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Layout optimization of multi-component structures under static loads and random excitations

Zhang Qiao, Zhang Weihong *, Zhu Jihong, Gao Tong

Engineering Simulation and Aerospace Computing (ESAC), School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, China

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ABSTRACT

Integrated layout optimization of multi-component structures under static loads and random excitations is studied in this paper. Dynamic responses are obtained by using the mode superposition method, and the prestress effect introduced by the static loads is taken into account in the analyses of dynamic responses. Locations of embedded components and pseudo-densities related to supporting structure are chosen as design variables. Design sensitivities of the dynamic responses with respect to the pseudo-densities are analytically derived. The optimization algorithm GCMMA (Global Convergent Method of Moving Asymptotes algorithm) is used to minimize simultaneously the static strain energy and dynamic responses. Three numerical examples are presented to show the validity of the optimization procedure and its potential application in practical designs.

1. Introduction

A multi-component structure is basically composed of a certain number of components with specific geometries and the support structure that interconnects the components as integrity. Most of the engineering structures involved in mechanism, automotive and aerospace products fall into this category where design compactness, structural efficiency, static and dynamic responses have to be optimized for the functionality requirements and mechanical performances. The traditional idea of topology optimization mainly concerned the optimal material layout over a prescribed design domain with given loads and boundary conditions, while locations and orientations of involved components are normally assumed to be non-designable. In the work of Johanson et al. [1], two or more components supported with flanges of specific locations were designed by topology optimization to improve the compliance of the overall structure. Jiang and Chirehdast [2] optimized the distribution of the connections for components of fixed geometry. Chickermane and Gea [3], Qian and Ananthasuresh [4] assigned each component and its connections as sub-design domain for topology optimization. Similarly, Li et al. [5] extended the ESO (Evolutionary Structural Optimization) method to the stress minimization for which component topologies and distributions of the connections are optimized. Khalaf and Saka [6] applied the ESO method in the stress design of steel gusset plates. Lyu and Saitou [7], Yildiz and Saitou [8], and Ma et al. [9] further presented optimal designs of multi-component beams with subdivided design domains and multiple material properties. Very recently, Zhu et al. [10–12] proposed the concept of integrated layout design of multi-component structure. The configuration of the design domain and the locations of the embedded components were simultaneously optimized to minimize the structural compliance. By defining the location and orientation of each component as geometric design variables, the optimal placements of these components are sought for subjected to geometric constraints for the overlap avoidance between the components. Meanwhile, topology optimization method is applied to optimize the material layout of the supporting structure that interconnects components.

However, most of the existing works mentioned above were focused on topology optimization problems in static loading cases. In practice, many engineering structures such as solar panels and antennas of aerospace structures experience not only static loads but also random excitations. To a large extent, some secondary structural designs are mostly based on random excitations [13]. As a result, some dynamic performances are introduced into the optimization problems [14,15], while the results related to dynamic responses topology optimization are few. Rong et al. [16] optimized the structural topology using ESO method where dynamic responses are assigned as design constraints. Later, Yang et al. [17] studied the topology optimization under static loads and narrow-band random excitations, where the static and dynamic response analyses were processed independently without any superposition. In fact, the dynamic response analysis and the

* Corresponding author.
E-mail addresses: zhq198466@163.com (Z. Qiao), Zhangwh@nwpu.edu.cn (Z. Weihong), JH.Zhu_FEA@nwpu.edu.cn (Z. Jihong), gaotong216@gmail.com (G. Tong).

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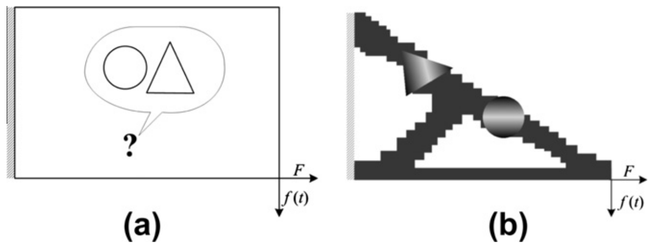

Fig. 1. Illustration of the multi-component structural optimization problem. (a) Problem definition. (b) Illustrative optimal design.

calculation of the corresponding design sensitivities become complicated when the static loads and random excitations are applied simultaneously. For beam and plate structures, when axial or in-plane static loads exist, the natural frequencies of the structures will be changed, and the geometrical stiffness must be considered in the equation of motion [18] during the dynamic response analysis. For example, Behzad and Bastami [19] found that the natural frequencies of long high-speed shaft are greatly influenced by the axial stress generated by the shaft rotation. Likewise, Bonakdar and Ahmadian [20] proved that the natural frequencies are influenced considerably by the centrifugal force. Chen et al. [21] indicated that the initial static load has a great influence on both the energy and dynamic responses of rock. Leissa [22] and Murphy et al. [23] studied the effect of in-plane forces upon the vibration of plates. Actually, there exist two different approaches that take into account the effect of static loads on the dynamic characteristics and responses. One is to carry out static and dynamic analyses, independently. The obtained responses are simply superposed to generate the final dynamic response [24]. This method is only applicable for linear structures. It is also found that the superposition is cost-ineffective for large-scale structures. The other one is suitable to both linear and non-linear structures without responses superposition because the prestress caused by the static loads is introduced into the dynamic response analysis. As illustrated in Fig. 1, the purpose of this work is to find the optimal placements of the components and the configuration of the supporting structure within a predefined design domain to improve the structural static and dynamic responses simultaneously. Meanwhile, both the static load F and the random excitation $f(t)$ are applied.

2. Responses optimization of multi-component structures

Since previously proposed techniques such as finite-circle method, density points, embedded meshing etc. are detailed in the previous works [10–12,25], only a brief description of the modeling process is presented here. On the other hand, the method for dynamic responses analyses were completely developed [26–28], and the mode superposition method was used to calculate the dynamic responses of structure.

2.1. Modeling process

To define a multi-component structural optimization problem, the placements of the components as well as the material distribution of the supporting structure have to be described with different kinds of design variables. Suppose there are n_c components, and the design domain is discretized with finite elements. Three geometrical design variables $(x_\varepsilon, y_\varepsilon, \theta_\varepsilon)$ are used to determine the position and orientation of the εth component $(\varepsilon = 1, 2, \ldots, n_c)$, where $(x_\varepsilon, y_\varepsilon)$ denotes the center point location of the εth component and θ_ε denotes the angle from the global coordinate to the local coordinate. The pseudo-densities η_j $(j = 1, 2, \ldots, n_d)$ are used to describe the material distribution of the supporting structure. Considering the simultaneous updating of the geometrical variables and the pseudo-densities during the iteration, the finite element model has to be rebuilt accordingly. The modeling process is outlined below:

(1) The design domain is firstly discretized with n_d fine elements, referred to as the basic mesh, as shown in Fig. 2a, where n_d density points are defined as fixed points located at the centers of the elements in the basic mesh. The pseudo-densities η_j $(j = 1, 2, \ldots, n_d)$ are then attached to density points.
(2) As shown in Fig. 2b, the εth component is located over the basic mesh according to its placement $(x_\varepsilon, y_\varepsilon, \theta_\varepsilon)$, then the finite elements are remeshed locally as shown in Fig. 2c to achieve a consistent finite element model.
(3) As shown in Fig. 2d, each finite element of the supporting structure is dominated by the nearest density point and receives the value of the pseudo-density η_j from the latter. Meanwhile, elements inside a component will be assigned by the material properties of the component itself.

With this procedure, the basic mesh will be simply restored whenever the position of each component changes. A remeshing is only needed for the affected elements around the components.

2.2. Geometrical constraints

For more than one component located in the design domain, some geometrical constraints have to be defined to avoid the overlapping. There are actually two kinds of geometrical constraints, i.e. the non-overlapping constraints between the components and the non-interference constraints between the components and the boundaries of the design domain. In this paper, both kinds of geometrical constraints are approximated using the Finite Circle Method (FCM) [25]. As shown in Fig. 3, a triangular component and a circular component and the boundaries of the rectangular design domain are approximated with a group of circles.

Consequently, these geometrical constraints are transformed into the non-overlapping constraints between different circles.

$$\begin{cases} \forall\varepsilon = 1, 2, \ldots, n_c;\ \varsigma = 1, 2, \ldots, m_\varepsilon;\ \forall\tau = 1, 2, \ldots, m_D; \\ \text{s.t.}: \quad \|O_{\varepsilon\_\varsigma}O_\tau\| \geqslant R_{\varepsilon\_\varsigma} + R_\tau \\ \forall\varepsilon1 = 1, 2, \ldots, n_c;\ \varepsilon2 = 1, 2, \ldots, n_c;\ \varepsilon1 \neq \varepsilon2; \\ \forall\varsigma1 = 1, 2, \ldots, m_{\varepsilon1};\ \varsigma2 = 1, 2, \ldots, m_{\varepsilon2}; \\ \text{s.t.}: \quad \|O_{\varepsilon1\_\varsigma1}O_{\varepsilon2\_\varsigma2}\| \geqslant R_{\varepsilon1\_\varsigma1} + R_{\varepsilon2\_\varsigma2} \end{cases} \tag{1}$$

where $O_{\varepsilon\_\varsigma}$ is the ςth circle center defined on the εth component, and $R_{\varepsilon\_\varsigma}$ is the corresponding radius. m_ε is the number of circles used to approximate the εth component. O_τ is the τth circle center for the design domain contour, and R_τ is the corresponding radius. m_D is the number of circles used to approximate the boundaries of the design domain.

Thus, the non-overlapping constraints are approximately transformed into some explicit and differentiable functions defined by the geometrical design variables $(x_\varepsilon, y_\varepsilon, \theta_\varepsilon)$ and can be dealt with easily. Notice that the approximation error can be improved by adjusting the numbers, radii and positions of the circles.

2.3. Structural analysis under static loads and random excitations

2.3.1. Static strain energy

The static equilibrium equation of a structure is expressed as

$$[K]\{U\} = \{F\} \tag{2}$$

where $\{F\}$ denotes the static force vector, $\{U\}$ is the nodal displacement vector, and $[K]$ is the global elastic stiffness matrix. The static strain energy E, i.e. the compliance is calculated by