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Ply Layup Optimization and Micromechanics Tailoring of Composite Aircraft Engine Structures

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A ply layup optimization and micromechanics tailoring capability for composites aircraft engine components is under development. The composites optimization methodology is multidisciplinary, encompassing structural, heat transfer, and aeromechanical design considerations. The methodology includes provision for handling multiple objective functions and a framework for approximation of both the response functions and its derivatives. Derivative approximations are found to be sufficiently accurate to guide the numerical search in the right direction. A micromechanics tailoring procedure to correlate the "calculated" and "measured" lamina properties at elevated temperatures is outlined. The micromechanics tailoring also provides the ability to back out effective (in situ) matrix properties as part of the composite. Several real life aircraft engine components are optimized for structural, thermal, and aeromechanical responses as design objectives and constraints.

I. Introduction

ADVANCED composite materials are now being extensively used for structural design, with applications ranging from aircraft and spacecraft structures to sporting goods. Composite materials offer the advantages of high strength and stiffness coupled with low density that can produce dramatic reduction in weight and major performance increases. Designing with composites is a challenge for the designer because of the wide range of parameters that can be varied and the complex behavior of these structures. Optimization technology, that can simultaneously deal with a wide range of parameters and consider multidisciplinary analysis requirements, is therefore essential to reduce the design cycle time and ensure compliance with multidisciplinary design constraints.

During their service life aircraft engine structures are subjected to a wide range of structural and thermal loads environment. Hence, it is necessary that these structures are designed not only for static strength and dynamic responses, but also for temperature variations, thermal deformations, and stresses. Few published works in the area of composites optimization for thermomechanical responses exist, and these include the structural tailoring of advanced turboprops[1] and hypersonic components.[2]

The primary focus of this article is on the development of an efficient methodology for ply layup optimization of composite engine components, for thermal and mechanical loading environments. The design of such practical components are very often driven by several objectives that are conflicting in nature. The concept of multicriteria optimization[3] where the objective function comprises of a set of distinct criteria is used here to address such design problems. In addition, an approximation concepts based framework to design optimization is adopted.[4] Taylor series approximations to the design objectives and constraints are used, and the applicability of certain derivative approximations, not commonly used in the structural optimization literature, is investigated. Several composite aircraft engine components are sized for optimal ply layup, with static, frequency, thermal, and/or aeromechanical responses as design objectives and constraints.

The second part of this article is on the development of a micromechanics tailoring procedure for correlating measured and calculated composite lamina properties. With micromechanics tailoring, the constituent matrix and fiber properties are treated as design variables, whereas the state variables correspond to the lamina properties. Apart from resulting in improved analytical models for use with the composite structural analysis, other benefits of this micromechanics tailoring procedure include the ability to back out the effective (in situ) matrix properties as part of the composite and the usefulness to micromechanics-based life and damage models.

II. Composites Optimization Problem

The problem of concern here is to find the "optimal" layup of a composite structure for structural and thermal requirements. This problem is cast as a nonlinear programming problem of the following form:

To find the set of design variables X that

Minimizes: $F(X)$ objective function

Subject to

$$g_j(X) \leq 0, \quad j = 1, m \quad \text{inequality constraints}$$

$$x_i^l \leq x_i \leq x_i^u, \quad i = 1, n \quad \text{bounds on variables} \tag{1}$$

The design objectives and constraints include responses such as weight, frequencies, buckling loads, deformations, ply failure, thermal stresses, aeromechanical quantities, etc. The parameters that can be treated as design variables include ply thicknesses and orientations. For micromechanics tailoring,

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the design variables include matrix properties (Young's modulus, thermal conductivity, coefficient of thermal expansion, etc.) and fiber volume ratio. The design of composite structures frequently involves the need to consider several conflicting objectives—like deflection, frequencies, and buckling loads—which in turn necessitates the use of multiobjective design optimization methods. Multiobjective optimization methods help the designer seek a compromise solution. The specific approach used in this work is briefly described in the following section.

Multiobjective optimization. A general multiobjective optimization problem can be stated as follows:

Find the set of design variables X that

Minimizes: $f_k(X)$, $k = 1, \ldots, l$ objective function

Subject to

$$g_j(X) \leq 0, \quad j = 1, m \quad \text{inequality constraint functions}$$

$$x_i^l \leq x_i \leq x_i^u, \quad i = 1, n \quad \text{bounds on variables} \tag{2}$$

Some of the reported research in this area include the use of the Pareto optimality concept for multiobjective design of antisymmetric angle-ply laminates,[5] and the optimization of composite structures for optimal damped dynamic performance based on multiple objectives.[6] Very often, the multiobjective problem is reduced to a problem of single objective by scaling each individual objective. This is efficient computationally and is appropriate to use in obtaining feasible tradeoffs towards reaching the optimal solution. A disadvantage with this "basic weighting" method is that the optimum is strongly influenced by the physical nature of each individual objective function.

The multiobjective approach used in this work is a "compromise programming"[3] method, which is a variation of the basic weighting method. Here the weighted objective function is given as

$$F(X) = \left[\sum_{k=1}^{l} \alpha_k^2 \left| \frac{f_k(x) - f_k^*}{f_{k\max} - f_k^*} \right|^2 \right]^{1/2} \tag{3}$$

where α_k is the weighting factor for the objective f_k, $f_k(x)$ is the value of the kth objective function, f_k^* is the kth "desired" objective value (which can be obtained from a single objective optimization), of this function, and $f_{k\max}$ is the "worst" known value of this objective before optimization.

III. Analysis of Composite Engine Structures

For composite analysis, a multidiscipline computer program called CSTEM[7] is used. CSTEM is the acronym for a program developed under NASA contract, "Coupled Structural/Thermal/Electromagnetic Analysis/Tailoring of Graded Composite Structures." The multidisciplines involved are all highly nonlinear and are implemented in a special three-dimensional finite element formulated to simultaneously tailor the geometrical, material, loading, and environmental complexities of composite structures.

A. Modeling of Layered Composites

Layered structures can be modeled using several different ways: 1) with a separate element for each layer, 2) with multiple layers in an element by calculating equivalent homogeneous material properties for the layers in the element, and 3) with multiple layers in each element by integrating each layer individually into the element stiffness. The use of a separate element per layer can quickly generate very large models to the point of being impractical. The use of equivalent homogeneous material properties results in manageable model sizes, but oversimplifies the problem somewhat. The stiffness of each layer is adequately accounted for in the generation of the equivalent properties, but effects of the distribution of the various layers within a cross section may be lost.

The use of elements that integrate each layer into the element stiffness includes not only the layer stiffness, but the location of the layer in the stackup as well. This multiple layer capability allows the modeling of composite structures with many material layers without the necessity of using an element for each layer. Material layers within an element are set up so that the upper and lower surfaces of a layer are parallel to a pair of element faces in isoparametric space. This means that in isoparametric space the layer surfaces are parallel to a plane defined by two structural axes with the third axis being perpendicular to the layer surfaces. The structural axis perpendicular to the layers defines the thickness direction. This method of defining element layers means that when modeling a layered structure, the mesh must follow the layer surfaces so that layers run between opposite element faces. Layers cannot cut diagonally across an element. Since the layers are of constant thickness in isoparametric space, if the element varies in thickness in the global coordinate system, then so do the layers.

The stiffness of an element with multiple layers is calculated using integration points located on the midplane of each layer within the element. Integration of these local characteristics over the volume of the element provides total element simulation of composite structures, including such effects as twist-bend coupling. The stress and strain are recovered at these same integration points. The stiffness of a layered element is calculated using a numerical integration scheme with a modified Gauss quadrature. This can be generally expressed as

$$F_{ij} = \sum_{l=1}^{\mathrm{nl}} \sum_{a=1}^{m} \sum_{b=1}^{n} \sum_{c=1}^{o} g(r_a, s_b, t_c, \delta_l) |J| W_a W_b W_c \mathrm{Vol}_l \tag{4}$$

where nl is the number of layers in the element, δ is a thickness coordinate, Vol_l is the volume of the element occupied by the layer, and one of m, n, or o has the value of 1 depending on which structural coordinate system axis (r, s, or t) is the through thickness axis. The function g can be written as $[B]^T[D][B]$, in which $[B]$ is the strain displacement matrix and $[D]$ is the material matrix for the layer in which the particular integration point is located. The material matrix is calculated from ply level material properties that are supplied as user inputs or calculated from micromechanics theory.

B. Layup Generation

With multiple layered elements, the definition of element layering is accomplished in an automated manner using a building block approach, in which the components are individual layers, generation sets, and generation orders. The information necessary to define an element layer is the layer material, the layer thickness, and the orientation of the layer, whereas a generation set is composed of groups of layers, and a generation order defines the sequence that generation sets are applied through a cross section of the model. The cross sections are specified using a beginning element number (usually a surface element) and a structural axis that defines the layer stacking direction. The normal sequence followed to specify element layering is 1) identify repeating layer subsets (individual layers or layer groupings); 2) define generation sets based on these repeating layer subsets; 3) establish a generation order (sequence of generation sets); and 4) assign generation orders to model cross sections.

The multiple layering capability described above is also used in heat transfer. This combined with the ability to specify orthotropic material thermal conductivities provides the capability to perform heat transfer analysis of composite materials. The material thermal conductivity and specific heat are required material properties that are supplied at the ply level as user inputs or calculated from micromechanics theory. The linear and nonlinear heat transfer analysis procedures

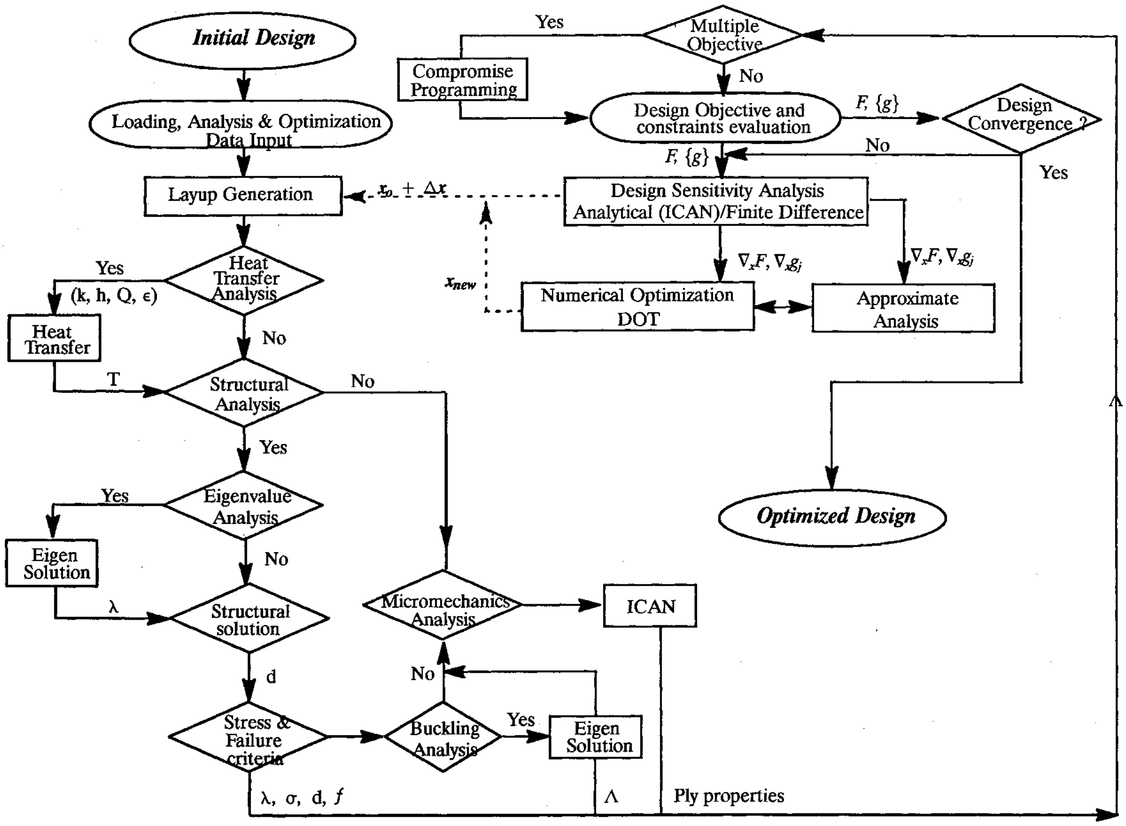

Fig. 1 Composites optimization program flow.

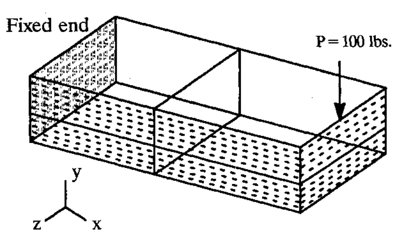

Fig. 2 Layered cantilever beam.

implemented in CSTEM are similar to the method described in Ref. 8.

IV. Approximation Concepts Based Composites Optimization

A. Architecture

The composites optimization capability implemented in CSTEM is shown in Fig. 1. The iterative design optimization process begins by first defining the loading, analysis, and optimization problem inputs. The next step is the layup generation, where the user-specified layering is assigned to the model cross section, which can be from one to a limited number of elements thick. The finite element analysis includes heat transfer and structural solutions. When doing the heat transfer as a part of a coupled solution, the calculated nodal temperatures are passed to the structural modules so that the structural material properties and thermal strains can be calculated using these temperatures. The responses obtained from finite element analysis are then used to evaluate the user specified design optimization objective and constraint functions. For multiple objective problems, the compromise function given by Eq. (3), is used to evaluate the "weighted" objective function. The next step is the calculation of design sensitivity coefficients for the objective and constraint functions. Either semianalytical approach or finite differencing equations can be used for sensitivity calculations. In this work, an approximation concepts based optimization philosophy[3] is adopted. Specifically, hybrid approximations[9] to the objective and constraint functions are used during the numerical optimization process. For numerical optimization, the modified method of feasible directions algorithm in the DOT software[10] is used. The convergence of the optimization process is based on the responses computed from the finite element analysis.

B. Move-Limits on Design Variables

As mentioned above, the approximation concepts approach to structural optimization is used in this work, where the design objective and constraint functions are approximated by linear terms. Due to the highly nonlinear nature of the design functions with respect to ply orientations and the region of validity of the approximations, move-limits are imposed on the design variables during the optimization process. However, in terms of computational efficiency, it is necessary that these move-limits be kept as large as possible so as not to slow down the convergence to an optimal design.

Numerical computations were performed to identify an acceptable set of move-limits based on the quality of the approximations. A composite beam modeled using four solid elements, shown in Fig. 2, is used for this investigation. The ply orientation pattern is $[0, 90, 90, 0]_{sym}$ with a thickness of 0.025 in./ply. The approximations for frequency and stress constraints with respect to ply thickness variables are found to be good for a wider region than with respect to the ply orientation angles. Specifically, for up to 50% perturbations from the design point at which the sensitivities are calculated, the approximations with respect to the ply thickness variables are found to be precise. However, when both the thickness and ply orientations are simultaneously perturbed, the approximations are found to be valid for less than 10% from the design point at which the sensitivities are computed. This is consistent with the highly nonlinear nature of the response functions with respect to ply orientations. Based on these studies, the following move-limit strategy is used:

$$\begin{aligned} x_i^{\text{lower}} &= x_i - |x_{\text{limit}} \times x_i| \\ x_i^{\text{upper}} &= x_i + |x_{\text{limit}} \times x_i| \end{aligned} \tag{5}$$

where x_{limit} is 0.10 and 0.05 for the ply thickness and orientation variables, respectively. The limits are reduced if the current iteration design is more violated than the previous iteration.

C. Scaling of Design Variables

In general, for optimization problems that have design variables with ranges very different from one another, scaling of variables becomes necessary for the robustness of the numerical search process. In this work the ply thickness variables are scaled as a ratio of the layer generation set thickness, and the ply orientation variables are scaled with respect to the largest allowable angle. For the micromechanics correlation problem, the constituent (matrix and fiber) property variables are scaled with respect to the maximum allowable property value.

D. Approximation of Gradients

In order to minimize the computational time required to solve large-scale problems, an approximation to the gradients of the composite structure responses, during optimization, is investigated here. One desirable form of approximation is the Broyden rank-one update, commonly used in numerical optimization. A more accurate form of gradient approximation, presented in Ref. 11, that is a slight variation from the Broyden rank-one update, is used here. This gradient approximation is of the form

$$G_{k+1} = G_k + 2.0\,\frac{(\Delta F - G_k^T \Delta x)}{\Delta x^T \Delta x}\,\Delta x \tag{6}$$

where

G_{k+1} = desired vector of sensitivities for design iteration $k + 1$
G_k = vector of sensitivities for design iteration k
ΔF = change in objective function between iterations k and $k + 1$
Δx = change in the design vector between iterations k and $k + 1$

This modified Broyden rank one update has been implemented in such a way that alternate design iterations will perform full-scale and approximate sensitivity computations, respectively. It should be noted that the original function sensitivities that are in turn used in Eq. (6) are computed by a finite differencing procedure. Present work is focused on replacing the finite difference sensitivity calculation with the semianalytical sensitivity analysis.

V. Aircraft Engine Components Design Optimization

A. Engine Outlet Guide Vane (OGV)

An aircraft engine outlet guide vane, shown in Fig. 3, is considered as the first design example. The OGV is modeled with a foam core and a composite shell over the foam core. At each of its ends, the OGV has a viton cap and a viton ring to reduce vibrations. Viton is a rubbery material that is used for vibration damping. The design criteria is to come up with an optimum composite shell thickness and ply orientations that would be a minimum weight design and make the structure stiffer. The stiffness (frequency) requirements are to prevent the viton cap/ring from degrading quickly and therefore having to frequently replace them. Composite ply layup manufacturing requirements are also included in the design problem.

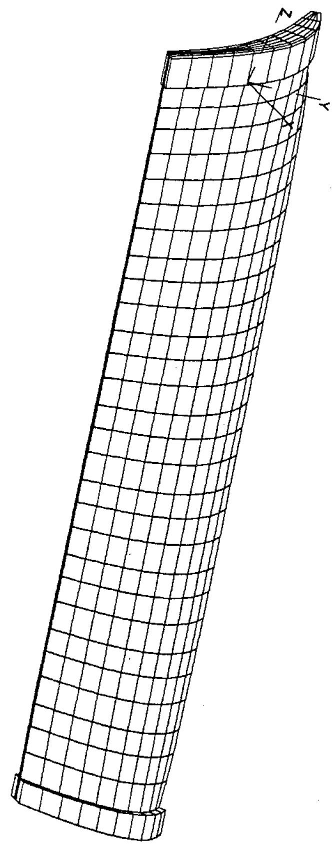

Fig. 3 Engine outlet guide vane (OGV).

The OGV is modeled using 990, 8-noded isoparametric elements, and is totally fixed at one end and restrained to move only in the radial direction at the other end. The composite layup is made up of two generation sets with 15 composite plies and 1 foam core thickness, respectively. The design variables consisted of the six outermost ply angles (θ_1 to θ_6) of the composite shell, three inner pattern ply angles (θ_A, θ_B, θ_C) of the composite shell, and the thickness of the composite shell over the foam core. The thickness of the composite shell is defined by the number of composite plies multiplied by the thickness per ply of 0.00515 in. The pattern for the inner plies was A, B, A, A, C, A. The layup is symmetric and is given by

$$[[\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6], [\theta_A, \theta_B, \theta_A, \theta_A, \theta_C, \theta_A]_n]_{\text{sym}}$$

The design requirements on the OGV frequencies, include

Mode 1 (1st flex) > 261 Hz
Mode 6 (3rd flex) < 1700 Hz
Mode 7 (3rd torsion) < 1700 Hz
Mode 14 (two stripe) > 2501 Hz

The manufacturing consideration on the composite ply layup include 1) the plies (layers) be layered as "3 ply" packs; 2) the first and third ply (layer) orientation in each pack be the same (θ_1, θ_2, θ_1); 3) difference in ply (layer) orientation between θ_1 and θ_2 in each pack be the same in sign and magnitude; and 4) all plies (layers) of constant thickness of approximately 5 mil.

After 6 design iterations, a final solution was obtained. This optimized solution was then adjusted slightly to reflect more realistic design variable values from a production point of view. A 7% weight reduction was achieved while satisfying all constraints. The initial and final design variables and responses are provided in Tables 1 and 2.

This OGV layup optimization problem was also solved as a multiobjective optimization problem, with weight minimization and the fundamental frequency maximization as the two objectives. During optimization, equal weighting was assigned to the two objectives. Constraints on the remaining frequencies and manufacturing requirements were included in the design problem. The final solution resulted in a slightly higher weight than the single objective design, but the fundamental frequency was higher, as desired.

B. Axial Channel Segment

The second example is an axial channel segment of an engine, shown in Fig. 4. The segment is modeled using very high heat resistant ceramic matrix composite material. This is an example where the structure is to be designed for thermal and structural boundary conditions and is a nonlinear steady-state heat transfer problem. The coupling between the thermal and structural disciplines is in terms of the nodal temperatures obtained from the heat transfer analysis.

The structure is modeled using 160, 8-noded isoparametric finite elements. The boundary conditions for the combined mechanical and thermal model are shown in Fig. 5. Displacement boundary conditions consist of an axial fixity at the left end and radial fixities at both ends. Pressure is applied on inner surface only almost along the entire length, but not the full length. Thermal boundary conditions are different on inner and outer surfaces and vary along the length that is divided into four sections. The thermal boundary conditions and orthotropic conductivities are provided in Tables 3 and 4.

Table 1 Design variables for OGV

Design variable, deg	Initial	Final
θ_1	0.0	0.0
θ_2	45.0	50.0
θ_3	0.0	0.0
θ_4	90.0	90.0
θ_5	−45.0	−40.0
θ_6	90.0	90.0
θ_A	0.0	−15.0
θ_B	45.0	35.0
θ_C	−45.0	35.0
Composite shell thickness (5.15 mil/layer)	15 plies	12 plies

Table 2 Design responses for OGV

Response	Initial	Final
Weight, lb	1.01	0.94
1st flex frequency, Hz	261.00	262.00
3rd flex frequency	1406.00	1441.00
3rd torsion frequency	1518.00	1561.00
Two stripe (2S) frequency	2502.00	2503.00

For this example, the input composite layup consists of one generation order, made up of one generation set with 6 plies (layers). For layering, this generation set is applied through a cross section of the model. Since all the elements in this model are of uniform thickness, each element is treated as a cross section. A representative element (or cross section) is then used for determining the layup, and this layup is assigned to all the elements in the model. The layup is symmetric and is given by

$$[\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6]_{\mathrm{sym}}$$

This use of a representative cross section to determine the layup and assigning the generated layup to several other cross sections cannot be done if each cross section is of a different thickness.

The design optimization problem is to determine the optimal layer orientations that would give the least thermal stresses. The design objective is to minimize the stress in the fiber direction (σ_{11}) with constraints on in-plane stresses (σ_{22}) to be less than σ_{11}. After optimization, the fiber direction stresses in the composite structure were reduced by 27%. The ply orientations and thermal stresses corresponding to the initial and final design are provided in Table 5. The final design had a Δt (temperature differential) of 7°F less than the initial design.

C. Engine Blade

The third example is a composite blade model of an engine, shown in Fig. 6. In this work, the design of the blade for frequency and flutter (aeroelastic response) is considered. A single parameter, referred to as mode shape slope (MSS), is used to quantify, in an approximate sense, the aeroelastic stability of the blade, and is given by

$$\mathrm{MSS} = (\phi b/\delta) \tag{7}$$

where ϕ is the twist angle in radians, b is half of the chord

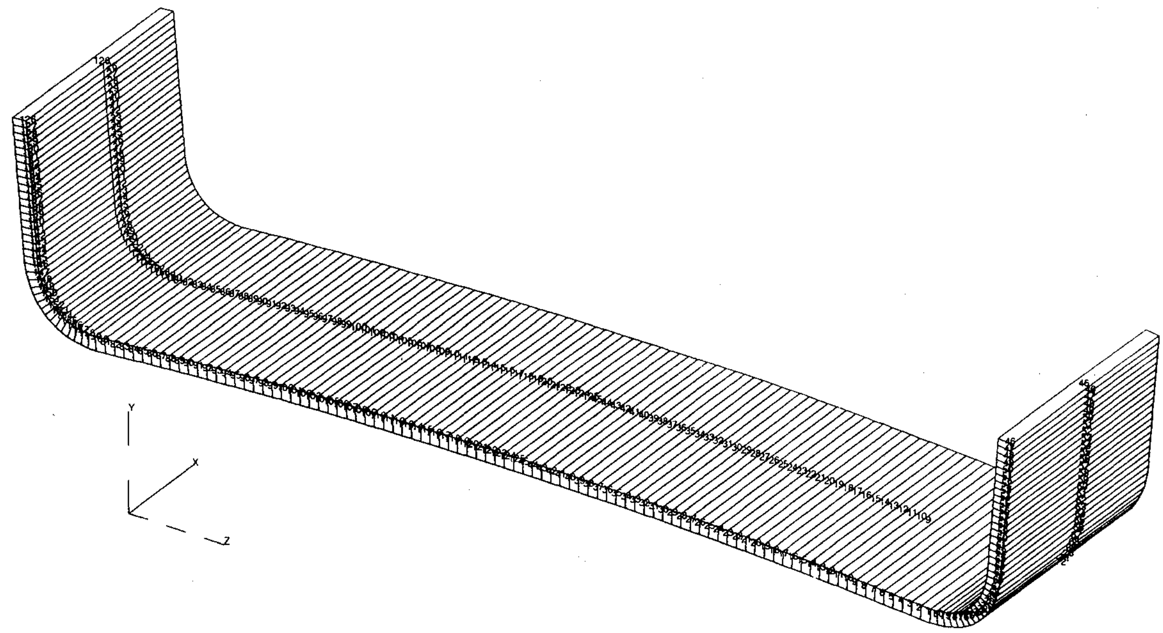

Fig. 4 Axial channel segment.

Table 3 Heat transfer boundary conditions for axial segment model

	Section			
	1	2	3	4
Inner surface				
Convection coefficient, BTU/h-ft-°F	292	331	289	265
Convection temperature, °F	1260	1363	1454	1488
Radiation temperature, °F	1350	1436	1478	1558
Outer surface				
Convection coefficient, BTU/h-ft-°F	144	95	91	96
Convection temperature, °F	3235	3235	3235	3235
Radiation temperature, °F	3235	3235	3235	3235

Table 4 Thermal conductivities (BTU/h-ft-°F) along material axes for axial segment model

Temperature, °F	K_{xx}	K_{yy}	K_{zz}
75	59.1	46.9	46.9
500	40.3	20.9	20.9
1000	31.4	20.5	20.5
1500	26.1	15.1	15.1
2000	20.8	12.7	12.7
2500	17.6	9.75	9.75

Table 5 Design variables and responses for axial segment problem

Design variable, deg	Initial	Final (full gradients)
θ_1	0.0	45.6
θ_2	0.0	31.1
θ_3	0.0	7.6
θ_4	0.0	−13.5
θ_5	0.0	−4.5
θ_6	0.0	−4.5
Thermal stresses		
Max. sigma_{11}, psi	54,576.6	39,151
Max. sigma_{22}, psi	24,557.5	39,051

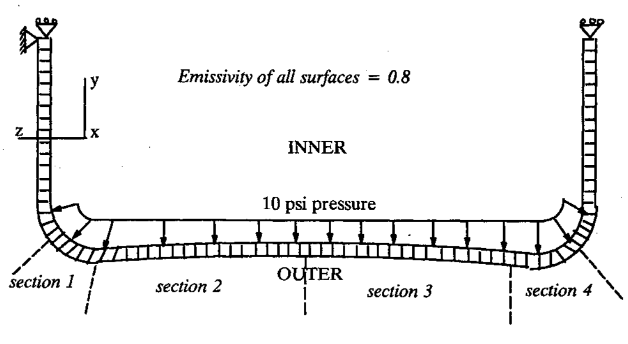

Fig. 5 Mechanical and thermal boundary conditions for axial segment.

length, and δ is a measure of blade translation at the span of interest. In practice, this MSS is calculated using the axial and tangential mode shape degrees of freedom (DOF) at leading, midchord, and trailing edge for a specific span.

The blade is modeled using over 500, 20-noded brick elements. The ply layup used for this model is symmetric and is given by

$$[0, 0, +45, [\theta_1, \theta_2, \theta_3, \theta_4], [\theta_1, \theta_2, 90, \theta_4], [\theta_1, \theta_2, \theta_3, \theta_4], [\theta_1, \theta_2, 90, \theta_4], [\theta_1, \theta_2, \theta_3, \theta_4]_n]_{\text{sym}}$$

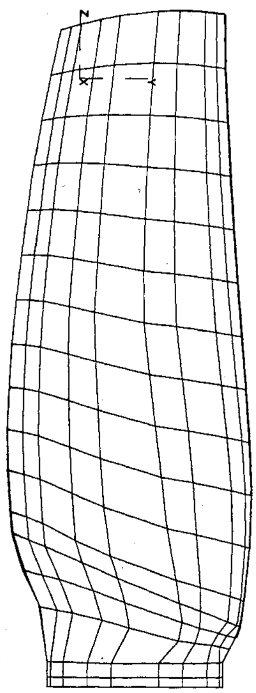

Fig. 6 Engine fan blade model.

The design variables are four independent composite ply orientation angles (θ_1, θ_2, θ_3, θ_4). The ply orientation angles corresponding to the initial design are (0, 45, 0, −45 deg). The blade contains over 300 plies at the maximum thickness region and, therefore, these four independent variables affect a large number of ply orientations.

The design problem includes dual objectives, including minimization of the first flexural MSS and the minimization of the second flexural frequency, at a specified speed. The first objective relates to the aeroelastic response of the blade, whereas the second is to avoid potential crossing with an excitation frequency. The initial design had a first flex MSS of 0.24 and a second flex frequency of 106.5 Hz. Design constraints are imposed on the first flexural, first torsion, and two stripe frequencies to be at least 90% of the baseline value. A large deformation analysis is performed to include the nonlinearities from the blade rotation speed ω.

After 8 design optimization iterations, a final solution with ply orientation angles of (−25, 50, 35, −55 deg) was obtained. This layup corresponds to a 9% reduction in second flexural frequency and over 25% reduction in MSS. The orientation angles were rounded to the nearest multiple of 5 deg and no significant change of performance was noticed. More specifically, the rounding process did not increase the second flexural frequency or the MSS and satisfied all frequency constraints.

VI. Use of Approximate Gradients in Optimization

The capability outlined in Sec. IV.D was used to solve the axial segment and the engine fan blade design optimization problems. The gradients of the relevant composite structure responses were approximated during alternate design optimization iterations. The design variables (ply orientations) corresponding to the final design, using approximate gradients, for the engine fan blade problem are (−21, 63, 30, −52 deg). The design variables (ply orientations) corresponding to the final design, using approximate gradients, for the axial segment problem are (45.9, 31.8, 26.6, −10.6, −4.2, −2.8 deg). A comparison of the results for the engine fan blade and axial segment problems with that of full gradient computation are provided in Figs. 7 and 8, respectively. It is clear from the results that a significant reduction in computational time can be obtained without affecting the quality of the optimization solution. The approximate derivatives are

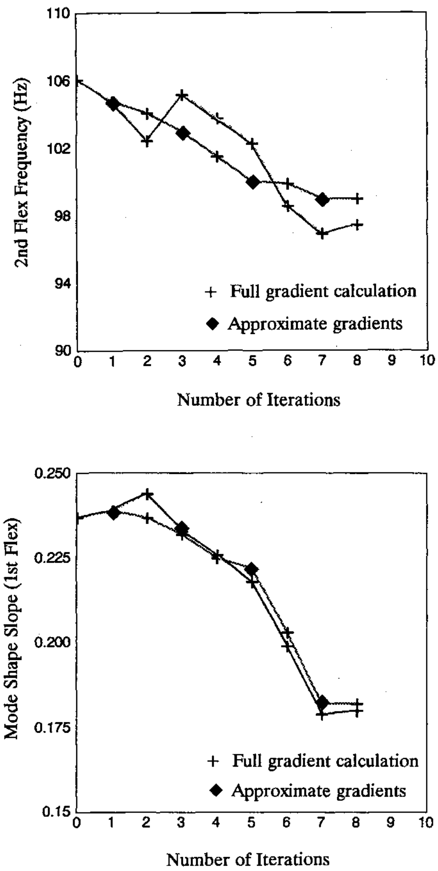

Fig. 7 Engine fan blade—full vs approximate gradients.

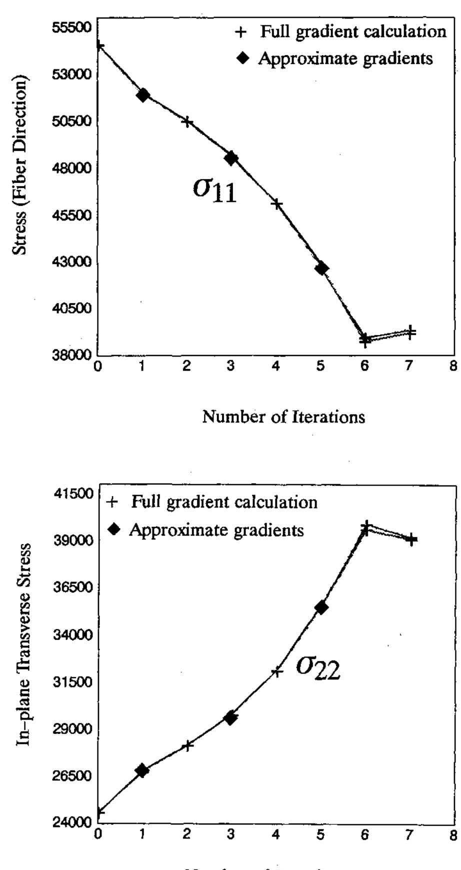

Fig. 8 Axial segment—full vs approximate gradients.

found to be sufficiently accurate to guide the design in the right direction. The reduction in computational time is due to the reason that detailed sensitivity analysis is not performed during alternate design iterations.

VII. Micromechanics Tailoring for Correlation of Measured and Calculated Layer Properties

Very often, there is a need to reconcile differences between measured and calculated composite ply properties, thereby resulting in an improved analytical model that can be used for detailed structural and heat transfer analyses. In this section, an optimization-based methodology is introduced for tailoring constituent (fiber and matrix) properties, in order to correlate measured and calculated unidirectional ply or balanced (0/90) weave properties. The correlation problem is defined as a minimization problem of a compromise function that accounts for the difference in measured and micromechanics calculated properties. For the minimization problem, the ply/weave properties are treated as the state variables, while the matrix properties are treated as design variables X and are varied to achieve the desired correlation. The compromise function is given by

$$E(X) = \left[\sum_{k=1}^{\mathrm{np}} \alpha_k^2 \left| \frac{p_k(x) - p_k^m}{p_k^{\mathrm{ic}} - p_k^m} \right|^2 \right]^{1/2} \tag{8}$$

where np is the number of unidirectional ply or balanced weave properties being correlated, α_k is the weighting factor for the kth uniply/weave property, $p_k(x)$ is the kth uniply/weave property's calculated value from micromechanics theory, p_k^m is the kth uniply/weave property's test measured value, p_k^{ic} is the initial calculated value of this property before correlation, and X is the vector of constituent properties or design variables, such as matrix modulus (E^m), matrix conductivity (K^m), matrix coefficient of thermal expansion (α^m), and fiber properties that can be varied within an admissible range to achieve the desired correlation in the state variables. Some of the state variables that are candidates for correlation include elastic modulus in 11 and 22 directions E_l, thermal conductivity in 11 and 22 directions K_l, coefficient of thermal expansion in 11 and 22 directions α_1, and the layer tensile strength S_{lT}. NASAs ICAN code, integrated in CSTEM, that incorporates micromechanics equations is used for the micromechanics analysis.[12]

In practice, the minimization of this compromise function is performed as a two-step procedure: 1) match uniply/weave properties at room temperature, by tailoring the matrix properties. Fiber properties are maintained fixed throughout the tailoring process; and 2) match at elevated temperature (or, operating temperature) by using the hydrothermal relations in ICAN. The equations used in ICAN to account for hygrothermal property conditioning of the matrix are

$$\begin{aligned} (E, G, S)_{\mathrm{wr}} &= (E, G, S)_{\mathrm{ro}} \Psi_{\mathrm{mp}} \\ (\alpha, K, C)_{\mathrm{wr}} &= (\alpha, K, C)_{\mathrm{ro}} \Psi_{\mathrm{tp}} \end{aligned} \tag{9}$$

where

E, G, S = matrix mechanical properties
α, K, C = matrix thermal properties
ro = corresponds to dry matrix properties at room temperature
Ψ_{mp} = mechanical property reduction ratio for hydrothermal effects
Ψ_{tp} = thermal property ratio

$$\begin{aligned} \Psi_{\mathrm{mp}} &= [(T_{\mathrm{gwr}} - T_u)/(T_{\mathrm{gdr}} - T_0)]^{\mathrm{EXP1}} \\ \Psi_{\mathrm{tp}} &= [(T_{\mathrm{gdr}} - T_0)/(T_{\mathrm{gwr}} - T_u)]^{\mathrm{EXP2}} \end{aligned} \tag{10}$$

Table 6 Correlation of measured and calculated lamina properties at room and elevated temperatures

A

Lamina properties (state variables at room temperature)	Measured	Micromechanics theory Precorrelation	Micromechanics theory Postcorrelation
Elastic modulus, tensile (MSI)	33.0	31.8	32.94
Thermal conductivity, in-plane (Btu/h-ft-°F)	11.0	10.89	11.0
Coefficient of thermal expansion in-plane (10^{-6}/°F)	1.7	1.99	1.7

B

Design variables (at room temperature)	Precorrelation	Postcorrelation
Matrix modulus, E_m (MSI)	36.6	39.1
Matrix conductivity, K_m (Btu/h-ft-°F)	14.3	14.4
Matrix coefficient of expansion α_m (10^{-6}/°F)	2.21	1.65

C

Lamina properties (state variables at 2000°F)	Measured	Micromechanics theory Precorrelation	Micromechanics theory Postcorrelation (after 2nd level)
Elastic modulus, tensile (MSI)	28.2	22.5	28.47
Thermal conductivity, in-plane (Btu/h-ft-°F)	8.8	7.61	9.0
Coefficient of thermal expansion, in-plane (10^{-6}/°F)	1.7	4.07	1.87

where

T_{gwr} = wet glass transition temperature
T_{gdr} = dry glass transition temperature for the resin matrix
T_u = use (operating) temperature
T_0 = reference temperature (70°F)

As seen from Eq. (9), the moduli and strengths of the matrix are multiplied by the reduction factor Ψ_{mp} to obtain the adjusted properties of the matrix. The thermal properties, such as coefficient of thermal expansion and thermal conductivity are multiplied by the factor Ψ_{tp} to account for the hygrothermal conditioning.

In this second level tailoring the exponents EXP1 and EXP2 (initial value of 0.5) in Eq. (10) are adjusted to correlate the micromechanics calculated and test measured unidirectional ply or weave properties. It is important to note here that by adjusting the exponents, the design variables (matrix properties) obtained from the first level of correlation are modified to correlate the unidirectional ply or balanced weave properties at the elevated temperature of interest.

The minimization of Eq. (8) using numerical optimization methods, require the sensitivity of the compromise function with respect to the correlation parameters contained in X, and this is given by

$$\frac{\partial}{\partial x} E(x) = \frac{\left\{ \sum_{k=1}^{np} \alpha_k^2 \frac{[p_k(x) - p_k^m] \frac{\partial}{\partial x} p_k(x)}{(p_k^{ic} - p_k^m)^2} \right\}}{E(X)} \tag{11}$$

The derivatives of the unidirectional ply properties that are required for evaluating Eq. (11) is in turn computed by analytically differentiating the micromechanics equations in ICAN. For balanced weave, a finite differencing procedure is used.

An example of a ceramic matrix composite (Nicalon fiber/Silicon Carbide matrix) laminate is used for demonstration of this correlation methodology. The results of the first level tailoring problem are summarized in Tables 6A and 6B. For this example, the initial micromechanics calculation is by itself close to the measured lamina properties and is further improved after the first level solution. The results of the second level tailoring for correlation of lamina properties at the elevated temperature of interest (2000°F) are provided in Table 6C. Clearly, after the tailoring process, an acceptable level of correlation is obtained in the lamina properties.

Several benefits of this micromechanics tailoring procedure exist, including 1) the ability to correlate micromechanics calculated ply properties with measured properties, and thereby resulting in improved analytical model for use in structural analysis; 2) the ability to back out the effective (in situ) matrix properties as part of the composite. This is the effective property of all constituents outside of load bearing fibers; and 3) the usefulness to micromechanics-based life and damage models.

The tailoring of the constituent properties is performed as a continuous variable problem, meaning, the matrix and fiber properties are treated as continuous variables. However, in reality these properties may have to take certain discrete values. Future work will address the use of genetic search strategy,[13] for the discrete variable micromechanics tailoring.

VIII. Summary

A composites ply layup optimization capability for aircraft engine structures that allows for multiple objective functions for mechanical and thermal loading environment is currently being developed. The approximation concepts based design optimization philosophy is adopted. The validity of certain gradient approximations, not commonly used in the structural optimization literature, is investigated. The overall capability is demonstrated on several realistic, large-scale, composite engine problems. Based on the examples presented here, it is concluded that design optimization technology can provide a robust approach for tailoring composite engine components for structural, thermal, and aeromechanical responses. In addition, the derivative approximations are found to be sufficiently accurate to guide the search in the right direction.

The second aspect of this article is on a numerical optimization based micromechanics tailoring procedure. This approach to tailoring composite constituent properties is found to be an efficient and useful methodology for correlating measured and calculated ply properties, and to back out the effective (in situ) matrix properties of the composite.

Present work is directed towards implementation of the semianalytic sensitivity analysis capability and a genetic search strategy based discrete variable optimization algorithm. Future efforts would be addressed towards providing for an integrated shape/material/layup optimization of composite aircraft engine components, for multidisciplinary design requirements.

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