TAILORED COMPOSITE WINGS WITH ELASTICALLY PRODUCED CHORDWISE CAMBER*

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SUMMARY

Four structural concepts have been created which produce chordwise camber deformation that results in enhanced lift. A wing box can be tailored to utilize each of these with composites. In attempting to optimize the aerodynamic benefits, we have found that there are two optimum designs that are of interest. There is a "weight" optimum which corresponds to the maximum lift per unit structural weight. There is also a "lift" optimum that corresponds to maximum absolute lift. Experience indicates that a large weight penalty accompanies the transition from weight to lift optimum designs.

New structural models, the basic deformation mechanisms that are utilized, and typical analytical results are presented. It appears that lift enhancements of sufficient magnitude can be produced to render this type of wing tailoring of practical interest.

INTRODUCTION

A combination of reasons are responsible for the popularity of resin matrix laminated composites. They resist chemical action, exhibit outstanding mechanical properties and high fatigue resistance, are light in weight and possess an established technology base. If mechanical performance can be compromised, a host of low cost manufacturing approaches can be utilized such as winding, weaving, braiding and pultrusion.

A significant attribute of laminated composites is their design flexibility. The layers or plies of a laminate are, in fact, modular units which can be selected to provide distinct material properties and fiber orientations. It is possible, therefore, to "tailor" the properties of composites to meet specific design requirements. Engineers are learning to exploit this flexibility to produce unique structures tailored to the application. An outstanding example is the swept forward wing of the Grumann/AF/DARPA X-29 Fighter.

A working definition of elastic tailoring is the use of structural concept, fiber orientation, ply stacking sequence and a blend of materials to achieve specific performance goals. In the design process, materials and dimensions are selected to yield specific elastic response characteristics which cause the goals to be achieved. Common choices for goals of elastic tailoring are the creation of favorable deformations, often for the purpose of preventing or controlling aeroelastic phenomena or vibration, improved aerodynamic performance and damage tolerance. Tailoring can be utilized effectively if

1) The behavior in question is thoroughly understood physically.
2) The mechanism(s) is (are) clearly identified.
3) Favorable changes of sufficient magnitude can be produced.

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It has become accepted practice to consider tailoring of wing bending and twisting deformations. In the present work, a new step is taken - - - tailoring of chordwise deformations.

Structural tailoring concepts have been developed to create wings with elastically produced camber for the purpose of increasing the lift generated by the wing. Currently, the usual means of accomplishing this is with controls, the most common of which are flaps. If natural, intrinsic means are used to enhance lift, flap requirements and their associated systems may be reduced or, possibly, even eliminated. The fundamental mechanisms that are utilized produce camber deformations in response to the usual loading of the wing such as bending moments and torque. The camber enhances the production of lift and further modifies the loads. Significant lift increases may be produced by using modern composite material systems.

A Record of Invention has been filed with the University of California Patent, Trademark and Copyright Office pertaining to our camber-producing structural concepts. It is designated UC Case No. 90-116-1 and is entitled "Wings With Elastically Produced Camber." Valentin Fikovsky ((415) 748-6600) is the attorney assigned to the case. Mr. Fikovsky's office would be glad to supply more details on the concept and authorize discussions of the invention under the cover of a Non-Disclosure Agreement. The desired effects are depicted in figure 1.

TAILORING CONCEPTS

In view of the proprietary nature of the camber producing structural concepts, detailed information may be obtained through Mr. Fikovsky's office as mentioned above. There are, however, several general concepts that have been used that are illustrated in figures 2 and 3. A central feature of our wing designs is the use of continuous filament grid stiffened configurations (figure 3) for the wing box covers. This type of stiffening concept is particularly useful for tailoring because unidirectional stiffeners can be oriented and placed to create a wide variation of elastic properties.

We have developed four methods of producing camber from elastic deformations. They have been designated the bending, twisting, pressure and thermal methods, respectively. Only results from the use of the first two methods will be presented.

MODELING AND ANALYSIS METHODOLOGY

The modeling and analysis methodology had its origin in the development and application of new structural models for composite rotor blades with both single and multiple cells. The theory for single cell construction is presented in ref. 1. An extensive numerical comparative study appears in ref. 2, which compares the new elementary theory's predictions with a finite element analysis. Both predictions are in excellent agreement for three benchmark loading cases for a Langley Research Center model blade.

In ref. 3 a comparison is made between theoretical predictions and experimental measurements on a thin-walled box beam. This study shows that strains at points can be predicted with the elementary beam-like theory. In addition, circular tube experiments conducted by Nixon (ref. 4) exhibit good agreement with the theory.

The body of knowledge consisting of the above references establishes a sound technology base for applications and design-related studies. Composite rotor blade modeling is reviewed in ref. 5. Additional studies (refs. 6-11) have been based upon the model of ref. 1. This beam-like model is generic and applies equally well to high aspect wings. The model has been modified appropriately for chordwise camber deformation and serves as the basis for the present work.

The wing box model appears in figure 4. Only the structural box is assumed to be load bearing. The structural model is based upon the center wing structural box of the Lockheed C-130 transport. This avoids the complexity of wing sweep. All dimensions other than skin thicknesses are those of the C-130.

For study of the bending method, a symmetric configuration with identical upper and lower wing covers for the single cell structural box has been selected. The primary structural elements are the stiffened covers. The material properties correspond to AS4/3501-6 graphite-epoxy; they appear in table 1.

DESIGN ANALYSIS: BENDING CASE

A design analysis algorithm has been created for evaluating the benefits of tailored camber. An allowable strain level for bending related response and a distributed axial loading in the covers are assigned initially. The running axial cover stiffness can be directly estimated.

$$K_{11} = \overline{N}_{xx}/\varepsilon \tag{1}$$

The distributed running load in the cover is $\overline{N}_{xx}$. The extensional membrane stiffness is K_{11}. The strain level ε is the allowable spanwise bending strain.

The stiffness K_{11} is composed of two contributions, one due to the skin and the other due to the stiffeners. The influence of stiffeners is accounted for in an averaged manner. The stiffeners are "smeared" or "averaged" over the area of the skin. Also, the stiffeners are taken to be unidirectional configurations with rectangular cross sections of the type that may be created by winding or weaving technology. Since membrane behavior is considered for the upper and lower wing box covers, local bending effects due to cover buckling or postbuckling are excluded at this level of modeling. The influence of the box webs are neglected for convenience. The stiffness may be written as

$$K_{11} = K^{o}_{11} + E^{1}_{11}\, h\, n\, F \tag{2}$$

We adopt the convention that supercripts "o" and "1" refer to the skin and stiffeners, respectively. The extensional modulus of the stiffeners is E^{1}_{11}, h is the skin thickness, n is the stiffening parameter and F is a parameter that reflects the stiffener spatial distribution and pattern.

The stiffening parameter n is defined as

$$n = A_1/p_1 h \tag{3}$$

The cross-sectional area of an individual stiffener is A_1 and p_1 is the pitch or distance between parallel rows of stiffeners.

It is convenient to define the membrane stiffness per unit skin thickness k_{11} as

$$k_{11} = K_{11}/h \tag{4}$$

This stiffness parameter may be calculated directly from lamination theory and a knowledge of the stiffener pattern. It permits the skin thickness to be evaluated as

$$h = \overline{N}_{xx}/k_{11}\,\varepsilon \tag{5}$$

An appropriate measure of structural weight for configurations fabricated from one material is the equivalent smeared thickness of skin and stiffeners denoted h'. It is

$$h' = h\,(1+nf) \tag{6}$$

The parameter f reflects the stiffener spatial distribution and pattern.

The incremental contribution to the section lift coefficient due to elastic camber may be expressed as

$$\Delta C_\ell = GS\,\varepsilon \tag{7}$$

This equation is based upon linear two-dimensional thin airfoil theory (ref. 12). The factor G is a geometric factor that depends on the cross-sectional shape, structural box dimensions and overall section dimensions. The factor S is a dimensionless stiffness factor which depends on stiffness-related material properties, stiffener configuration and skin layup configuration.

The design analysis proceeds as follows:

1. A configuration is selected and k_{11} is determined;
2. The skin thickness is found using Equation (5);
3. The lift coefficient contribution is calculated using Equation (7);
4. The weight related measure of the lift created is evaluated from the parameter.

$$\Delta C_\ell/h'$$

5. Parametric and optimization studies can be conducted based upon the lift created (eq. (7)) or lift per unit of structural weight (step 4).

In attempting to optimize the aerodynamic benefits, we have found that there are two optimum designs that are of interest. There is a "weight" optimum which corresponds to the maximum lift per unit structural weight. There is also a "lift" optimum that corresponds to maximum absolute lift. Experience indicates a large weight penalty accompanies the transition from weight to lift optimum designs.

DESIGN ANALYSIS: TWISTING CASE

If the twisting method of producing camber deformations is employed, a design analysis algorithm can be created which parallels that associated with the bending method. In addition to specifying a design level for bending strain, a design level of shear strain or shear flow must be prescribed. In place of eq. (7), the following equation must be used:

$$\Delta C_\ell = G(S_1\varepsilon + S_2\,\gamma) \tag{8}$$

The factors S_1 and S_2 are stiffness-related. They depend upon material properties, stiffener configuration and skin layup configuration. The shear strain in the covers is denoted by γ.

While configuration details will not be given, it is well to mention that optimal configurations for the bending and twisting methods are distinct and bear little resemblance to each other.

RESULTS AND DISCUSSION

Benchmark Wing Cover Design

A benchmark configuration was created and analyzed for which no effort was made to create elastically produced camber. This configuration carries the design level bending strain and utilizes AS4/3501-6 graphite-epoxy as a material system. The stiffeners are unidirectional and oriented at [0] degrees to the wing beam axis. The skin is composed of only [±45] plies.

The overall level of stiffening, as indicated by the factors "nF" in eq. (2), remains comparable (but not necessarily equal) in all designs. Also the design extensional strain level ε is taken as 4500 microinches per inch. The applied running load $\overline{N}_{xx}$ is set at 25,000 pounds per inch, a value consistent with the center wing of a large transport. Rather than prescribe shear strain, we have elected to use a design value of shear flow of 5000 pounds per inch.

Bending Method Design

Optimal values for bending method designs are presented in table 2. The results correspond to n = 1.5, which is considered to be heavy stiffening. It is to be noted that the section lift coefficient increments for both the weight optimum design (WOD) and lift optimum design (LOD) are large enough to be of practical interest. As a reference, the basic lift contribution due to angle of attack from linear thin airfoil theory is

$$\Delta C_\ell \cong 0.110\ \alpha \tag{9}$$

where α, the angle of attack, is given in degrees.

The transition from the WOD to the LOD corresponds to an approximate increase in section lift coefficient of 18 percent. The weight increase, however, is 56 percent. Thus, as mentioned earlier, a substantial weight penalty is required for the additional lift. Also, the two designs correspond to <u>totally different configurations</u>.

Even though no effort was made to produce elastic camber with the benchmark design, there is a small contribution due to anticlastic curvature. The transition from the benchmark design to the WOD corresponds to an increase of 234 percent in section lift coefficient for a weight increase of only 11 percent. This suggests that elastic camber tailoring is weight efficient.

Twisting Method Design

Optimal values for twisting method designs are presented in table 3. The absolute section lift coefficient increments achieved by this method are somewhat less than for the bending method. They are large enough to be of practical interest and the corresponding weights (thicknesses) are less. On the basis of the parameter $\Delta C_\ell/h'$ (inches^{-1}), the twisting method gives 0.295 in.$^{-1}$ and the bending method yields 0.299 in.$^{-1}$ for WOD's. Therefore on a relative basis, the two methods are competitive.

If absolute lift is important, the twisting method is more efficient. Twisting method designs and bending method designs correspond to entirely different configurations, however. There are, therefore, manufacturing factors which would enter into the decision of which method to adopt.

CONCLUDING REMARKS

A new type of elastic tailoring for wings which produces chordwise camber has been created and demonstrated. Typical results for lift enhancement of a transport wing are of sufficient magnitude to warrant practical consideration. Detailed configuration and design information have not been provided due to the fact that a patent is being pursued. Complete information may be obtained under the cover of a Non-Disclosure Agreement through the University of California Patent, Trademark and Copyright Office.

All of the design analysis results presented herein are based upon the premise that the wing sections are completely free to deform in chordwise camber. If restraints to this form of deformation are present, such as may be near a wing-fuselage juncture, section lift benefits will be diminished locally.

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TABLE 1. - NOMINAL MATERIAL PROPERTIES FOR AS4/3501- 6 UNIDERECTIONAL GRAPHITE - EPOXY (ROOM TEMPERATURE, DRY)

YOUNGS MODULUS (TENSION), FIBER DIRECTION (E_{11})	20.0×10^6 PSI
YOUNGS MODULUS (TENSION), TRANSVERSE DIRECTION (E_{22})	1.7×10^6 PSI
SHEAR MODULUS, IN - PLANE (G_{12})	0.85×10^6 PSI
POISSON RATIO (V_{12})	0.30

TABLE 2. - OPTIMUM VALUES - BENDING METHOD

(n = 1.5)

	ΔC_l	h' (IN.)
LIFT OPTIMUM	0.138	0.610
WEIGHT OPTIMUM	0.117	0.391
BENCHMARK	0.035	0.353

TABLE 3. – OPTIMUM VALUES – TWISTING METHOD

(n = 1.5)

	ΔC_l	h' (IN.)
LIFT OPTIMUM	0.125	0.429
WEIGHT OPTIMUM	0.109	0.369
BENCHMARK	0.035	0.353

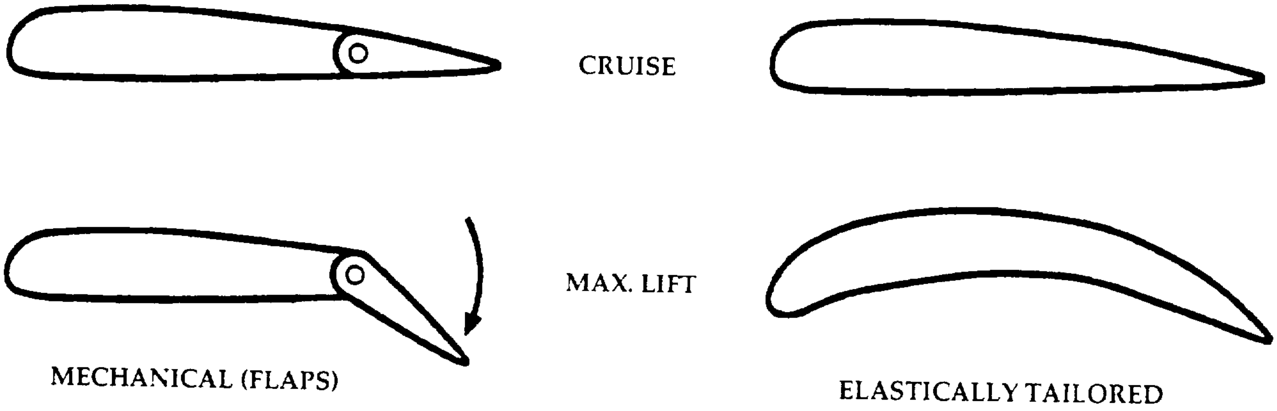

FIGURE 1. – METHODS OF INCREASING AIRFOIL LIFT

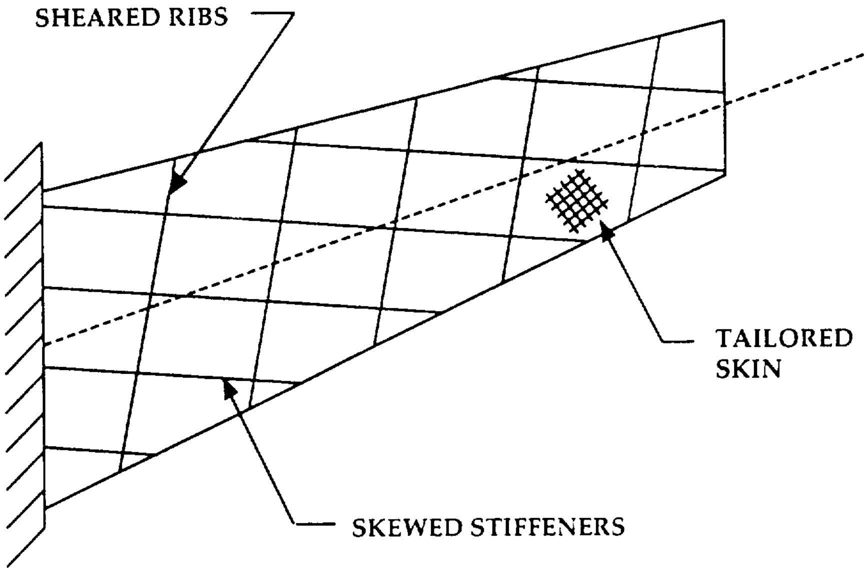

FIGURE 2. - METHODS FOR PRODUCING ELASTIC COUPLING IN HIGH ASPECT RATIO WINGS

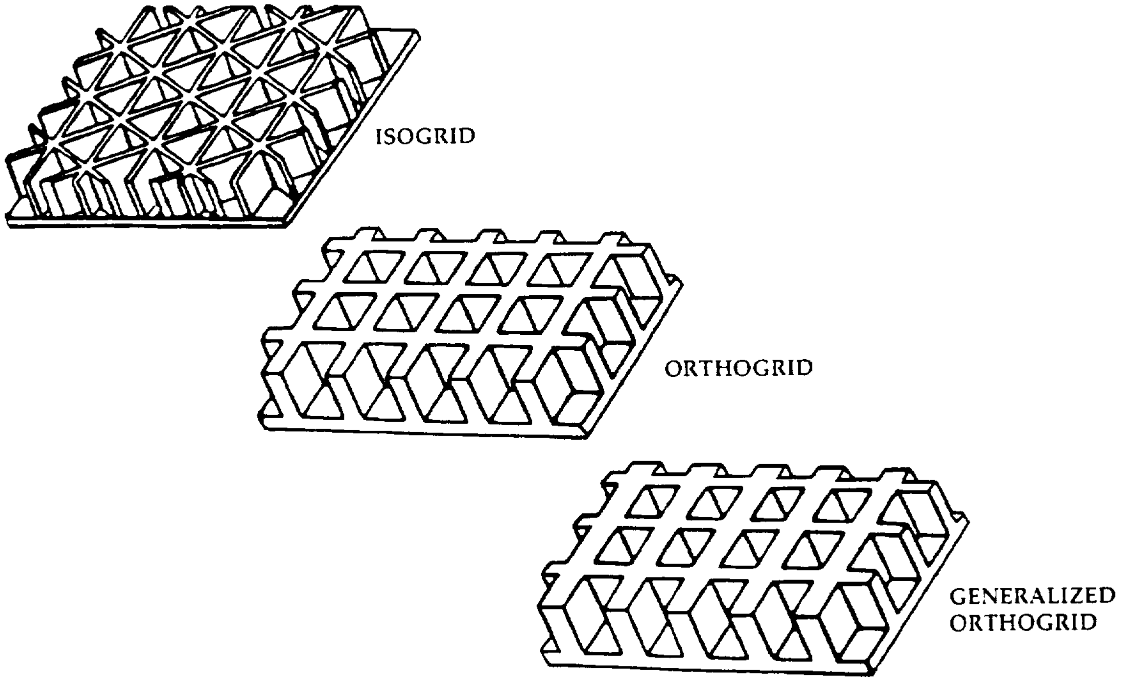

FIGURE 3. - GRID CONFIGURATIONS

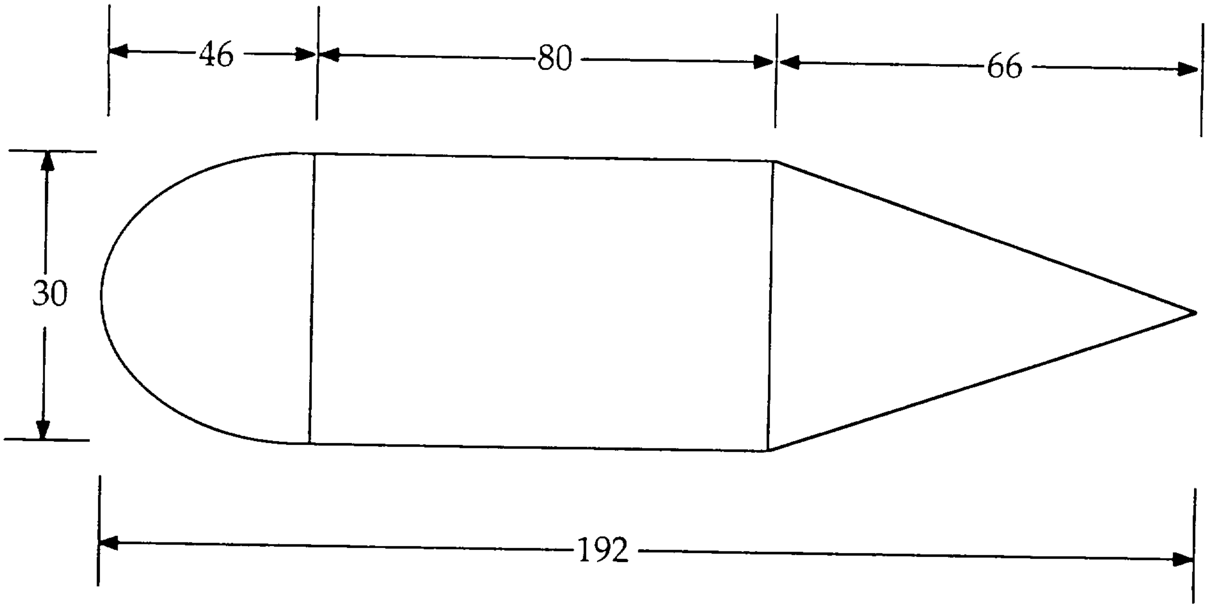

FIGURE 4. - C-130 CENTER WING BOX MODEL

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16. Abstract

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