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Dynamic response reliability based topological optimization of continuum structures involving multi-phase materials

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ABSTRACT

For the purpose of improving structural dynamic reliability, a topological optimization methodology for maximizing the dynamic response reliability index is proposed based on the bi-directional evolutionary structural optimization (BESO) method. The objective of the present study is to maximize the dynamic response reliability index at specified points on the structure under random excitation, subject to volume constraints on multi-phase materials over the admissible design domain. The sensitivity of the dynamic response reliability index with respect to the design variables is derived. The optimization procedure of the extended BESO method is presented. A series of numerical examples in both 2D and 3D are presented to demonstrate the effectiveness and efficiency of the proposed approach.

1. Introduction

Structural topology optimization has been an important design tool in the conceptual design phase. In essence, topology optimization is to find the optimal material distribution within a prescribed design domain in order to obtain the best structural performance. Since the original homogenization method was proposed, topology optimization techniques have developed in a number of different directions, including density method, level set method, topological derivative, phase field, evolutionary approaches and several others [1].

Previous research on topology optimization of continuum vibrating structures focused primarily on structural dynamic characteristics, including frequencies and frequency response. Xie and Steven [2,3] proposed ESO (evolutionary structural optimization) method to solve a wide range of frequency optimization problems, which include maximizing or minimizing a chosen frequency of a structure, keeping a chosen frequency constant, maximizing the gap of arbitrarily given two frequencies, as well as considerations of multiple frequency constraints. Zhao et al. [4,5] extended ESO method and investigated the effect of the element contribution factor to the natural frequency based on the energy conservation principle, simultaneously optimizing several different natural frequencies. Yang et al. [6] applied the bi-directional ESO (BESO) method to structural topology optimization subject to frequency constraints. Huang et al. [7] proposed a new BESO method based on a modified solid isotropic material with penalization (SIMP) model for the frequency optimization of continuum structures. Zuo et al. [8] extended BESO method to structural topology optimization with multiple displacement and frequency constraints. The main advantage in using the ESO method or its improved method-BESO method, lies in the fact that it is simple in concept and easy to be implemented and linked to existing finite element codes. Maeda et al. [9] designed the vibrating structures that targets desired eigenfrequencies and eigenmode shapes. Du et al. [10] developed a method to handle topology optimization problems associated with multiple eigenfrequencies so as to maximize specific eigenfrequencies and distance between two consecutive eigenfrequencies of the continuum structures. Tsai et al. [11] proposed a technique for determining the material distribution of a structure based on SIMP to obtain desired eigenmode shapes for problems of maximizing the fundamental eigenfrequency. Zhou [12] put forward a method to maximize the natural frequencies of vibration of truss-like continua with a constraint on the material volume. Yoon [13] used the topology optimization based on the internal element connectivity parameterization method for nonlinear dynamic problems, where element instability is avoided and

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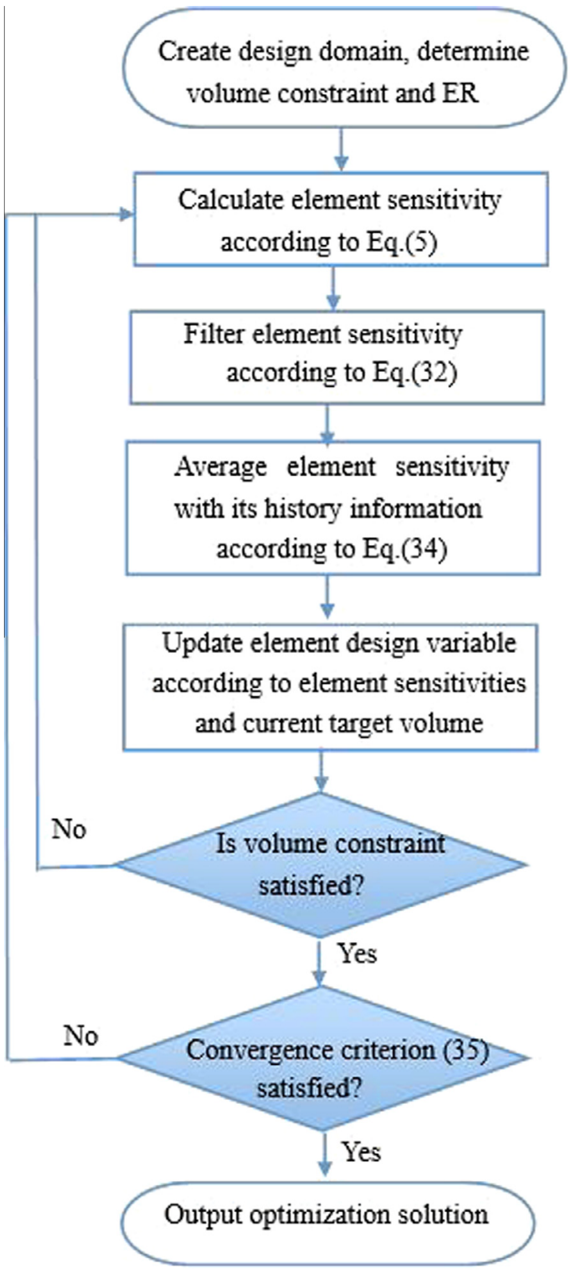

Fig. 1. Flow chart of the proposed BESO procedure.

localized vibration modes is controlled. Xu et al. [14] presented a bi-level optimization methodology for the non-probabilistic reliability optimization on frequency of continuum structures with uncertain-but-bounded parameters.

However, for the topology optimization of vibrating structures, it is necessary to consider several different problems: frequency response problem, transient response problem, and others besides the eigenvalue problem. These different problems may require different solution techniques, and solutions may be of very different natures. A modified optimality criteria method is developed for structural frequency response based topology optimization [15]. Jog [16] minimized the vibrations of structures subjected to periodic loading by topology optimization method. An efficient procedure based on frequency responses represented by Pade approximants for topology optimization of dynamics problems was proposed [17]. Yoon [18] pointed out that the Ritz vector and quasi-static Ritz vector methods can be used as two kinds of excellent model reduction schemes for stable optimization. Shu et al. [19] proposed level set based topology optimization method for minimizing frequency response. Vicente et al. [20] extended BESO method to optimize the frequency response of fluid–structure interaction systems by topology optimization. Further, the transient response analysis of engineering structures is related to both the external excitations and the inherent dynamic characteristics of the structure. Therefore, the dynamic response based topology optimization has been considered [21]. Rong et al. [22,23] used the ESO method and SQP method to obtain the optimal topology of the continuum structures under random excitations. Zhang et al. [24] proposed an efficient optimization procedure integrating pseudo excitation method and mode acceleration method for the topology optimization of large-scale structures subjected to stationary random excitation. In order to reduce the computational cost, Jang et al. [25] presented an equivalent static load method in time domain for dynamic response based topology optimization problem. However, no attempts have been made on the dynamic reliability based topology optimization. The optimum design of structures considering dynamic response reliability is of great importance, particularly in the aeronautical and automotive industries.

This paper is composed as follows: In Section 2, the general topology optimization problem on structural dynamic response reliability is introduced. The sensitivity of dynamic response reliability index with respect to the design variables is derived in Section 3. In Section 4, the numerical techniques and the optimization procedure based on the BESO method are presented. In Section 5, a series of numerical examples in 2D and 3D are presented. Conclusions are drawn in Section 6.

2. Optimization problem statement

The dynamic response reliability based topology optimization problem for continuum structures with multi-phase materials can be formulated as follows

$$\text{Maximize}: \; P(\boldsymbol{\alpha})$$
$$\text{subject to}\begin{cases} V_q^* - \sum_{i=1}^{N_e} \alpha_{i1}\alpha_{i2}\cdots\alpha_{i(q-1)}(1-\alpha_{iq})V_i = 0 \quad q = 1,2,\cdots,n-1 \\ V_n^* - \sum_{i=1}^{N_e} \alpha_{i1}\alpha_{i2}\cdots\alpha_{in}V_i = 0 \\ \mathbf{M}\ddot{\mathbf{X}} + \mathbf{C}\dot{\mathbf{X}} + \mathbf{K}\mathbf{X} = \mathbf{f}(t) \\ \alpha_{ij} = 0 \text{ or } 1 \end{cases} \tag{1}$$

where $P(\boldsymbol{\alpha})$ is the dynamic response reliability index corresponding to the specified points or surfaces on the structure under random excitation. V_i is the volume of element i, V_q^* is the prescribed volume for phase material q and n is the total number of material phases. α_{ij} is the design variable as defined in [26]. $\mathbf{X}$, $\dot{\mathbf{X}}$ and $\ddot{\mathbf{X}}$ are the system displacement, velocity and acceleration vectors. $\mathbf{f}(t)$ is the external force vector. $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the system mass, damping and stiffness matrices. The system stiffness and mass matrices can be respectively expressed as

$$\mathbf{K} = \sum_{i=1}^{N_e} \int_{\Omega_i} \mathbf{B}^T \Big\{ (1-\alpha_{i1}^{\eta_1})\mathbf{D}_1 + \sum_{q=2}^{n-1} \Big[(\alpha_{i1})^{\eta_1} \cdots (\alpha_{i(q-1)})^{\eta_{(q-1)}} (1-\alpha_{iq}^{\eta_q})\mathbf{D}_q \Big] + (\alpha_{i1})^{\eta_1}(\alpha_{i2})^{\eta_2}\cdots(\alpha_{in})^{\eta_n}\mathbf{D}_n \Big\} \mathbf{B}dV \tag{2}$$

$$\mathbf{M} = \sum_{i=1}^{N_e} \int_{\Omega_i} \mathbf{N}^T \Big\{ (1-\alpha_{i1}^{\theta_1})\rho_1 + \sum_{q=2}^{n-1} \Big[(\alpha_{i1})^{\theta_1} \cdots (\alpha_{i(q-1)})^{\theta_{(q-1)}} (1-\alpha_{iq}^{\theta_q})\rho_q \Big] + (\alpha_{i1})^{\theta_1}(\alpha_{i2})^{\theta_2}\cdots(\alpha_{in})^{\theta_n}\rho_n \Big\} \mathbf{N}dV \tag{3}$$