CONCURRENT MULTI-SCALE OPTIMIZATION DESIGN OF COMPOSITE FRAME STRUCTURES WITH MAXIMUM FUNDAMENTAL FREQUENCY

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Keywords: Composite frame, Multi-scale optimization, Fundamental frequency maximization, Fiber winding angle, Semi-analytical sensitivity analysis

ABSTRACT

Glass or carbon fiber reinforced composite frames are ideal lightweight and high-span structures in the field of aerospace. Fundamental frequency is a key performance indicator in the process of the composite frame structure design. Increasing the value of fundamental frequency of the frames could avoid the phenomenon of structural resonance. Based on the structure and material concurrent optimization concept, the concurrent multi-scale optimization design for the maximum fundamental frequency of fiber reinforced frame structure is proposed. An optimization model based on the maximum structural fundamental frequency and the specified fiber material volume constraint has been established. The objective function sensitivity information about the two geometrical scales design variables are deduced with semi-analytical method. Numerical example in the paper shows that the concurrent multi-scale optimization for the maximum fundamental frequency can further explore the coupling effect between the macro-structure and micro-material to increase the fundamental frequency. The new two geometrical scales optimization model provides a choice for the design of composite frame structure in aerospace and other industries.

1 INTRODUCTION

Frame structures composed of glass or carbon fiber reinforced polymers (GFRP/CFRP) have been extensively used in aerospace vehicles [1], such as main load-bearing structure of satellite and space stations [2, 3], where large-scale space, high strength, high stiffness and light weight are emphasized. In the most above application cases, frame structures should be designed as light as possible in order to reduce the total structural weight. On the other hand, one of the most important design criterions of composite frame structures is the dynamic performance. The uaual demand is that the natural frequency should be away from the frequency of the exciting force or the frequency bandwidth of the servo system to avoid the severe structural resonance.

The pioneering work about the truss structure layout optimization can be traced back to Michell [4] in 1904 considering equal tension and compression stress constraints. Takezawa et al. [5] minimized structural compliance and maximized fundamental frequency with the moment of inertia of the beam cross-section as design variables. Pedersen and Nielsen [6] studied the simultaneous size, shape, and topology optimization of three dimensional truss structures considering displacement, stress, stability, and frequency as constraints where the cross-section areas of the truss bars and the joint positions were considered as design variables. Liu et al. [7] adopted the automatic grouping genetic algorithm with improvements in crossover operator and penalty function to study the singular optimum topology of skeletal structures with frequency constraints. Ni et al. [8] proposed some particular forms of area/moment of inertia-density interpolation schemes to overcome the strongly singular difficulty in the topology optimization of skeletal structures with exact frequency constraints. Kanno [9] considered the global optimization of a frame structure by formulating the compliance minimization with discrete design variables as a mixed-integer second-order cone programming problem. At the same time, some researchers applied a variety of evolutionary techniques to solve the frequency optimization problem of the isotropic material truss [10, 11].

The GFRP/CFRP composite frame is a kind of structural material that means the designers can tailor the material properties in the micro-material scale. The fiber winding parameters (fiber winding angle, winding thickness and winding ply stacking sequence) of the composite frames have an obvious influence on the structural stiffness. The characteristic provides designers with larger design space to meet the specific performance requirements of structural lightweight design such as the optimization of compliance, stress and natural frequency by adjusting the microscopic parameters of the laminates of frames. Many researchers have carried out corresponding optimal design of composite structures. Bert [12] maximized the fundamental frequency of composite laminates considering the fiber orientation angles in each layer as continuous design variables. Fukunaga et al. [13] adopted four kinds of lamination parameters as design variables to study the maximum fundamental frequency problem of symmetric laminates and considered coupling effects of bending and warping in the vibration analysis. Kam et al. [14] realized the dynamic optimization design of medium thickness composite laminates with the length-width ratio, fiber ply thickness and fiber angle as design variables by using a global constrained optimization method. Abdalla et al. [15] used lamination parameters to maximize fundamental frequency of variable stiffness composite panels with the fiber orientation and the fiber volume fraction as design variables. Bruyneel et al. [16] realized the optimal stacking sequence design of laminated composites while considering several manufacturing constraints adopting SFP interpolation scheme. Sørensen and Lund et al. [17, 18] carried out the serial works on thickness and material choice design of laminated composites with certain manufacturing constraints.

Taking above problems into consideration, the multi-scale design optimization method of structure has already become an active research area covering a variety of the physical problems, which optimizes the structural configuration and material parameters concurrently. Du [19] pointed out that the concurrent optimization with material and structure is a new way for structural lightweight design. Ashby [20] proposed that a more efficient design was taking both the macro-structure configuration and micro-material selection into account. Thus it is important for lightweight design of composite materials to achieve the coupling effect between the two kinds of variables above in two geometrical scales and maximize the potential property of structures and materials. Rodrigues [21] adopted a hierarchical method to optimize porous materials and structures. Ferreira et al. [22] considered the cross section of reinforcing fibers as the microscopic design variables and presented a simultaneous macroscopic and microscopic design of composite structures. Liu et al. [23] adopted SIMP and PAMP penalization approaches in micro-scale and macro-scale respectively, to realize the concurrent topology optimization of ultra-light structures. Deng et al. [24] applied the concurrent optimization model to study multi-objective design of thermo-elastic structures composed of homogeneous porous material. Gao and Zhang [25] proposed an efficient scheme to optimize the layout design of structures composed of multiphase material under the mass constraint. Niu et al. [26] presented a two-scale optimization method to realize the optimization of cellular materials to maximize the structural fundamental frequency. Recently, An et al. [27, 28] implemented an adaptive genetic algorithm to achieve the simultaneous optimization of stacking sequence and cross-section size of composite laminates. Yan et al. [29] proposed a concurrent topology optimization method for structure and material to minimize the compliance of thermo-elastic structures composed by cellular materials. Duan et al. [30] introduced the modified Heaviside penalty function to replace the polynomial material interpolation formula in the classical DMO, and proposed an improved discrete material penalty model labeled as HPDMO. The HPDMO method is adopted in that paper to realize the micro-scale optimization of the discrete fiber winding angle. Based on the HPDMO method, Yan et al. [31] considered the macro tube radius and the micro fiber winding angle as the independent design variables, respectively, and realized the concurrent optimization of composite frame structures with minimum structural compliance.

As an extension of the concurrent optimization of composite frame structures with minimum structural compliance [31], the present paper proposed a concurrent multi-scale optimization model of composite frame structures with respect to maximum fundamental frequency under the specified volume constraint considering the coupling effects between the macro-structure and micro-material. The inner radius of circular tube's cross-section and fiber winding angle are introduced as independent design variables in the macro- and micro-scale.

The organization of the remainder parts of the paper is as follows. The concurrent multi-scale optimization concept with maximum fundamental frequency is described in Section 2. In Section 3, the mathematical formula of maximizing the fundamental frequency and the sensitivity analysis are introduced. Section 4 presents the multi-scale concurrent optimization results. Finally, a series of conclusions are proposed.

2 CONCURRENT MULTI-SCALE OPTIMAL DESIGN OF COMPOSITE FRAMES

Innovative structural configuration and material selection are often carried out independently in traditional structure optimization which generally requires a large number of iterations and spends lots of time and computing resources. Regarding composite frame structures, both the micro fiber ply parameters (fiber winding angle, layer thickness and ply stacking sequence) and the macro structural characteristics (area of cross section and topology configuration) have an obvious influence on the dynamic performance of the frame structure. Thus a concurrent optimization model with maximum fundamental natural frequency is proposed to adequately consider the coupling effect of macro and micro design variables and take advantage of the potential of composite structures.

Considering the actual applications in the practical engineering, frames made of tubes with constant circular cross-sections and a fixed number of layers are investigated in the present paper. The joints connecting the composite tubes can transfer moments and are assumed infinitely stiff. Figure 1 shows the concurrent optimization schematic of the composite frame structure and material considering the dynamics frequency performance. In macro-scale, the inner radii of the circular cross-section (r_i) are considered as macro design variables. The same as the classical topology optimization of the frame structure, when the area of a macro tube's cross-section attains the lower limit, the tube can be regarded to be deleted from the original ground structure shown as the dotted line tube. Thus the size optimization and topology optimization of macroscopic structure configuration are achieved. In micro-scale, the continuous fiber winding angles ($\theta_{i,j}$) are considered as microscopic design variables, and the optimal microscopic fiber winding angles under specific load conditions can be attained.

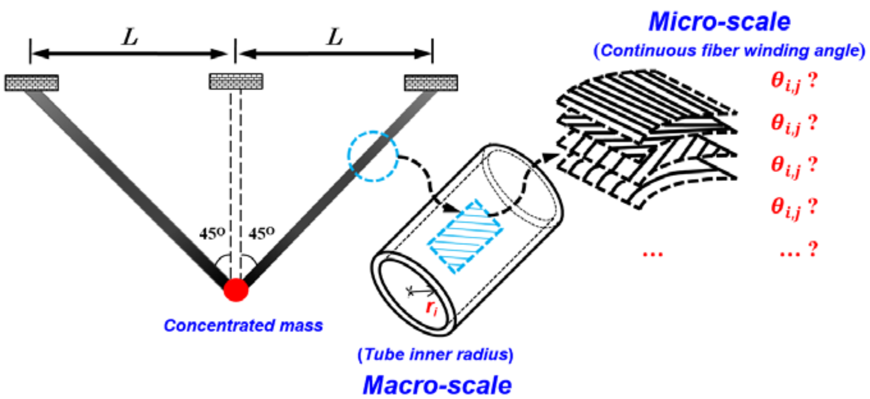


Figure 1: Schematic of two-scale optimization of the composite frame.

3 COMPOSITE FRAME ANALYSIS AND OPTIMIZATION FORMULA

3.1 Mathematical formula of maximizing the fundamental frequency

In the paper, we establish the concurrent multi-scale optimization model of the composites frame with the objective of maximizing the fundamental frequency under the total volume constraint. The coupling effect of macro- and micro-scale design variables can be fully considered to further explore the potential of composite structures. The mathematical formula of the optimization problem can be expressed as follows:

$$\text{find} \quad \boldsymbol{X} = \{r_i, \theta_{ij}\} \tag{1}$$

$$\max \quad f = \omega_1^2(r_i, \theta_{i,j}) \tag{2}$$

$$\text{s.t.} \quad \left.\begin{array}{l} \boldsymbol{K\Phi}_k = \omega_k^2 \boldsymbol{M\Phi}_k \\ V(r_i) = \sum_{i=1}^{N^{Tub}} \pi \left[{t_{tot}^i}^2 + 2 r_i t_{tot}^i \right] \mathrm{L}_i \le \bar{V} \\ -90^\circ \le \theta_{i,j} \le 90^\circ \\ r_{\min} \le r_i \le r_{\max} \\ i = 1,2,\dots,N^{Tub}, j = 1,2,\dots,N^{Lay} \end{array}\right\} \tag{3}$$

where $f = \omega_1^2(r_i, \theta_{ij})$ is the objective function. ω_1 is the fundamental natural frequency. The macro-scale design variable r_i is the inner radius of the composite tubes with circular section. The micro-scale design variable $\theta_{i,j}$ is the continuous fiber winding angle, where the subscript i and j denote the number of tubes and layers respectively. ω_k is the kth order frequency and $\boldsymbol{\Phi}_k$ is the corresponding eigenvector. $\boldsymbol{K}$ and $\boldsymbol{M}$ are the symmetric and positive definite stiffness and mass matrix. t_{tot}^i is the total layer thickness of the ith composite tube. L_i denotes the length of the ith tube. N^{Tub} and N^{Lay} denote the total number of tubes and layers. $\bar{V}$ is the entire volume of the macro-design domain. In the paper, all the physical quantities are dimensionless. $r_{\max}$ ($r_{\max} = 0.2$ in present paper) is the upper limit of the radius. $r_{\min}$ ($r_{\min} = 0.0001$) is a small positive value to avoid the singularity during the optimization iterations.

Considering the realization of the topology optimization and the harmonious relation about the radius and thickness of the tube in the practical engineering, in this paper, we adopt a punitive relationship between the winding layer thickness and the tube's inner radius as follows:

$$\tilde{t}_i = (r_i/r_0)^\alpha \times t_0 \qquad \text{if } r_i < r_0 \tag{4}$$

where $\tilde{t}_i$ is the layer thickness of tube i after the punishment. r_i is the inner radius of tube i in the current iteration. r_0 is the initial inner radius of the tube. α is the punitive ratio and we set $\alpha = 1$ in the paper. Through the punitive relationship, the layer thickness change with the inner radius of each tube when the inner radius is lower then initial value, so that we can establish an adaptive process within macro radius and layer thickness. Based on the ground structure approach of topology optimization [32, 33], the decrease of the macro radius proves that the tube has lower contribution to the stiffness of the whole structure, so that we can give more material to the other tubes to improve the stiffness by decreasing the layer thickness of the weak one. When the macro radius is close to the lower limit, the layer thickness is small enough to be deleted. In this way, we can not only achieve the topology optimization, but also reduce the amount of calculation considering the thickness to improve the optimization iterative efficiency.

3.2 Composite frame analysis

The response analysis of composite frame structure is based upon the extension of the beam finite element tool named BEam Cross section Analysis Software (BECAS) which was presented by Blasques [34]. BECAS is a powerful analysis tool for anisotropic and inhomogeneous beam with arbitrary geometry sections. It has been successfully used by Blasques and Stolpe [35], Blasques [36] to compute the multi-material topology optimization of the wind turbine blade with respect to static and dynamic problems. In the present paper, the BECAS analysis tool is extended to deal with the composite frame structure with discrete material interpolation scheme. More detailed descriptions about the BECAS, please refer to the references (Blasques [34]; Blasques and Stolpe [35]; Blasques [36]).

3.3 Sensitivity analysis

In order to perform gradient-based optimization efficiently, the work adopts the semi-analytical method (SAM) (Lund [37]; Cheng and Olhoff [38]; Blasques and Stolpe [39]) which has high computational efficiency and wide applications in the sensitivity analysis of finite element models. This section only presents the fundamental frequency sensitivity analysis with respect to the micro design variable $\theta_{i,j}$. The sensitivity about the macro-scale design variable r_i can be obtained in a similar procedure. The direct approach to obtain the eigenvalue sensitivities is to differentiate the generalized vibration eigenvalue equation without damping $\boldsymbol{K\Phi}_k = \omega_k^2 \boldsymbol{M\Phi}_k$ with respect to the design variable $\theta_{i,j}$ as given as Eq. (5):

$$\frac{\partial \boldsymbol{K}}{\partial \theta_{i,j}} \boldsymbol{\Phi}_k + \boldsymbol{K} \frac{\partial \boldsymbol{\Phi}_k}{\partial \theta_{i,j}} = \frac{\partial \omega_k^2}{\partial \theta_{i,j}} \boldsymbol{M\Phi}_k + \omega_k^2 \frac{\partial \boldsymbol{M}}{\partial \theta_{i,j}} \boldsymbol{\Phi}_k + \omega_k^2 \boldsymbol{M} \frac{\partial \boldsymbol{\Phi}_k}{\partial \theta_{i,j}} \tag{5}$$

Pre-multiplying Eq. (5) by ${\boldsymbol{\Phi}_k}^{\mathrm{T}}$, we can get Eq. (6):

$${\boldsymbol{\Phi}_k}^T \frac{\partial \boldsymbol{K}}{\partial \theta_{i,j}} \boldsymbol{\Phi}_k + {\boldsymbol{\Phi}_k}^T \boldsymbol{K} \frac{\partial \boldsymbol{\Phi}_k}{\partial \theta_{i,j}} = {\boldsymbol{\Phi}_k}^T \boldsymbol{M\Phi}_k \frac{\partial \omega_k^2}{\partial \theta_{i,j}} + \omega_k^2 {\boldsymbol{\Phi}_k}^T \frac{\partial \boldsymbol{M}}{\partial \theta_{i,j}} \boldsymbol{\Phi}_k + \omega_k^2 {\boldsymbol{\Phi}_k}^T \boldsymbol{M} \frac{\partial \boldsymbol{\Phi}_k}{\partial \theta_{i,j}} \tag{6}$$

Pre-multiplying $\boldsymbol{K\Phi}_k = \omega_k^2 \boldsymbol{M\Phi}_k$ by $\left(\frac{\partial \boldsymbol{\Phi}_k}{\partial \theta_{i,j}}\right)^{\mathrm{T}}$, we can obtain Eq. (7):

$$\left(\frac{\partial \boldsymbol{\Phi}_k}{\partial \theta_{i,j}}\right)^{\mathrm{T}} \boldsymbol{K\Phi}_k = \omega_k^2 \left(\frac{\partial \boldsymbol{\Phi}_k}{\partial \theta_{i,j}}\right)^{\mathrm{T}} \boldsymbol{M\Phi}_k \tag{7}$$

Then the sensitivity of the fundamental frequency with respect to micro-scale design variables can be further expressed as Eq. (8) by substituting Eq. (7) into Eq. (6).

$$\frac{\partial \omega_k^2}{\partial \theta_{i,j}} = \frac{{\boldsymbol{\Phi}_k}^{\mathrm{T}} \frac{\partial \boldsymbol{K}}{\partial \theta_{i,j}} \boldsymbol{\Phi}_k - \omega_k^2 {\boldsymbol{\Phi}_k}^{\mathrm{T}} \frac{\partial \boldsymbol{M}}{\partial \theta_{i,j}} \boldsymbol{\Phi}_k}{{\boldsymbol{\Phi}_k}^{\mathrm{T}} \boldsymbol{M\Phi}_k} \tag{8}$$

Adopt the mass-normalized mode shape $\widehat{\boldsymbol{\Phi}}_k$, which satisfies ${\widehat{\boldsymbol{\Phi}}_k}^{\mathrm{T}} \boldsymbol{M} \widehat{\boldsymbol{\Phi}}_k = 1$, then Eq. (8) can be written as Eq. (9).

$$\frac{\partial \omega_k^2}{\partial \theta_{i,j}} = {\widehat{\boldsymbol{\Phi}}_k}^{\mathrm{T}} \frac{\partial \boldsymbol{K}}{\partial \theta_{i,j}} \widehat{\boldsymbol{\Phi}}_k - \omega_k^2 {\widehat{\boldsymbol{\Phi}}_k}^{\mathrm{T}} \frac{\partial \boldsymbol{M}}{\partial \theta_{i,j}} \widehat{\boldsymbol{\Phi}}_k \tag{9}$$

In the current implementation, the sensitivities $\frac{\partial \boldsymbol{K}}{\partial \theta_{i,j}}$ and $\frac{\partial \boldsymbol{M}}{\partial \theta_{i,j}}$ are determined by semi-analytical forward differences. The approach has higher computational efficiency than the OFD (overall finite difference) method, because the computation of the frequency equation with global stiffness and mass matrices, which is the most time-consuming part in the optimization, will be only calculated once for N design variables. Contrarily, in the OFD method, the frequency equation needs to be calculated at least $\mathrm{N}+1$ times for N design variables. Actually, the mass matrix $\boldsymbol{M}$ is independent of $\theta_{i,j}$ in this work. The sensitivity of $\boldsymbol{K}$ with respect to micro variables $\theta_{i,j}$ is expressed as follows:

$$\frac{\partial \boldsymbol{K}(\theta_{i,j})}{\partial \theta_{i,j}} \approx \frac{\boldsymbol{K}\left((\theta_{i,j}) + \mathrm{s} \cdot \theta_{i,j}\right) - \boldsymbol{K}(\theta_{i,j})}{\mathrm{s} \cdot \theta_{i,j}} \tag{10}$$

where s represents the step factor and has been set to 1×10^{-6} in this implementation. Then the sensitivity of the fundamental frequency with respect to r_i can be obtained in a similar procedure as $\theta_{i,j}$.

The global volume constraint in Eq. (3) is only a function of the macro radius design variables. The sensitivity of the volume with respect to the radius r_i of the frame can be easily obtained as

$$\frac{\partial V(r_i)}{\partial r_i} = 2\pi r_i \frac{t_{tot}^i}{r_i^0}\left(\frac{t_{tot}^i}{r_i^0} + 2\right)\mathrm{L}_i \tag{11}$$

where t_{tot}^i and r_i^0 are the original total layer thickness and inner radius.

4 NUMERICAL EXAMPLES AND DISCUSSIONS

To confirm the effectiveness of the concurrent multi-scale optimization model of composite frame structures with maximum fundamental frequency proposed in present paper, this section shows the numerical example of spatial sixteen-tube structure. The previous literatures [30, 31] had detailed descriptions about the single- and multi-scale optimization of composite material structures, and pointed out the advantage of the concurrent multi-scale optimization design. Therefore, the present paper will only presents the concurrent multi-scale optimization results of composite frame structures with maximum fundamental frequency. More about the comparisons about the single- and multi-scale optimization please refer to the literatures [30, 31].

The Loading/boundary conditions and geometric sizes of the spatial sixteen-tube composite frame are shown in Figure 2. The red marks in the picture are concentrated mass on the nodes which have the magnitude of 30. The bottom parts of the structure are fixed. Adopting the concurrent two-scale optimization model like Eqs. (1)-(3), we achieve the concurrent multi-scale optimization of composite frame with maximum fundamental frequency under the material volume constraint.

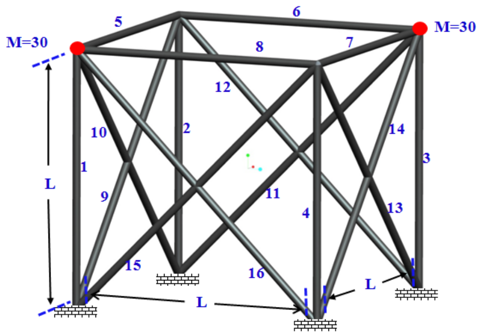


Figure 2: The example of sixteen-tube composite frame structures.

The orthotropic properties of the fiber reinforced composites are as follows: $\mathrm{E}_{11} = 1.43\mathrm{E}11$, $\mathrm{E}_{22} = 10\mathrm{E}9$, $\upsilon_{12} = 0.25$, $\mathrm{G}_{12} = 6\mathrm{E}9$, $\mathrm{G}_{23} = 5\mathrm{E}9$, $\rho = 2900$. Every tube is assumed to be composed with ten winding layers. The initial layer thickness and inner radius of the circular tube are assumed as $t_0 = 0.008$, $r_0 = 0.2$, respectively. The inner tube radii r_i are chosen as the macro-scale design variables, and the value range is $0.0001 \leq r_i \leq 0.2$. The fiber winding angles $\theta_{i,j}$ are chosen as the micro-scale design variables, and the value range is $-90^{\circ} \leq \theta_{i,j} \leq 90^{\circ}$ with the initial angle $\theta_{i,j} = 45°$. The 0° winding angle means fiber is along the tube's axial direction. The volume constraint is the total amount of the composite material, $V(r_i) = \sum_{n=1}^{N^{Tub}} v_n \leq \bar{V}$, and $\bar{V}$ is the upper limit which is taken as the initial structural volume.

Table 1 shows the concurrent optimization results of the sixteen-tube composite frame with the macro variable r_i and the micro variable $\theta_{i,j}$.

Tube number	Optimized macro variables r_i	Optimized fiber winding angle/ °
1	0.0578	-3/-4/-4/-4/0/0/0/0/0/0
2	0.0531	-6/-6/-6/-4/-5/-4/0/0/0/0
3	0.0655	-2/-3/-3/-2/-2/1/1/2/1/1

4	0.0456	-7/-8/-8/-9/-4/-4/1/1/1/-2
5	0.0006	-2/14/19/16/14/11/-5/0/0/0
6	$r_{\min}$	11/16/21/22/21/15/-5/0/1/1
7	$r_{\min}$	13/19/24/24/24/24/21/-10/0/0
8	0.0005	-5/17/21/21/21/16/-5/-1/-1/1
9	0.0208	-6/-12/-12/-11/-6/-5/-3/-3/-2/2
10	0.0247	9/14/15/14/8/4/0/0/0/0
11	0.0219	-3/10/11/-11/-7/-3/-1/0/0/-1
12	0.0318	12/15/16/14/10/4/0/-1/-1/-2
13	0.0225	-9/-15/-16/15/-10/-4/-2/-1/1/1
14	0.0257	12/12/16/11/10/3/2/2/0/-1
15	0.0207	-6/13/-15/-14/-10/-5/-4/0/-1/-1
16	0.0212	2/12/12/12/7/3/2/1/1/0
Optimal fundamental frequency ω_1		296.1600

Table 1: Concurrent optimization results of sixteen-tube composite frame.

Figure 3-5 show the iteration history, optimal topology structure and the first order vibration mode of the sixteen-tube structure, respectively.

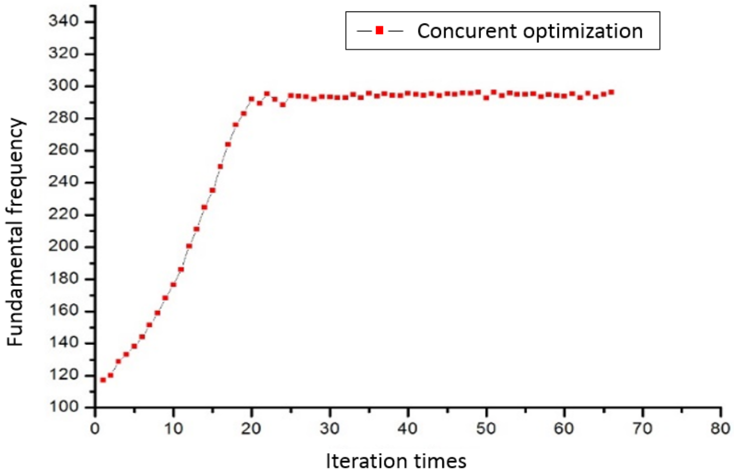


Figure 3: The structural fundamental frequency iteration history of the spatial sixteen-tube frame.

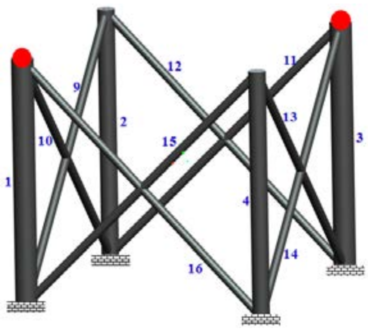
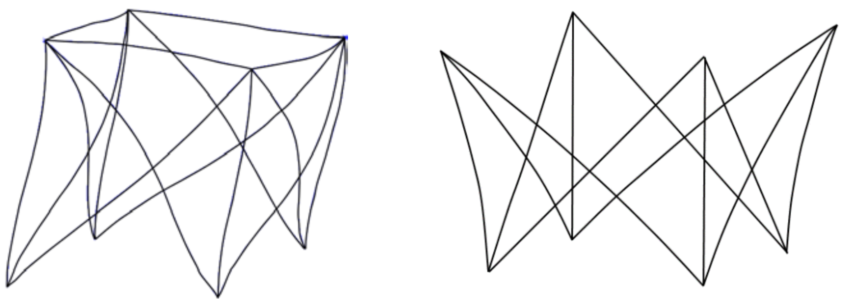


Figure 4: The optimal topology structure of the sixteen-tube composite frame.



(a). Original structure (b). Optimal structure

Figure 5: The first order vibration mode of original and optimal structures.

Discussion

1. From Figure 3, we can find that the fundamental frequency enhances 152.50% compared with the initial fundamental frequency of the structure, which significantly improved the dynamic performance of the structure. Table 1 shows that tubes 6-7 reach the lower limit. Tubes 5,8 are very close to the lower limit and relatively small compared with other tubes. So we consider that tubes 5-8 can be deleted from the ground structure. As shown in the macro optimal topology structure in the Figure 4, the tubes 1-4 have large inner radius, and tubes 1, 3 which connected to the concentrated mass are thicker than other tubes. It demonstrates that giving more material to the four erect tubes will lead to a great contribution to the overall stiffness especially the tubes connected to the lumped mass. The slanting tubes are relatively thinner under the constraint of material volume.
2. The micro variables of the optimal results in Table 1 show that all the tubes in the structure have non-zero winding angles in some layers. Generally, 0° winding angle contributes more to the bending stiffness which is the most important stiffness parameters in beam structures. Observing Figure 5, the first order vibration mode of sixteen-tube structure is relatively complex. Besides the vibration of the whole structure, each tube of the structure will vibrate in different directions so that more bending and torsion deformation occur. To resist the shear force caused by bending and torsion deformation, the non-zero winding angle will contribute more to the overall stiffness than that from angle 0°. Winding angles in different layers have different effects on the structural stiffness. For example, most of the outer winding angles are approximate to 0°, which improve the bending stiffness of the structure, and all of the inner winding angles are non-zero, which improve the torsion stiffness. Meanwhile, the optimization fully takes into account the coupling effect of macro-and micro-variables. It should be noted that most of the composite frame structures are in the form of space and the vibration modes are complex, so it is extremely important to investigate the effect of micro fiber winding angles on the structure stiffness and dynamic frequency performance.

5 CONCLUSION

The urgent demand of the aerospace industry for lightweight design accelerates the development of new materials and innovative structural configuration. However, simple materials or structures of the single-scale optimization no longer satisfy this requirement. Combining with the concurrent optimization of material and structure design concept, the present paper proposed a novel method to realize the concurrent multi-scale optimization of composite frame with maximum fundamental frequency under the composite material volume constraint. The paper fully considers the coupling effect of the macro-scale structure and micro-scale material to further explore the potential of the structure and material. In the optimization model, the inner cross-section radius and fiber winding angle are defined as the independently design variables in macro- and micro-scale, respectively. Considering the harmonious relation between the inner radius and the layer thickness, the punishment function is established to realize the topology optimization of macro structure, which enormously reduces the number of design variables, and improves the efficiency of optimization iteration. The spatial numerical example shows the effectiveness of the concurrent optimization model proposed in the present paper which also provides a new approach for the lightweight design of the composite frame structures.

ACKNOWLEDGEMENTS

Financial supports for this research were provided by the National Natural Science Foundation of China (No. 11372060, 11672057 and 11711530018), Program (LJQ2015026) for Excellent Talents at Colleges and Universities in Liaoning Province, the 111 project (B14013), and the Fundamental Research Funds for the Central Universities (DUT16ZD215). These supports are gratefully acknowledged.

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