. For example, as to a problem having the three-factors-three-levels, the number of experiment runs of the FFD is $3^k = 27$, while it is $2^k + 2k + 1 = 15$ for the FCCD. The use of FCCD drastically reduces the number of simulations required and saves the computational costs.

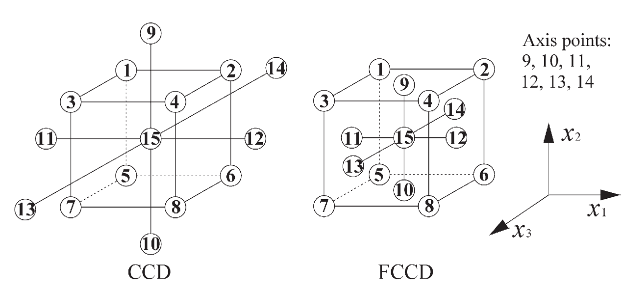

Fig. 1. Central composite design and faced central composite design (three-factors-three-levels).