Subsonic and supersonic chordwise pressure distribution are shown in Fig. 2. Figure 2a shows a large drop in leading-edge pressures as a result of optimization. Optimization results in evenly distributed chordwise loading and the adverse pressure gradient shifts further rearward, delaying flow separation. The local load distribution toward the wing tips is reduced by optimization, decreasing the root-bending moment. In supersonic flow, some drop in leading-edge pressure is observed as a result of optimization (Fig. 2b); however, peak loading and the start of the adverse pressure gradient remain close to the leading edge. Reduction in local load distribution toward wing tips due to optimization is marginal because of the conical nature of the flow.

Conclusions

The computer code OPSGER is useful for the aerodynamic optimization of arbitrary wing planforms. OPSGER features analysis and optimization in the presence of several constraints, and can be applied to wake studies.

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Preliminary Weight Estimation of Conventional and Joined Wings Using Equivalent Beam Models

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Introduction

THE implementation of optimum design methods in automated synthesis programs makes available a significant capability for assessing new concepts in aircraft design. Such methods, however, tend to be computationally demanding, particularly if detailed analysis is used in each participating discipline of this multidisciplinary exercise. This Note outlines an efficient approach to obtaining optimum weight estimates of conventional and joined wing structures and is based on representing the detailed finite-element models of the structure by equivalent beam models. The latter are considered more efficient in an optimization environment, which requires repetitive analysis of several candidate designs.

A joined wing design[1] is obtained by replacing the horizontal tail in a conventional airplane with a forward swept wing that is joined to the front wing at the tip or an intermediate span station (Fig. 1). The resulting truss formed by the front and aft wings has its primary load-carrying plane inclined to the horizontal by an angle determined by the dihedral on the wings. The loads have an in-plane and an out-of-plane component, where the latter tends to concentrate material on the upper surface of the leading edge and the lower surface of the trailing edge of the airfoils. As seen in Fig. 1, the effective beam depth that defines stiffness in bending is dependent on the chord length and the dihedral angle, in contrast to the thickness profile for conventional wings. An optimization study to quantify this potential[2] employed detailed finite-element models in the analysis at a substantial computational cost. To reduce analysis costs, the present approach proposes the use of reduced-order equivalent beam models.

Equivalent Beam Models

The central idea behind this approach was to represent the spanwise distribution of sectional moments of inertia I_{yy} and I_{zz}, the product of inertia I_{yz}, and the torsional constant Q (Fig. 2) for the built-up wing structure on an equivalent beam. The mass per unit length of the wing span M was also introduced to establish a weight relation between the wing and beam models. Before transferring the section properties from the wing to the beam, they must be scaled to account for shear lag effects. If this scaling were not used, the resulting beam structure would be artificially stiff. In this work, the lag factor was obtained by a process of numerically matching the reponse of the built-up wing model to its equivalent beam model for nominal values of the section dimensions. Details of obtaining this scale factor are described in Ref. 3. The beam section to which these five section properties are attributed is shown in Fig. 2. It can be described in terms of five independent wall thicknesses and can accommodate an unsymmetrical material distribution typical of swept conventional and joined wing configurations.

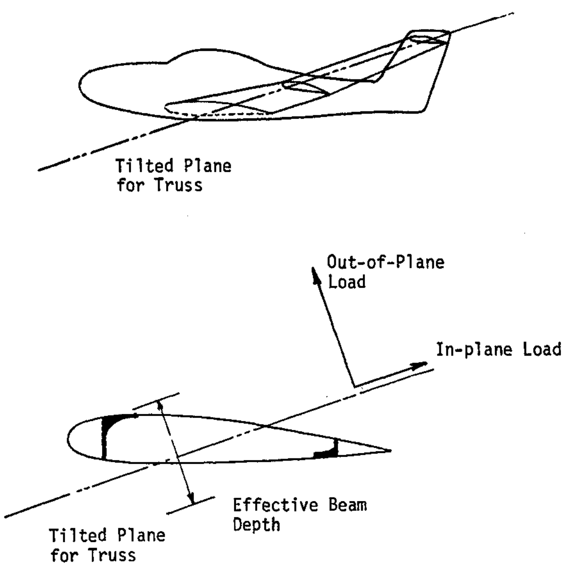

Fig. 1 Joined wing structure depicting the tilted truss formed by the fore-aft wings and the material concentration in the structural box.

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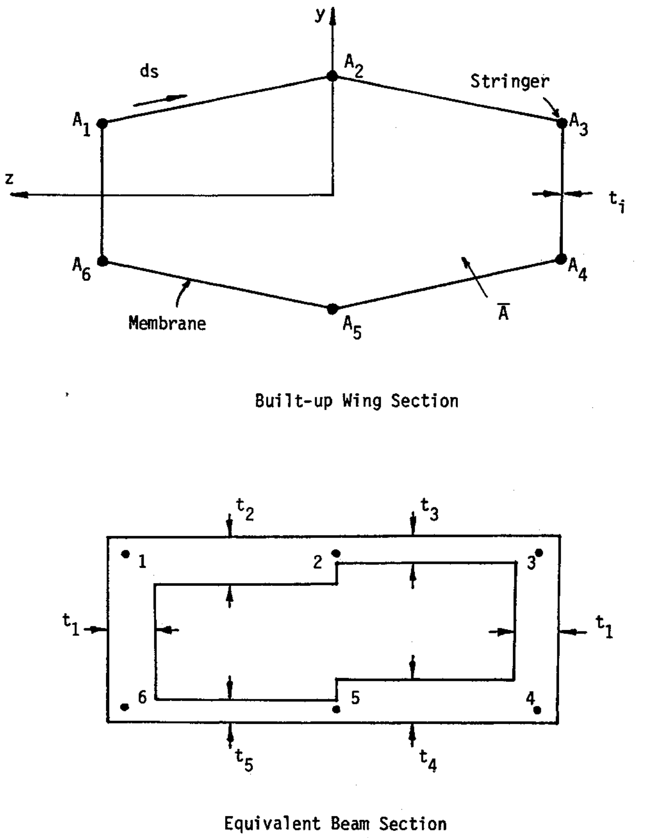

Fig. 2 Cross sections of built-up wing structure and equivalent unsymmetrical beam.

Optimum Design

The equivalent beam model obtained as described can be sized for minimum weight and prescribed constraints on stress, displacement, and frequency. The general mathematical statement for this problem can be written as follows:

$$\text{Minimize} \quad W(\bar{d}) \tag{1}$$

$$\text{Subject to} \quad g_j(\bar{d}) < 0 \qquad j = 1,2,\ldots m \tag{2}$$

$$d_i^{\ell} < d_i < d_i^{u} \qquad i = 1,2,\ldots n \tag{3}$$

Any nonlinear mathematical programming algorithm can be used to obtain a solution to this problem. In the work described here, a fully stressed design approach was used to size the wall thicknesses of the beam model for stress constraints. A feasible usable search direction algorithm[4] was used to obtain the optimum beam design for constraints on nodal displacements and on the natural frequencies. The fully stressed design is based on the hypothesis that a strength-governed design is optimal when all elements are stressed to their maximum. The beam model is considered a good candidate for this approach. The stress ratio algorithm updates the ith wall thickness at a given span station for the $j+1$th iteration by the formula

$$t_i^{j+1} = t_i^j \frac{|\sigma_i^j|}{\sigma_{\text{all}}} \tag{4}$$

where σ_i^j is the stress at the jth iteration and σ_{all} is the allowable stress. Stresses were recovered at six locations on the cross section, and these are labeled 1–6 in Fig. 2. The thicknesses of the vertical sections 1–6 and 3–4 were kept equal in the resizing process.

The optimum design for the equivalent beam model can also be used to obtain the membrane thickness in the wing structure. This aspect is unique to the present work. The vector of section properties $\{S\}^T = \{I_{yy}, I_{zz}, I_{yz}, Q, M\}$ at each of the prescribed spanwise stations are functions $\{f\}$ of membrane thickness t_i, $i = 1,2,\ldots5$, and stringer areas A_j, $i = 1,2,\ldots6$. The sectional properties $\{S^*\}$ obtained from the optimum equivalent beam, using either a fully stressed design or a nonlinear programming algorithm, are adjusted to account for shear lag effects and denoted as $\{\bar{S}\}$. Membrane thicknesses t_i^* corresponding to $\{\bar{S}\}$ can be obtained as a solution to a set of nonlinear algebraic equations:

$$(\{\bar{S}\} - [f(t_1^*, t_2^*, \ldots, t_5^*, A_1, A_2, \ldots, A_6)]) = \{0\} \tag{5}$$

Stringer areas were not resized during the optimization cycles. A modified Levenberg-Marquardt algorithm[5] was used in the solution of the nonlinear equations. An alternate scheme that circumvents the need to solve nonlinear equations is based on a piecewise linearization of the section properties. For a wing section with membrane thicknesses t_i and the corresponding section property vector $\{\bar{S}\}$, and the Jacobian of $\{\bar{S}\}$ denoted as $[J]$, one can write the following expression for changes in the thickness distribution vector $\{\Delta t\}$:

$$\{\bar{S}\}' - \{\bar{S}\} = [J]\{\Delta t\} \tag{6}$$

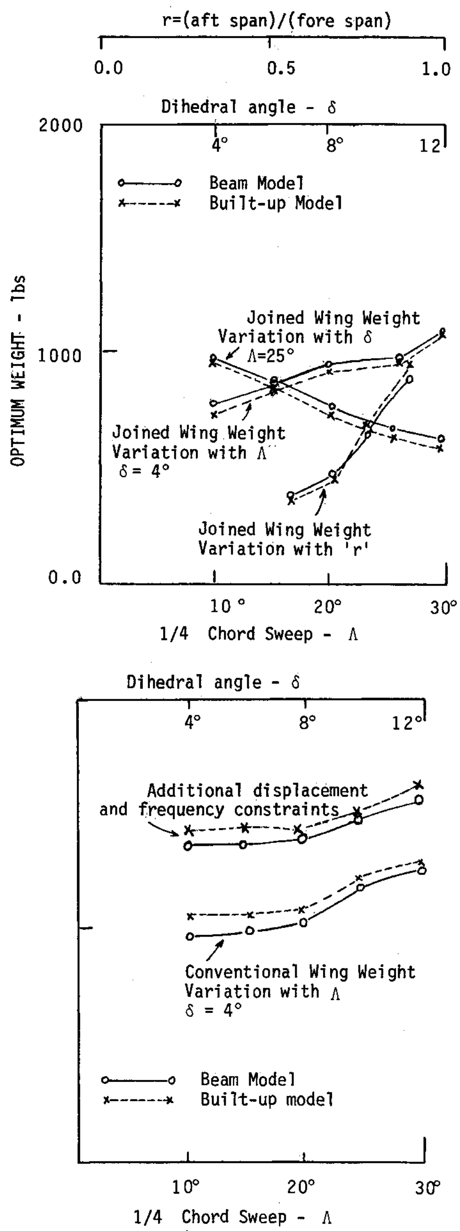

Fig. 3 Optimum weight variation for dihedral and sweep for joined and conventional wings (semispan = 450 in., root chord = 60 in., tip chord = 24 in., thickness ratio = 0.12, semispan load = 30,000 lb).

In Eq. (6), the vector $\{\bar{S}\}'$ is obtained from the optimal beam and scaled for shear lag effects. For the linearity assumption in this equation to be valid, lower and upper bounds were prescribed for the design variable change in the nonlinear programming algorithm. In fully stressed design, this was achieved by starting with arbitrarily large values of allowable stress and reducing this bound in steps to the desired value. The matrix $[J]$ was obtained inexpensively at each iteration as it was computed from algebraic relations.

Discussion of Results

A structural resizing methodology that reduces analysis costs by replacing large-degree-of-freedom finite-element models by reduced-order models is discussed and validated through a sequence of test problems consisting of both joined and single wing structures. Several geometric configurations that involve changes in sweep, dihedral, and spanwise location of the joint between the fore and aft wings were sized for an allowable stress of 35 ksi. Additionally, a constraint on the first frequency, $\omega_1 > 3.5$ Hz, and a constraint to limit the lateral tip displacement to less than 60 in. was also imposed in the optimal sizing. For the frequency and displacement constraint, the wall thicknesses at a span station were scaled by a single design variable for each section. In each such design, the displacement constraint was active at the optimum. The variation of optimum weight with dihedral angle, sweep angle, and joint location is summarized in Fig. 3. A good agreement in the qualitative trends for weight estimates vindicates the use of the method. Furthermore, the ability to recover information pertaining to material distribution on the actual wing model is seen as a new approach in optimum synthesis that bears further investigation. As an example, a conventional cantilever wing of a semispan of 450 in., root and tip chord values of 60 and 24 in., 1/4 chord sweep of 20 deg, dihedral of 4 deg, thickness ratio of 12%, and a semispan load of 30,000 lb was sized using an equivalent beam and yielded a weight of 1052.3 lb. The wing model membrane thicknesses were recovered from the section properties and resulted in a structural weight of 1045.5 lb, which is in good agreement with the predicted fully stressed weight of 1112.4 lb. Finally, it is emphasized that the approach is a preliminary weight estimation technique for new concepts in wing design and is not meant to replace formal methods of optimal design using more detailed models.

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