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DYNAMIC AEROELASTIC BEHAVIOR OF SLENDER COMPOSITE SWEPT WINGS

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ABSTRACT

The aim of this work is to study the dynamic aeroelastic behavior of slender composite swept wings using a modified equivalent plate approach. The present modified analysis incorporates transverse shear deformation and satisfies the shear stress conditions, which significantly improves the accuracy of thick wing results. This analysis is used to study the problem of flutter of several slender composite wings having different aspect ratios, taper ratios, sweep angles, numbers of layers and fiber orientations. Comparisons and conclusions regarding the influence of the above parameters on the wings' dynamic aeroelastic performance are presented. All analyses are confined to the incompressible flow regime.

1. INTRODUCTION

All critical speeds [1-3] of composite wings were found to improve by wise selection of wing structural parameters. This fact is the basis of what is known as aeroelastic tailoring [4]. Many efforts have been made in the last two decades to study and improve aeroelastic characteristics of composite wings.

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The Wing Aeroelastic Synthesis Procedure (TSO) developed at General Dynamics-Fort Worth during the early 1970's is a preliminary design tool which employs a Ritz equivalent plate model of the wing. The flutter and Strength Optimization Procedure (FASTOP) is also a finite element-based two-step design procedure developed for the same purpose.

Green [5] used an integrating matrix method to solve the fourth-order differential equation representing the aeroelastic behavior of a high aspect ratio swept-back wing. In his analysis he used an anisotropic plate beam model and neglected transverse shear effects. Chen, Dugundji and Dunn [6, 7] conducted intensive theoretical and experimental investigations on graphite/epoxy cantilever forward-swept wings. The mathematical flutter model was formulated using Rayleigh-Ritz method. Librescu and Simovich [8] formulated a closed-form solution for the divergence problem of composite swept wings taking the effect of warping restraint at the wing root into consideration. They used a simple beam model for structural modelling and the classical aerodynamic strip theory to calculate aerodynamic loads. Liu et al [9] investigated flutter of cantilever composite plates in subsonic flow.

An attempt to investigate the sensitivity of divergence speed, spanwise lift distribution and induced drag of composite wings to several shape parameters was made by Barthelemy and Bergen [10]. The structural response was obtained using the equivalent plate method, and the aerodynamic response was predicted using Weissinger's L-method. Vanderplaats and Weisshaar [11] showed how the addition of aeroelastic stiffness constraints to wing optimization problems leads to significant increases in the wing weight.

Several complexities were added to aeroelastic models representing aircraft wings to make them closer to real wings. For example, Lottati [12] investigated the effect of adding fuselage weight at the wing semispan and pylon weight at the wing tip on the aeroelastic characteristics of the airplane as an unconstrained vehicle. Recently, Koo and Lee [13] incorporated the effect of structural damping in their study of flutter of swept plate wings. The wing structure was modeled by the finite element method using shear deformable laminated plate elements, while the doublet-point method was used to predict the three-dimensional unsteady aerodynamic forces acting on the oscillating wing. The present authors investigated the static aeroelastic behavior of composite swept wings using a modified equivalent plate approach based on a higher-order shear deformation theory [14].

2. EQUIVALENT PLATE MODELING OF COMPOSITE WINGS

The term "equivalent plate" is used to describe an aircraft wing modeling technique in which all the displacement functions and wing geometry are functions of the coordinates in the wing reference plane in a manner similar to that of plate problems. In this technique, the Rayligh-Ritz method is used to obtain an approximate solution to the variational condition on the total potential energy of the wing structure and applied loads. The total energy E associated with the analytical model used is:

$$E = U - W_{ext} - T \tag{1}$$

where U is the strain energy of the structure, W_{ext} is the work done by external loads, and T is the kinetic energy of the structure.

These energy terms can be expressed as functions of the wing deflections which, in turn, can be expressed in terms of a set of specified displacement functions that satisfy the boundary conditions at the root. The Ritz minimization technique requires that E have a stationary value, a condition that is used to determine the contribution of each displacement function to the wing deflection.

An equivalent plate model based on the classical plate theory was first suggested by Giles [15,16], which is capable of modeling sandwich wings. Another first-order shear deformable equivalent plate model was suggested by Livne [17]. The model is capable of representing both sandwich and box composite wings of general planform. In reference [18], the present authors developed an improved equivalent plate model based on a higher-order shear deformation theory which satisfies the zero transverse shear stress condition. The model is capable of taking the contributions of the wing skin, spar caps and spar webs to the strain and kinetic energies into consideration. In this model, the wing displacements u, v, w in the x, y, z directions are expressed as:

$$
\begin{aligned}
u(x,y,z) &= u_o(x,y) + z[\phi - 4(w_x + \phi)/3(h/z)^2] \\
v(x,y,z) &= v_o(x,y) + z[\psi - 4(w_y + \psi)/3(h/z)^2] \qquad (2) \\
w(x,y,z) &= w_o(x,y)
\end{aligned}
$$

where ϕ, ψ are the rotations of the normals to the plate about the x and y axes, and h is the plate thickness.

3. UNSTEADY AERODYNAMICS OF SLENDER WINGS

Unsteady aerodynamic loads on slender wings can be reasonably approximated by assuming 2-dimensional flow. This subject has been widely treated in the literature; see for example references [1, 19, 20]. Starting from the basic continuity and momentum equations, and assuming a velocity potential function and harmonically oscillating airfoil, the lift and pitching moment can be expressed in terms of airfoil parameters and a complex function C(k).

Smilg and Wasserman [19] defined the aerodynamic forces for the case of aileron overhang and unsealed gap in terms of several T- and ϕ- functions. Their results for the lift and twisting moment per unit span are cast in the form:

$$L' = \pi\rho b^3\omega^2\left\{L_h\frac{h}{b}+\left[L_\alpha-(1/2+a)L_h\right]\alpha+\left[L_\beta-(c-e)L_z\right]\beta\right\} \tag{3}$$

$$M' = \pi\rho b^4\omega^2 \times$$

$$\left\{\left[M_h-(1/2-a)L_h\right]\frac{h}{b}+\left[M_\alpha-(1/2+a)(L_\alpha+M_h)+(1/2+a)^2L_h\right]\alpha\right. \tag{4}$$

$$\left.+\left[M_\beta-(1/2+a)L_\beta-(c-e)M_z+(c-e)(1/2+a)L_z\right]\beta\right\}$$

where all geometric and aerodynamic coefficients are defined in the above references. Figs. (1) and (2) show the cross section and planform of slender swept wings and their important parameters.

4. WING FLUTTER

The total vertical surface displacement is given by:

$$w(x,y,t)=w_b(y,t)-x\theta(y,t)$$

The bending and twisting functions $w_b(y,t)$ and $\theta(y,t)$ can be cast in the form:

$$w_b(y,t)=w_R(t)f(y)$$

$$\theta(y,t)=\theta_R(t)g(y)$$

where w_R(t) and θ_R(t) are the bending and twisting displacements of a reference wing station, normally selected at 0.75 the half span, and f(y) and $g(y)$ are preselected functions which satisfy the root boundary conditions.

Substituting into the equations of motion [1] we get:

$$\ddot{w}_R\int_0^l mf^2dy-\ddot{\theta}_R\int_0^l S_\alpha fg\,dy+w_R\omega_h^2(1+ig_d)\int_0^l mf^2dy=\int_0^l L'f\,dy \tag{5}$$

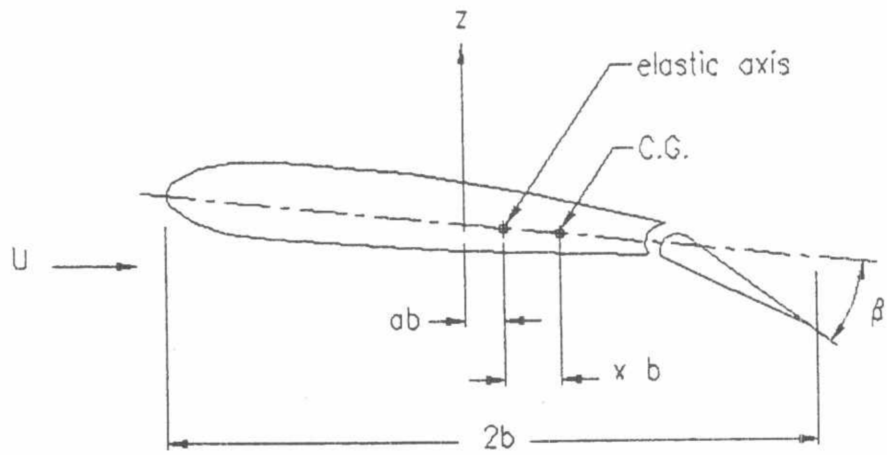

Fig. 1 Geometry of a typical airfoil used in unsteady aerodynamics.

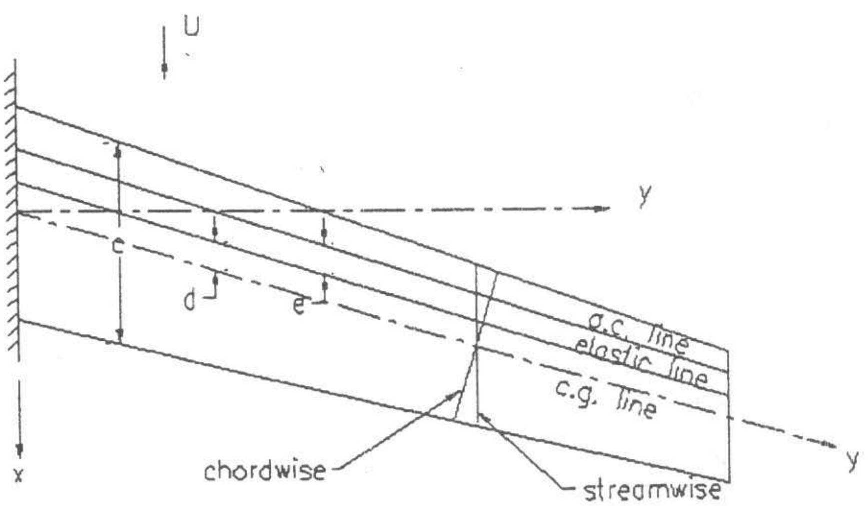

Fig. 2 Slender swept wing with spanwise and streamwise segments.

$$\ddot{\theta}_R\int_0^l I_\alpha g^2 dy - \ddot{w}_R\int_0^l S_\alpha f g dy + \theta_R\omega_\alpha^2(1+ig_d)\int_0^l I_\alpha g_d^2 dy = \int_0^l M' g dy \tag{6}$$

where g_d is the damping coefficient, assumed to be equal in the bending and the torsional modes. Assuming simple harmonic variation of h and α, we get the flutter eigenvalue problem. This problem can be solved by several methods, among which we choose the U-g method [1].

The above flutter model is applied to the same slender wing of Fig. (2). Flutter speeds are calculated for several composite wings having sweep angles 30° and -30°, and ply orientations ranging between 0° and 180° [21]. Results are plotted in Figs. (3) and (4). Inspection of the figures leads to the conclusion that certain ply orientations increase flutter speed while others decrease flutter speed for each wing sweep angle, and that for each wing sweep angle, there are certain ply orientations in which flutter ceases to occur, because the divergence speed is lower than the flutter speed.

Finally, the general effect of wing sweep on the critical aeroelastic speeds when the principal material stiffness direction coincides with the wing reference direction is indicated in Fig. (5).

5. CONCLUSIONS

The present work deals with the dynamic aeroelastic performance of composite swept wings. The investigation involves the development of an efficient structural model based on the equivalent plate technique, and a 2-dimensional unsteady aerodynamic model based on the Smilg and Wasserman approximation.

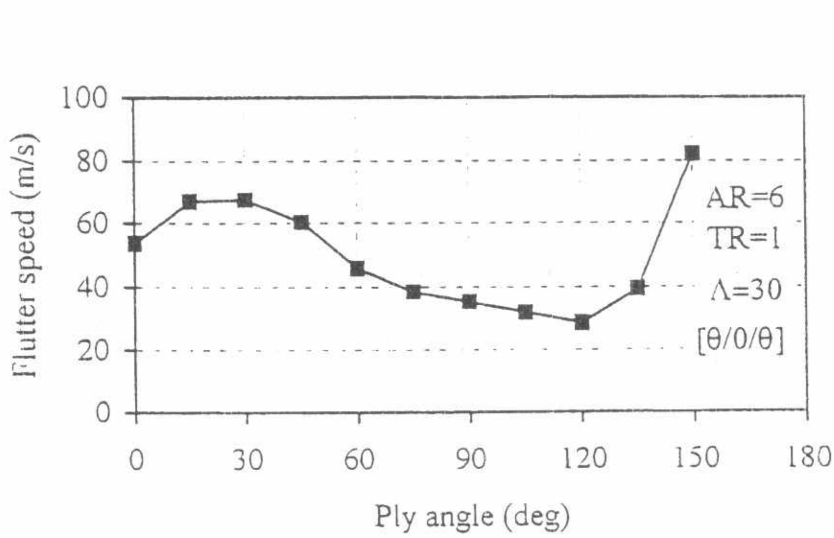

Fig. 3 Variation of flutter speed with ply angle for a [θ/0/θ] swept-back cantilever wing.

AR: Wing aspect ratio.

TR: Wing thickness ratio.

Λ: Wing backward sweep angle.

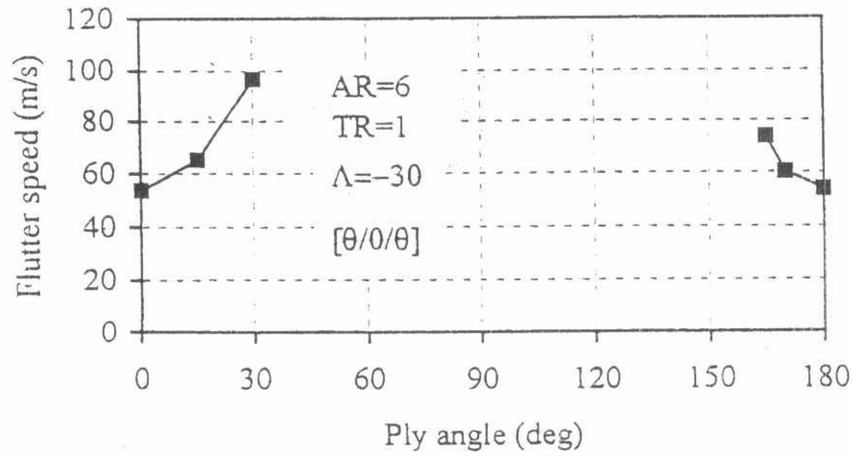

Fig. 4 Variation of flutter speed with ply angle for a [θ/0/θ] swept-forward cantilever wing.

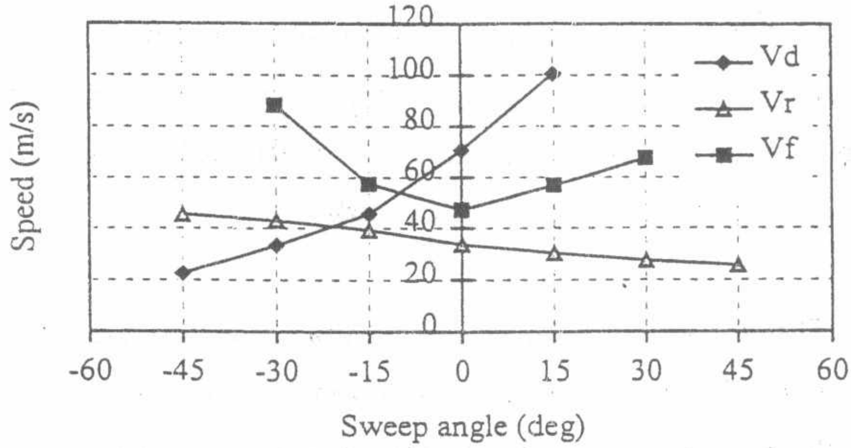

Fig. 5 Effect of sweep angle on critical aeroelastic speeds when the fibers are in the wing reference direction.

V_d: divergence speed.

V_r: aileron reversal speed.

V_f: flutter speed.

The structural model has been modified to improve the accuracy of thick wing deflection calculations by incorporating shear deformations. Thus, it is capable of modeling sandwich and box wing structures without discontinuities in cross section or planform with an accuracy of about 3% in calculating deflections and natural frequencies. It has the important advantage of small computational time compared to current finite element models. Hence, it adopts itself to preliminary aeroelastic design procedures in which both static deflections and natural frequencies are repeatedly calculated.

The above structural and aerodynamic models are combined to solve the problem of flutter of composite swept wings. This package was used to determine the influence of various design parameters on the wing critical speed. Better still, the package can be linked to an optimization routine to reach the optimum wing design under given aeroelastic constraints. The ability to express wing planform and cross-section parameters in polynomial form greatly reduces the number of design variables, and makes it possible to use efficient and powerful optimization procedures.

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