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Aeroelastic optimization of an aerobatic aircraft wing structure

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Abstract

This paper aims at presenting an investigation into a minimum weight optimal design and aeroelastic tailoring of an aerobatic aircraft wing structure. Firstly, analytical and FE models were created for the original metallic wing and an improved composite wing box structures. In order to validate the numerical models, predicted vibration parameters of the metallic wing box were compared with the experimental results. Comparison was also made for the predicted stress results between the metallic and the composite wing box structures of different dimensions and laminate layups. Secondly, based on a minimum weight composite wing box model of adequate strength the investigation was focused on the aeroelastic tailoring of the wing box by employing the gradient-based deterministic optimization method. The study demonstrates that in addition to a significant weight saving, up to 30% increase of flutter speed for the composite wing box can be achieved by optimizing the fibre orientations of the wing skin and spar web laminates. The optimized laminates are trimmed and reinforced to meet the manufacture and strength requirements with little compromise of flutter speed and a minor weight penalty.

Keywords: Aeroelastic tailoring; Optimization; Composite wing box; Laminate layup

1. Introduction

In addition to the favorable high specific strength and stiffness, fiber reinforced composite materials also offer great potential for designers to achieve desirable directional stiffness and aeroelastic behavior of a wing structure by optimizing the fibre orientation with minimum weight penalty. Some previous work in this field has demonstrated that the divergence speed of a forward swept composite wing can be increased by optimizing the laminate layup and restraining the wash-in stiffness coupling warping effect [18–20,25]. The elastic or stiffness coupling produced by unsymmetrical laminate layups could also have significant effect on the dynamic aeroelastic behavior of a composite wing [15,23]. Therefore investigation has been made into optimizing the laminate stacking sequence of composite wing structures for desirable aeroelastic behaviors [10, 13,21,22]. Previous research has also shown that an optimization solution obtained by a gradient-based deterministic method (GBDM) depends on the initial design variables set at the beginning of the optimization process [11]. However, the optimum solution from this method is reliable based on a continuous and finite gradient of objective function at each step of the process. This method is computationally more efficient comparing with a genetic algorithm based on a stochastic procedure [12]. In the unconstrained optimization problem presented here, the boundary specified for the design variables virtually draws a line to limit the numerical variation of the fiber orientations. The location of the design variables or optimum design relative to the boundary has no significant influence on the behavior and gradient of the objective function. A small deviation of the layup from the optimum solution will not lead to a significant change of the objective function. This allows the optimized layup be trimmed within the manufacture constraint for a practical design option that is close enough to the optimum layup. However this may not be true for a general case where the sensitivity of an optimum design may depend on its location relative to the boundary.

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Nomenclature

A_{ij}, A_e	coefficient of the laminate axial stiffness matrix $[A]$ and the enclosed area of a thin-walled anisotropic closed-section beam
$A(s)$, $B(s)$, $C(s)$	reduced axial, coupling and shear stiffness of the closed-section beam
C_{ij}	stiffness coefficients of the closed-section beam
M_x, M_y	bending moment and torque applied to the beam
EI, GJ, CK	bending, torsion and bending-torsion coupling rigidities of the beam respectively
h, ϕ	transverse displacement and rotation of a thin-walled wing box beam
m, I_p	mass and polar mass moment of inertia per unit length of a wing box beam
X_α	distance between the mass and elastic axes of the wing box cross-section
b, ρ, V	wing semi-chord, air density and velocity
$\omega, k = \omega b/V$	oscillating frequency of the wing (rad/s) and reduced frequency
V_f	flutter speed .... m/s
θ, $f_v(\theta)$	lamina fiber orientation (deg); objective function
$[K_D(\omega)]$	frequency dependent generalized dynamic stiffness matrix
$\{q\}$, $[D]$	generalized coordinate and damping matrix of the structure
$[QA]_R$, $[QA]_I$	real and imaginary parts of the generalized unsteady aerodynamic matrix

The objective of this paper is to present an investigation to achieve an optimal design for an aerobatic aircraft wing structure to meet the lightweight, strength and aeroelastic design requirements. The investigation was conducted in two stages. In the first stage, effort was made to design and model a composite wing for a minimum weight structural option. An analytical method was used for vibration and aeroelastic analysis and the finite element method (FEM) was employed for structural stress analysis. Vibration test data of the original metallic wing was used to validate the analytical model by comparing the measured and predicted structural modes. In the second stage, the study was focused on aeroelastic tailoring of the basic composite wing model to achieve the maximum flutter speed under the strength limit. To minimize the computing demand in aeroelastic optimization process, an analytical method was employed, which has been developed and used by a number of researchers to evaluate the structural rigidities of a composite thin-walled box beam [1,4,14,16,24]. This method was initially based on the two-dimensional shell theory for asymptotic analysis and further developed by Berdichevsky et al. to derive the governing equations of anisotropic thin-walled beams based on the variational asymptotical theory [4]. Later Armanios and Badir extended this theory to the free vibration analysis of anisotropic thin-walled beams [1]. In the present paper, the method has been adapted to determine the bending, torsion and bending-torsion coupling rigidities of the thin-walled composite wing box structure. The stiffness and mass matrices in the governing equations were established by using the dynamic stiffness method [2,3]. The Wittrick–Williams algorithm [26] was then used to calculate the wing structural modes for accuracy and computational efficiency.

Examples presented in this paper demonstrate four cases of aeroelastic tailoring in a condition of 88 kg fuel stored in the wing box. Additional case study was conducted to include an additional 40 kg external payload mounted below the middle of the wing. In this example, the lifting surface theory was used for the incompressible airflow unsteady aerodynamic force calculation [6]. In the aeroelastic optimization stage, flutter speed was chosen as the primary parameter in the objective function and the fiber orientation of the laminate was taken as the design variable. This has resulted in an optimized solution without weight penalty. Comparing with the metallic wing, it is noted that a composite wing box made of the widely used quasi-isotropic laminate layup is not necessarily better in terms of the strength, stiffness and flutter speed apart from being a lighter structure. Instead of the usual constrained optimization [5,22], the unconstrained aeroelastic tailoring was conducted separately from the stress analysis in this current investigation. This approach has provided the flexibility for a designer to make a suitable and necessary structural reinforcement in a post process to meet the strength requirement. Based on an example presented in this paper, it has been demonstrated that a composite wing box can be optimized to achieve the maximum flutter speed and meet the strength requirement by aeroelastic tailoring and reinforcement.

2. Analytical and numerical methods

2.1. Analytical and finite element methods

In this investigation, the wing box between the front and rear spar of a wing as illustrated in Fig. 1 was assumed to be the primary structure of the wing and the principal load carrier. The components and surface after the rear spar were only counted in calculating the mass, inertia and aerodynamic force of the wing. For stiffness and vibration analysis, the tapered wing box structure clamped at the root section was divided into a number of spanwise segments. Each of the wing box segments was modelled as a uniform thin-walled single-cell box beam and the whole wing box was modelled as an assembly of those beams. For a circumferentially asymmetric stiffness configuration and based on the analytical method by Armanios and Badir [1], the relationships between the bending moment M_x, torque M_y and transverse and twist deflections at the end of an anisotropic thin-walled closed-section beam, as shown in Fig. 2, are expressed below.

$$M_y = C_{22} \cdot \phi' + C_{23} \cdot h'' \quad \text{and} \quad M_x = C_{23} \cdot \phi' + C_{33} \cdot h'' \tag{1}$$