Structural Modeling and Aeroelastic Analysis of High-Aspect-Ratio Composite Wings

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Abstract: A unified structural model for high-aspect-ratio composite wing with arbitrary cross-section is developed. Two types of lay-ups of the composite wing, namely, circumferentially uniform stiffness (CUS) configuration and circumferentially asymmetric stiffness (CAS) configuration, are investigated. The present structural modeling method is validated through ANSYS FEM software for the case of a composite box beam. Then, the case of a single-cell composite wing with NACA0012 airfoil shape is considered. To investigate the aeroelastic problem of high-aspect-ratio composite wings, the linear ONERA aerodynamic model is used to model the unsteady aerodynamic loads under the case of small angle of attack. Finally, flutter speeds of the high-aspect-ratio wing with various composite ply angles are determined by using U-g method.

Key words: structural modeling; aeroelastic analysis; high-aspect-ratio composite wing

大展弦比复合材料机翼结构建模与气动弹性分析. 赵永辉, 胡海岩. 中国航空学报(英文版), 2005, 18(1): 25-30.

摘 要:建立了具有任意截面形状的大展弦比复合材料翼的结构模型。研究了机翼的两种铺设方式:即周向均匀刚度配置(CUS)和周向反对称刚度配置(CAS)。对于复合箱梁情形,目前的结构建模方法正确性通过ANSYS 有限单元软件得到了验证。为了研究具有NACA0012 翼型的大展弦比复合材料机翼的气动弹性问题,利用线性ONERA空气动力模型来描述小攻角情形下的非定常空气动力载荷。最后,利用U-g 法预示了机翼在各种复合层铺设角度下的颤振速度。

关键词:结构建模; 气动弹性分析; 大展弦比复合材料机翼
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High-aspect-ratio wings have come into prominence recently due to the interest in High Altitude and Long Endurance (HALE) aircrafts for future military as well as civilian missions[1]. Schoor[2] and Tang[3,4] studied the aeroelastic problem of high-aspect-ratio wings, but they dealt with the isotropic wing only. Because of the high-performances provided by new composite materials, anistropic composite thin-walled structures are likely to play an increasing role in the construction of actual and future generation of high performance flight vehicles, especially for the HALE aircrafts[5]. Many researchers modeled the composite wing as a box beam[6,7]. This excessive simplification cannot reflect the real structure of the composite wing.

This paper deals with the high-aspect-ratio composite wing with NACA0012 airfoil shape. The composite wing is modeled as a single-cell, closed cross-sectional shell, and the asymptotically consistent theory for anisotropic thin-walled beams[8,9] is employed to derive the equations of motion of this system. The structural modeling method for the case of composite box beam is validated by ANSYS FEM software. Then, the present modeling method is straightforwardly extended to the composite wing with NACA0012 airfoil shape. The linear ONERA aerodynamic model[10] is used to

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perform aeroelastic analysis of composite wing.

1 Structural Model

1.1 Basic assumptions

The study begins with a single-cell, closed cross-section, fiber-reinforced composite thin-walled shell as shown in Fig. 1 with the following assumptions made for the sake of simplicity.

(1) All deformations are small enough so that the linear theory of elasticity works well.

(2) The composite shell is a thin-walled structure. That is, its thickness and the cross-section dimension are far smaller than wing semi-span.

(3) It is reasonable to neglect the transverse shear strains in the cross-sectional displacement field.

(4) The out-of-plane cross-sectional warping is incorporated.

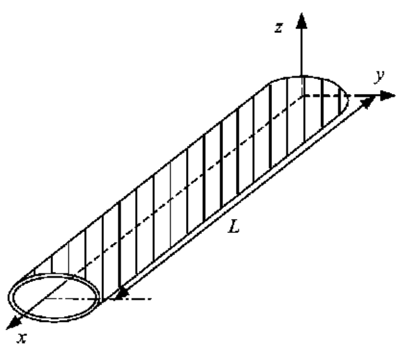

Fig. 1 A single-cell, closed cross-sectional shell

1.2 Strain energy density

Fig. 2 shows the displacement field of the composite shell, where (x, s, n) denotes the curvilinear coordinate system of a point on the closed contour Γ in the shell cross-section, s is measured along the tangent to the closed contour Γ

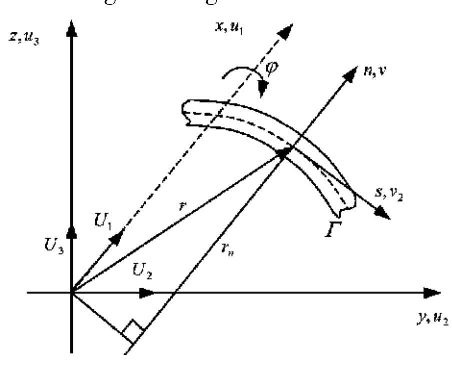

Fig. 2 Displacement field of the composite shell

in a clockwise direction, U_1, U_2 and U_3 denote the displacement components of a point at $(y, z) = (0, 0)$, and φ is the twist angle, positive in the nose-up rotation. The displacement field of the shell can be expressed as

$$u_1(x, s) = U_1(x) - y(s)U_2'(x) - z(s)U_3'(x) + w(x, s) \tag{1a}$$

$$u_2(x, s) = U_2(x) + z(s)\varphi(x) \tag{1b}$$

$$u_3(x, s) = U_3(x) - y(s)\varphi(x) \tag{1c}$$

where $(')= \mathrm{d}(\ )/\mathrm{d}x$; $w(x, s)$ denotes the out-of-plane warping of the cross-section. The strain energy density of the shell can be written as

$$\Phi = \frac{1}{2}(A_{11}\gamma_{11}^2 + A_{22}\gamma_{22}^2 + 4A_{66}\gamma_{12}^2 + 2A_{12}\gamma_{11}\gamma_{22} + 4A_{16}\gamma_{11}\gamma_{12} + 4A_{26}\gamma_{12}\gamma_{22}) \tag{2}$$

where $\gamma_{11} = \varepsilon_{11}$; $\gamma_{22} = \varepsilon_{22}$; $\gamma_{12} = (1/2)\varepsilon_{12}$.

The relation between the strain and the deformation gives

$$\gamma_{11} = U_1'(x) - y(s)U_2''(x) - z(s)U_3''(x) + w'(s, x) \tag{3a}$$

$$2\gamma_{12} = z(s)\varphi'(x)\frac{\mathrm{d}y}{\mathrm{d}s} - y(s)\varphi'(x)\frac{\mathrm{d}z}{\mathrm{d}s} + \frac{\partial w(x, s)}{\partial s} \tag{3b}$$

$$\gamma_{22} = (U_2(x) + z(s)\varphi(x)) \cdot \left(\frac{\partial^2 y(s)}{\partial s^2} - \frac{1}{R}\frac{\partial z(s)}{\partial s}\right) + (U_3(x) - y(s)\varphi(x))\left(\frac{\partial^2 z(s)}{\partial s^2} + \frac{1}{R}\frac{\partial y(s)}{\partial s}\right) \tag{3c}$$

where R is the radius of curvature of the middle surface. Note that $\sigma_{22} \approx 0$. Thus, one obtains

$$\gamma_{22} = -(A_{12}\gamma_{11} + 2A_{26}\gamma_{12})/A_{22} \tag{4}$$

Substituting Eq. (4) into Eq. (2) gives

$$\Phi = \frac{1}{2}(A(s)\gamma_{11}^2 + 2B(s)\gamma_{11}\gamma_{12} + C(s)\gamma_{12}^2) \tag{5}$$

where

$$A(s) = A_{11} - \frac{A_{12}^2}{A_{22}},\ B(s) = 2\left(A_{16} - \frac{A_{12}A_{26}}{A_{22}}\right)$$

$$C(s) = 4\left(A_{66} - \frac{A_{26}^2}{A_{22}}\right),\ A_{ij} = \sum_{k=1}^{N}\overline{Q}_{ij}^{k} t_{\mathrm{ply}}$$

$$(i, j = 1, 2, 6)$$

Here, the stiffness $A(s)$ corresponds to the axial extension; $B(s)$ to the shear; $C(s)$ is a coupling

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