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Surendra N. Singhal
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

Christos C. Chamis
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

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Surendra N. Singhal[1]
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

Christos C. Chamis[2]
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

A computational simulation procedure is described for multidisciplinary analysis and tailoring of layered multi-material hot composite engine structural components subjected to simultaneous multiple discipline-specific thermal, structural, vibration, and acoustic loads. The effect of aggressive environments is also simulated. The simulation is based on a three dimensional finite element analysis technique in conjunction with structural mechanics codes, thermal/acoustic analysis methods, and tailoring procedures. The integrated multidisciplinary simulation procedure is general-purpose including the coupled effects of nonlinearities in structure geometry, material, loading, and environmental complexities. The composite material behavior is assessed at all composite scales, i.e., laminate/ply/constituents (fiber/matrix), via a nonlinear material characterization hygro-thermo-mechanical model. Sample tailoring cases exhibiting nonlinear material/loading/environmental behavior of aircraft engine fan blades, are presented. The various multidisciplinary loads lead to different tailored designs, even those competing with each other, as in the case of minimum material cost versus minimum structure weight and in the case of minimum vibration frequency versus minimum acoustic noise.

Introduction

Advanced composite materials are making inroads in structural applications in general, and in propulsion systems in particular, leading to light weight, structurally sound and cost effective replacements of conventional materials. In cases such as the High Speed Civil Transport with extreme temperatures, conventional materials simply won't suffice. The feasibility of an acceptable design hinges on the use of advanced composite materials which can be tailored for required performance. Designing with composite materials poses multi-faceted challenges in the areas of material selection, fabrication processes, thermo-structural interaction, durability, and life. Then, there are special considerations such as acoustic noise. The design process is further compounded due to additional complexities such as aggressive environments, nonlinear material/structural behavior, and coupling between responses induced by discipline-specific loads. Present design procedures are usually based on loosely coupled tailoring schemes. The result is a design which satisfies some, but not all, sometimes conflicting requirements, resulting in premature failures. Clearly, coupled multidisciplinary analysis/tailoring methods capable of simulating all involved discipline-specific loads and their interaction with each other, are needed. Experiments being generally expensive and requiring a relatively long time from developing the test methods to interpreting the results, computational simulation of the physical phenomena governing the response of the structure, is the cost-effective way of designing complex composite structures.

One of the early efforts recognizing the need for developing coupled multidisciplinary analysis and tailoring methods/codes, is described in a National Aeronautics and Space Administration (NASA) report[1]. The effort continues to evolve and contains a multitude of discipline-specific as well as integrated codes covering a vast spectrum of consistent, compatible, and interactive methods/computer codes[2]. Recently, a stand-alone multidisciplinary analysis and tailoring procedure/code was developed by integrating the three dimensional finite element analysis method with several single-discipline (thermal, acoustic[3]) codes including those for integrated composite mechanics[4] and optimization methods[5].

The objective of the present paper is to demonstrate the computational simulation of the multidisciplinary design tailoring procedures for layered multi-material hot composite structures, exemplified for propulsion components (Fig. 1).

Multidisciplinary Tailoring - Brief Description

A general-purpose methodology based on finite elements formulation was developed to computationally simulate the coupled multidisciplinary heat transfer, structural, vibration, and acoustic tailoring of hot composite structures in propulsion environments. The various disciplines are coupled for nonlinear geometrical, material, and environmental effects. Fig. 2 shows the integrated multidisciplinary analysis and tailoring methodology for computationally simulating the response of composite structures. The various single-discipline analysis capabilities are listed on the top center of Fig. 2. The thermal, mechanical, and acoustic properties of the composite material are nonlinear functions of parameters such as temperature and environments. The composite mechanics, used for computing laminate properties for structural analysis and for computing the local structural response at various composite scales, is handled via an Integrated Composite Analyzer, ICAN[4]. An optimizer based on feasible directions formulation is used for tailoring the results of the multidisciplinary analysis.

The Integrated Composite Analyzer ICAN, shown in Fig. 3, is used for determining thermal/mechanical properties at various scales (fiber/matrix constituents, ply, and laminate) of the composite structure based on composite micro-mechanics and laminate theories, given the reference properties of the constituents. A nonlinear material characterization hygro-thermo-mechanical model[6] shown in Fig. 4, is used at the matrix scale to simulate the degradation in material properties due to applied temperature, time, and environmental effects, via an iterative approach, as shown in Fig. 3. The ICAN module uses composite micromechanics and laminate theories to automatically calculate the multi-scale composite properties of the undamaged arbitrary combinations of layered multi-material composite configurations, as well as for the degraded configurations at various stages of the composite structure life-cycle. The room temperature properties of fiber/matrix constituents for typical aircraft structure materials are automatically extracted from the ICAN resident data bank which can be augmented for properties of new materials. This feature results in a considerable saving of time required for searching and inputting the composite material property data.

The modular structure of the computer code developed based on the methodology described above, is shown in Fig. 5. The simulation procedure is controlled through an executive module. The user provides the input through the executive module as shown on top center of Fig. 5. The left side of Fig. 5 shows the analysis modules as required by the various discipline-specific loads. As shown on the right side of Fig. 5, the code contains a dedicated database for efficient data manipulation, nonlinear solvers and history tracking routines to simulate the various nonlinearities and time dependencies, and several utility routines for resident data processing capabilities. The output, as shown on the bottom center of Fig. 5, can be in various forms including tables, graphs, and videos.

The tailoring procedure is shown in Fig. 6. The first step is the specification of the tailoring input. The tailoring input consists of the objective function, design variables, constraints, and convergence tolerances. The next step is to establish the current design via the initial multidisciplinary analysis based on values of the current design variables. The many discipline-specific loads activate the required multidisciplinary analysis modules, listed on the right side of Fig. 6. It can be seen in Fig. 6 that the tailoring procedure is iterative. The gradients of the objective function and constraints are computed with respect to the design variables. The search direction vector is defined. A new set of design variables is chosen along the search direction. A new proposed design based on the new design variables is then simulated. The multidisciplinary analysis is used for computing the new design. Based on the specified tolerances, the objective function, design variables, and constraints are checked for an optimum design. The iterative procedure is repeated until an optimum design, that satisfies all the constraints, is reached.

Fig. 7 shows the flow of the various multidisciplinary analysis modules needed for multidisciplinary tailoring. First, the Model Definition module generates the finite element model of the structure geometry, composite configuration, boundary conditions, and loads. The Integrated Composite Analyzer module, ICAN[4] is then used for determining the thermal and mechanical properties at various scales (fiber/matrix constituents, ply, and laminate) of the composite structure, as explained in Fig. 3.

The computational procedure for coupled heat transfer, structural, vibration, and acoustic analysis is based on the three dimensional finite element formulation. The heat transfer response is computed via the Thermal Analysis module, THEAN, capable of performing linear steady state, nonlinear steady state, linear transient, and nonlinear transient analyses with thermal properties computed and updated via the ICAN module. The coupled composite-mechanics/heat-transfer analyses with iteratively tailored design updates, thus, allow thermal tailoring of composite materials/structures.

The same finite element mesh that was used for the heat transfer analysis, is also used for the structural and vibration analyses. This minimizes the data preparation time and eliminates the errors incurred in transforming the temperatures from one finite element mesh to another. Two types of structural analyses: (1) static and (2) buckling can be performed, at the end of any heat transfer analysis step. The vibration analysis computes the modal response, ie., the free vibration frequencies and mode shapes. The environmental effect (temperature and moisture) on the structural and vibration response is accounted for via the ICAN module. Nonlinear geometric effects such as large deformation/centrifugal stiffening are accounted for via updated Lagrange analysis. The local structural response at ply and fiber/matrix scales of the composite structure, is computed via ICAN, as shown on the right side of Fig. 3. The structural and vibration tailoring of composite structures can be performed including the coupling between all interactive disciplines (composite-mechanics/heat-transfer/structural-analysis/vibrations) including geometric, material, and loading nonlinearities and environmental effects.

The acoustic analysis module, ACOAN computes the acoustic noise emitted from the composite structure, due to (1) free vibration, or (2) forced vibration induced by applying a force at a point of the structure, selectively exciting the vibration modes of interest. The acoustic noise is computed by first calculating radiation efficiencies of the structure for each natural vibration mode as a function of forced vibration frequency. The total noise power for each forced vibration frequency is then calculated by summing the contribution from each free vibration mode. A part of the structure can be masked from emitting the noise. The acoustic tailoring of composite structures can be performed with desired coupling between all interacting disciplines (composite-mechanics/heat-transfer/structural-analysis/vibration/ acoustic-noise) including geometric, material, and loading nonlinearities and environmental effects.

The multi-load step analysis feature allows coupling among all the participating disciplines by passing the updated geometry and updated material behavior back to any one or all analysis disciplines via a nonlinear iterative procedure.

The coupling between the various disciplines due to geometrical, material, loading, and environmental complexities described above, allows many combinations of coupled multidisciplinary analyses, as has been demonstrated for a fan blade[7]. There are several other advanced features in this computational simulation procedure, not discussed herein as they are not included in the demonstration cases presented in this paper.

Sample Cases - Fan Blade

A layered, multi-material aircraft engine fan blade was tailored for multidisciplinary thermal, vibration, and acoustic response as well as material cost and structure weight. The geometry, boundary conditions, material, composite configuration, environment, and thermal/structural/acoustic loads are shown in Fig. 8. A summary of the various tailoring cases including the objective function, design variables, and constraints, is provided in Table 1.

Blade Structure, Material, and the Finite Element Model

The blade consists of a twisted aerofoil shape with varying thickness along the span. As shown in Fig. 8, the blade is made of layered multi-material composite - 50% thickness of titanium core and 50% thickness of outer layers of T300/IMHS material with 30 degree fiber orientation (with respect to the radial direction, x) and 0.6 fiber volume ratio. The T300 stands for the graphite fibers and IMHS for intermediate high strength epoxy matrix. The thermal and mechanical properties of the T300 fibers and IMHS matrix at room temperature can be found in Ref. 7. The finite element model consisted of 40 20-noded (8 corner and 12 mid-side) brick elements with 110 nodes.

Thermal Tailoring

The root of the blade was held at a constant temperature of 200 °F and the blade surface was subjected to fluid flow at 300 °F (Fig. 8). The thermal material properties; thermal conductivity and coefficient of heat convection, were considered temperature-dependent via the Integrated Composite Analyzer, ICAN. A nonlinear steady-state heat transfer analysis coupled with composite mechanics was conducted. Two tailoring cases were performed: (1) for minimizing the maximum blade temperature, and (2) for minimizing the maximum blade temperature gradient. The design variables include thickness and orientation of the layers, with different upper and lower bounds for different material layers, as shown in Table 1. The total blade thickness is constrained to remain constant.

The thermal tailoring of the fan blade resulted in about 5% reduction of the maximum temperature and about 17% reduction of the maximum temperature gradient, which will significantly reduce thermal stresses in the tailored design. The design before and after tailoring, for the minimization of maximum temperature gradient, is shown in Fig. 9. The tailoring paths for the objective function and design variables are shown in Fig. 10. The thickness of the less thermally conductive titanium layer decreased up to its specified lower bound and the combined thickness of the T300/IMHS layers increased so as to keep the total blade thickness constant. Similarly, the orientation of the T300/IMHS layers became more radial (than circumferential) to maximize thermal conduction in the radial direction, consistent with higher thermal conductivity of the fibers compared to that of the matrix.

Vibration Tailoring

The root of the blade was fixed. Two tailoring cases were performed at room temperature with no moisture absorption: (1) for minimizing the fundamental vibration frequency, and (2) for maximizing the fundamental vibration frequency. The design variables include orientation of all layers with upper and lower bounds, as shown in Table 1. The total blade thickness is constrained to remain constant. The second and third vibration frequencies are also constrained by upper and lower bounds.

The vibration tailoring of the fan blade resulted in about 18% reduction for the minimization of the fundamental vibration frequency. And, the maximization of the fundamental vibration frequency resulted in about 64% increase. The tailoring results for the maximization of fundamental vibration frequency are shown in Figs. 11 and 12. The orientation of the T300/IMHS layers became more radial (than circumferential) to maximize the stiffness in the radial direction, consistent with higher stiffness of the fibers compared to that of the matrix.

Acoustic Tailoring

The root of the blade was fixed and sinusoidal forced vibrations of 10 lb amplitude were applied at the leading edge tip in the blade thickness direction, at the forcing frequency of 79 cps (Fig. 8). Note that the fundamental vibration frequency of the blade is 79.1 cps. One tailoring case was performed for minimizing the acoustic noise emitted from the fan blade at room temperature with no moisture absorption. The design variables include orientation of the layers, with upper and lower bounds, as shown in Table 1. The total blade thickness is constrained to remain constant. It is to be noted that the tailoring can be performed with many special features available in the simulation procedure, but not demonstrated in the present paper. One such feature is the inclusion of the damping of the composite material and its interaction with material and environmental parameters. The modal loss factors used for this evaluation are only estimates. The computational simulation of damping in composite materials has been developed[8,9] and will be included in future studies.

The tailoring for acoustic noise emitted from the fan blade resulted in about 85% reduction in noise power. The equivalent reduction in decibels is about 9% which is significant considering the fact that the decibel scale is logarithmic. The tailoring results for the minimization of acoustic noise are shown in Figs. 13 and 14. To minimize the acoustic noise from the fan blade, its composite configuration must change to cause maximum difference between the applied forced acoustic excitation frequency and the changed blade vibration frequency. Since, the 79.1 cps vibration frequency of the fan blade is very close to the 79 cps forced acoustic excitation frequency, the noise level can be decreased by either decreasing or increasing the blade vibration frequency. However, as noted in the vibration tailoring results, the maximum tailorable reduction in the blade vibration frequency was only about 18%, whereas the maximum tailorable increase in it was a significant 64%. Hence, the minimum noise level is achieved by increasing the blade vibration frequency which occurs by aligning the T300/IMHS fibers more towards the radial direction. Note that above discussion is based on the fundamental vibration mode. The total noise level emitted from the blade depends on the modal summation of the noise power generated due to all blade vibration modes. However, for the sample case under discussion, the major contribution to the noise power is from the fundamental vibration made.

Cost Tailoring

The material cost for the T300 fibers was considered to be five times that of titanium. One tailoring case was performed for minimizing the material cost for the composite fan blade. The design variables include thickness of all layers, with different upper and lower bounds for different materials, as shown in Table 1. The total blade thickness is constrained to remain constant.

The material cost tailoring of the fan blade resulted in about 27% reduction in the total material cost. The tailoring results are shown in Fig. 15. The tailored design shows a significant reduction in the more expensive T300/IMHS layer thicknesses versus an increase in the less expensive titanium layer thickness, up to its allowable upper bound.

Weight Tailoring

The density for titanium is about three times that of T300/IMHS composite. One tailoring case was performed for minimizing the structure weight for the composite fan blade. The design variables include thickness of all layers, with different upper and lower bounds for different materials, as shown in Table 1. The total blade thickness is constrained to remain constant.

The structure weight tailoring of the fan blade resulted in about 30% reduction in the total structure weight. The tailoring results are shown in Fig. 16. The tailored design shows a significant combined increase in lighter weight T300/IMHS layer thickness versus a reduction in the heavier weight titanium layer thickness, up to its allowable lower bound.

Tailoring in Aggressive Environments

Sample cases were simulated for multidisciplinary tailoring in aggressive environments. The effect of propulsion environments was simulated for tailoring the vibration and acoustic response under (1) uniform temperature rise from 70 to 300 °F with no moisture absorption and (2) combined uniform temperature rise from 70 to 300 °F and 2 % absorption of moisture in the composite, by weight. The thermal and mechanical properties were considered temperature-dependent via ICAN.

The current and tailored fundamental vibration frequency and acoustic noise emitted from the blade for the various environmental conditions are shown in Figs. 17 and 18, respectively. As the temperature and moisture absorption increase: (1) the vibration frequency, both for the current and tailored designs, decreases due to degradation in the material stiffness, and (2) the acoustic noise emitted from the blade undergoes competing influences. The forced acoustic excitation frequency moves farther away from the blade vibration frequency causing decreased noise levels and the blade material becomes less stiff causing increased vibration amplitudes and hence increased noise levels. Fig. 18 shows an increase in the noise level due to increased temperature and moisture absorption.

In summary, minimization of maximum blade temperature/maximum temperature gradient, maximization of vibration frequency, and minimization of acoustic noise require T300 fibers to be oriented more in the radial (than circumferential) direction. However, tailored fiber orientations differ significantly for different tailoring disciplines. And, minimization of maximum blade temperature/maximum temperature gradient/structure weight require thicker T300/IMHS layers whereas minimization of cost requires thicker titanium layers.

The significant observation is that the various multidisciplinary loads lead to different tailored designs, sometimes just opposite of each other, as in the case of (1) minimum material cost versus minimum structure weight, (2) minimum vibration frequency versus minimum acoustic noise, and (3) minimum vibration frequency versus minimum temperature/temperature gradient. The multidisciplinary analysis/tailoring procedure/code demonstrated in the present paper provides a complete set of results for all applicable loads via one single code, minimizing the time spent by the analyst/designer in collecting all the necessary information.

General Remarks

A stand-alone computational simulation procedure has been demonstrated for multidisciplinary analysis and tailoring of an aircraft engine fan blade under simultaneous thermal/structural/vibration/acoustic loading in hot and humid propulsion environments. The information generated for each discipline-specific design with optimization of maximum temperature, maximum temperature gradient, vibration frequency, and acoustic noise, demonstrate the effectiveness of multidisciplinary computational simulation and the various, sometimes competing design requirements. Results for tailored design variables, such as those related to the composite configuration, required for the optimum response obtained from all the involved disciplines, provide a complete set of comprehensive multidisciplinary boundaries for various design parameters. And, the results, such as the decrease in tailored vibration frequency and increase in tailored acoustic noise levels by accounting for environmental effects, exhibit the significance of coupled multidisciplinary simulation of the blade. In an effort to satisfy the competing requirements imposed by individual discipline-specific behavior, many design variations/parameters will need to be considered. Multidisciplinary computational simulation is the approach that will provide a realistic assessment of the various competing design requirements of advanced composite materials/structures. Unlike experimental data generation that may be untimely and costly, computational simulation is able to produce rapid reasonable results for specific designs.

Summary

A general-purpose computational simulation procedure is presented for coupled multidisciplinary thermal, structural, vibration, and acoustic analysis and tailoring of hot composite structures in propulsion environments. All the disciplines are coupled for nonlinear geometrical, material, loading, and environmental effects. The thermal, mechanical, and acoustic properties of the composite material are nonlinear function of design parameters such as temperature and environments. The procedure is embedded in a stand-alone state-of-the-art computer code, enabled by integrating the three dimensional finite element technique with in-house codes for integrated composite mechanics, thermal/acoustic analysis, and optimization methods. A nonlinear material characterization model is used to simulate the degradation in material properties due to applied temperature, time, and environmental effects. Sample cases exhibiting multidisciplinary tailoring of an aircraft engine fan blade, were presented. Results lead to reduced temperatures and substantially reduced temperature gradients, reduced or increased vibration frequencies depending on the design needs, significantly reduced acoustic noise, and reduced material cost/structure weight for the tailored design of the composite fan blade structure. Collectively, the results provide a wealth of information for effective utilization of composite materials/structures.

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Table 1: Multi-disciplinary Tailoring Demonstrated for Fan Blade

Discipline	Objective Function	Design Variables	Constraints
Thermal	(i) Maximum Nodal Temperature (ii) Maximum Temperature Gradient	Layer Thickness: t T300/IMHS: (0.1 inch < t < 0.7 inch) Titanium: (0.2 inch < t < 0.7 inch) Layer Orientation: Θ T300/IMHS: (-90 deg. < Θ < 90 deg.)	Constant total blade thickness
Vibration	Fundamental Vibration Frequency	Layer Orientation: Θ T300/IMHS: (-90 deg. < Θ < 90 deg.)	(i) Constant total blade thickness (ii) Upper and lower bounds on second and third vibration frequencies
Acoustic	Acoustic Noise Emitted by the Blade	Layer Orientation: Θ T300/IMHS: (-90 deg. < Θ < 90 deg.)	Constant total blade thickness
Cost	Material Cost	Layer Thickness: t T300/IMHS: (0.1 inch < t < 0.7 inch) Titanium: (0.2 inch < t < 0.7 inch)	Constant total blade thickness
Weight	Structure Weight	Layer Thickness: t T300/IMHS: (0.1 inch < t < 0.7 inch) Titanium: (0.2 inch < t < 0.7 inch)	Constant total blade thickness

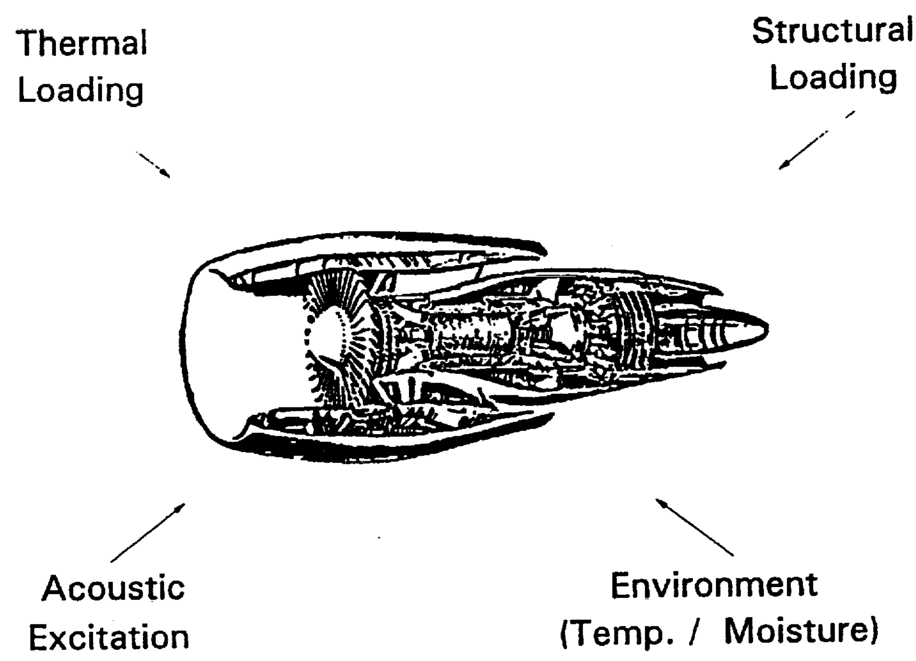


Fig. 1: Engine Components Under Multidisciplinary Loadings

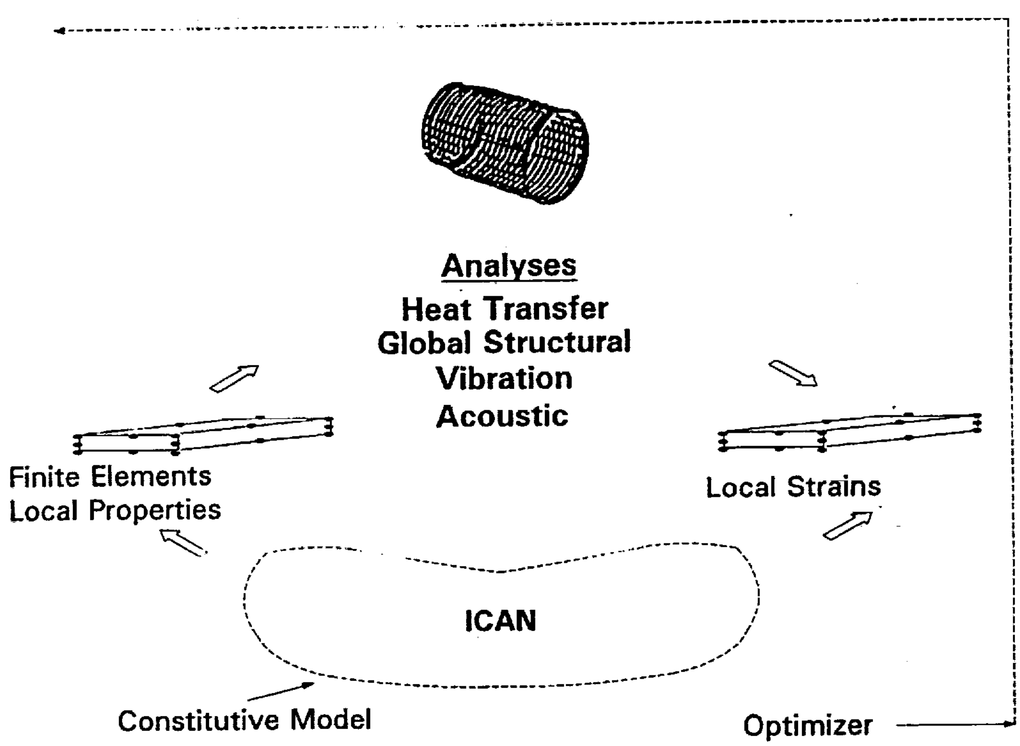


Fig. 2: Multidisciplinary Analysis/Tailoring Coupled with Integrated Composite Analyzer

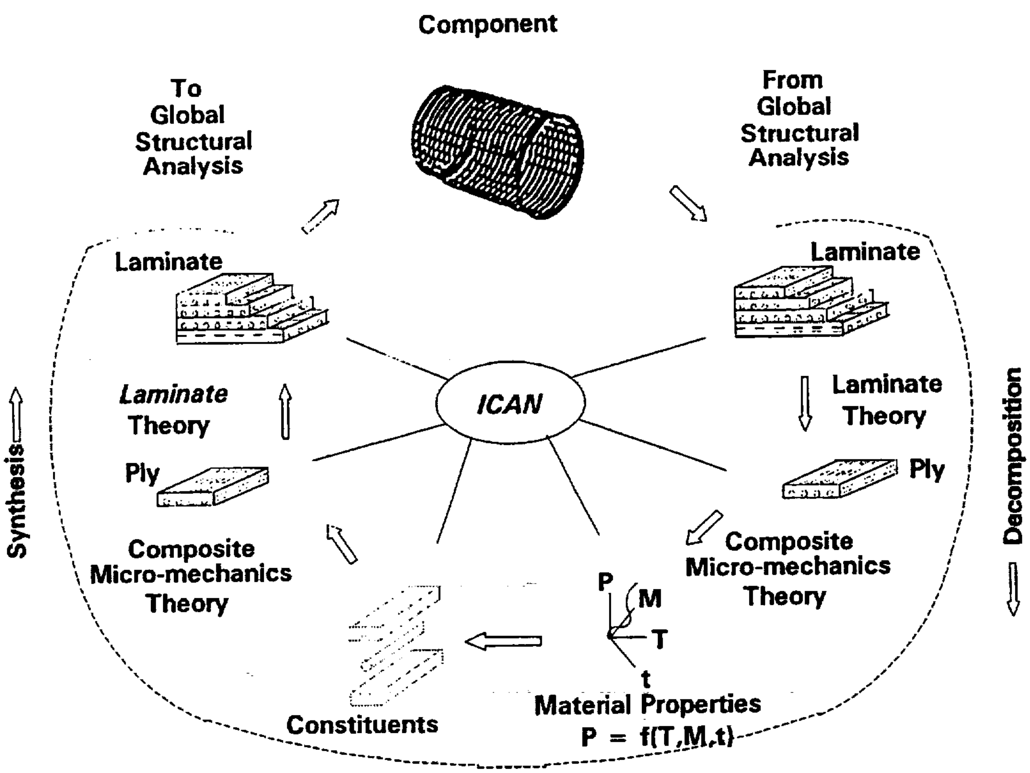
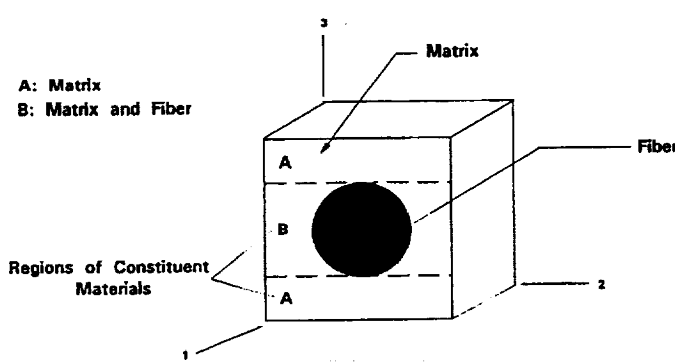


Fig. 3: Integrated Composite Analyzer (ICAN)



$$\frac{P_M}{P_{Mo}} = \left[\frac{T_{GW} - T}{T_{GD} - T_o}\right]^{1/2}$$

$$T_{GW} = (0.005\,M^2 - 0.1\,M + 1)T_{GD}$$

P_M = Matrix Property at Current Temp., T

P_{Mo} = Matrix Property at Reference Temp., T_o

T_{GW} = Wet Glass Transition Temp.

T_{GD} = Dry Glass Transition Temp.

M = Moisture

Fig. 4: Regions of Constituent Materials and Nonlinear Material Characterization Model

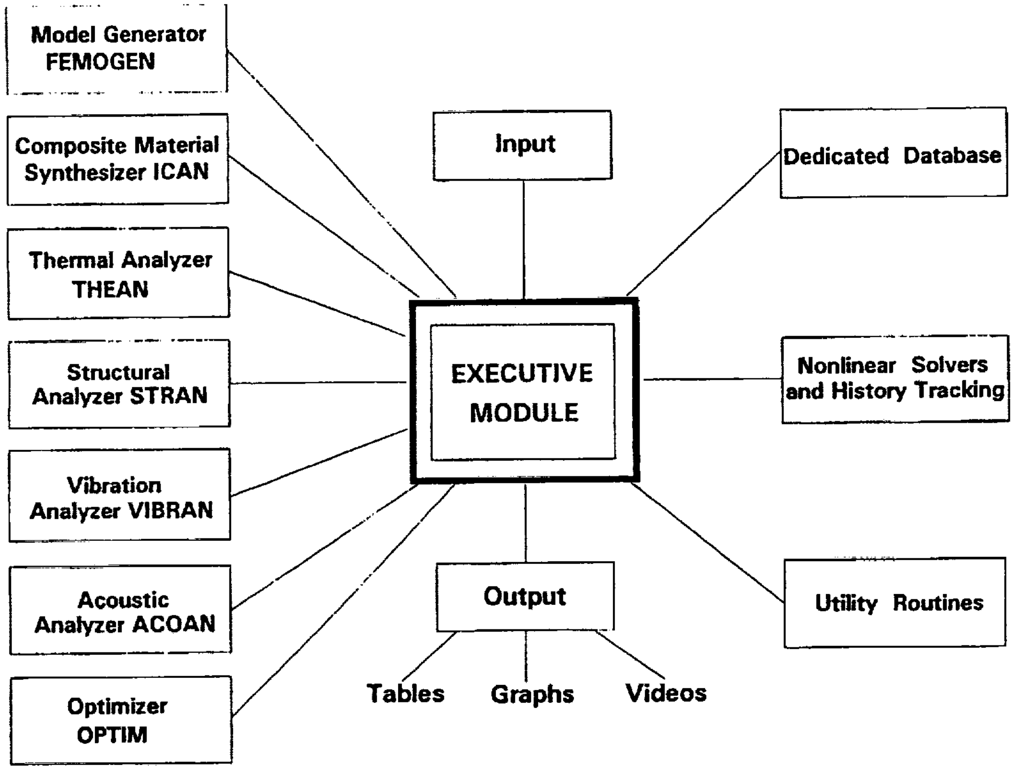


Fig. 5: Multidisciplinary Modular Structure

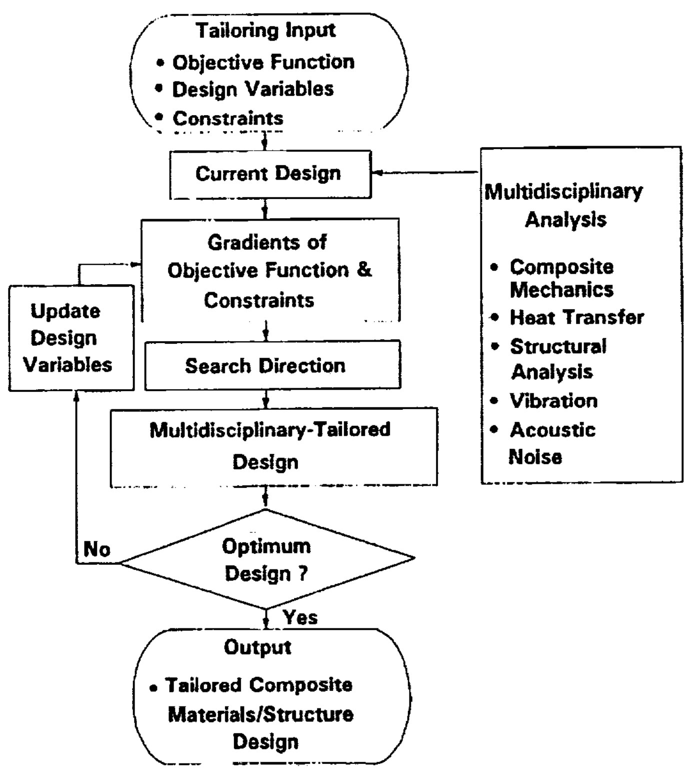


Fig. 6: Multidisciplinary Tailoring Procedure

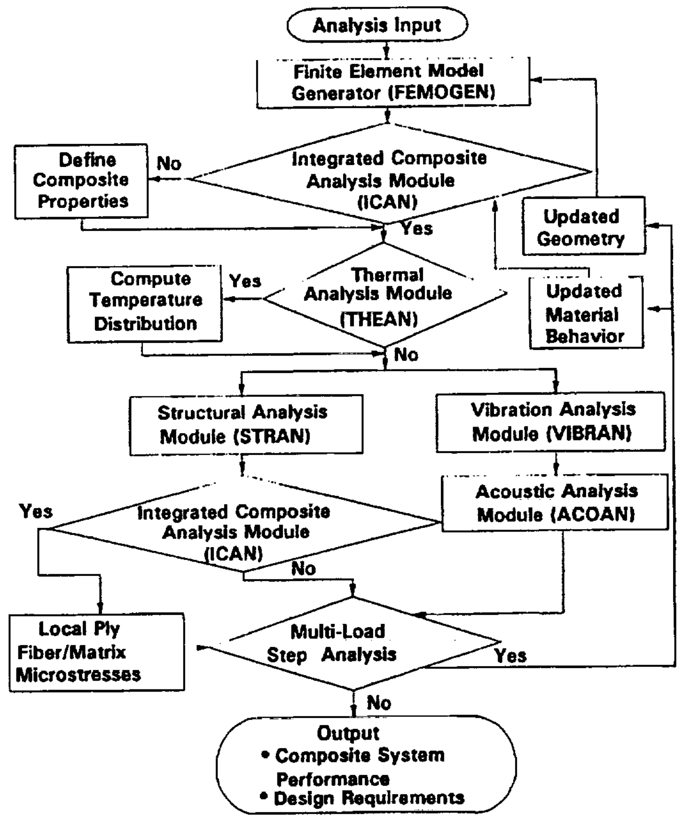
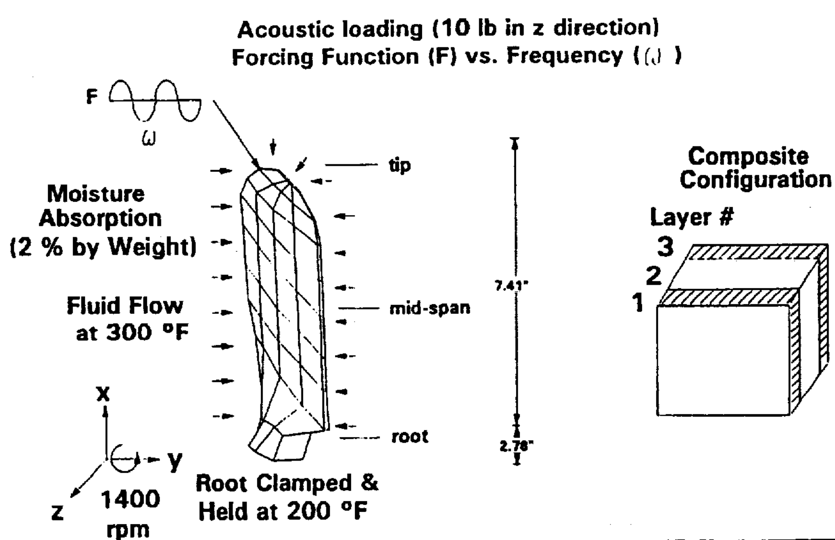


Fig. 7: Multidisciplinary Analysis Procedure



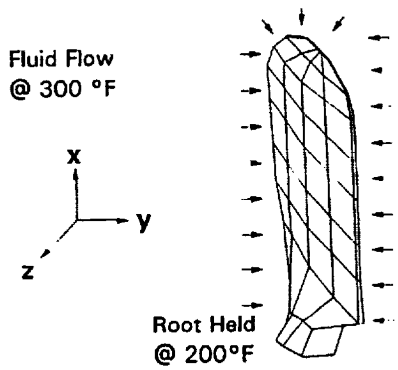
Current Design Values

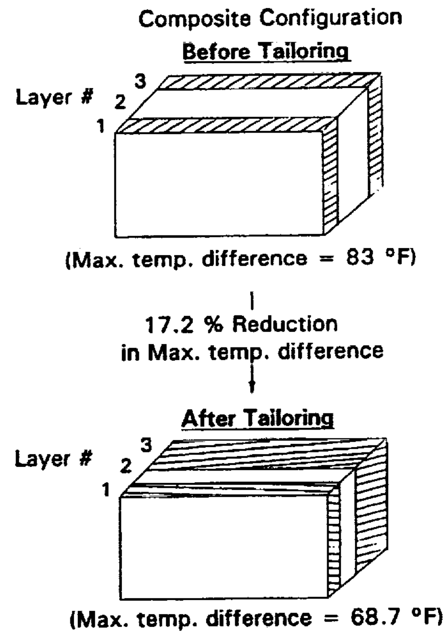
Layer #	Material	Thickness (fraction)	Orientation w.r.t. x-axis (deg.)
1	T300/IMHS	0.25	30
2	Titanium	0.5	0
3	T300/IMHS	0.25	30

Region	Dimension			
	Chord (inch)	Twist (deg. w.r.t. root)	Thickness (inches) @ leading edge	Thickness (inches) @ trailing edge
tip	1.22	39.8	0.01	0.007
mid-span	3.64	21.5	0.07	0.04
root	0.67	0.0	0.1	0.08

Fig. 8: Fan Blade: Current Design under Multidisciplinary Loading

Objective:	Minimize Maximum Temperature Difference
Design Variables:	Layer Thicknesses (0.1 < Layer Thickness < 0.7) for T300/IMHS
	(0.2 < Layer Thickness < 0.7) for Titanium
	T300/IMHS Layer Orientations (-90 deg. < Layer Orientation < 90 deg.)
Constraint:	Constant Total Thickness





Design Before & After Tailoring

Layer #	Material	Thickness (fraction)		Orientation w.r.t. x-axis (deg.)	
		Before	After	Before	After
1	T300/IMHS	0.25	0.21	30	-12.8
2	Titanium	0.5	0.20	0	0
3	T300/IMHS	0.25	0.59	30	5.2

Fig. 9: Thermal Tailoring of Composite Fan Blade: Design Before and After Tailoring

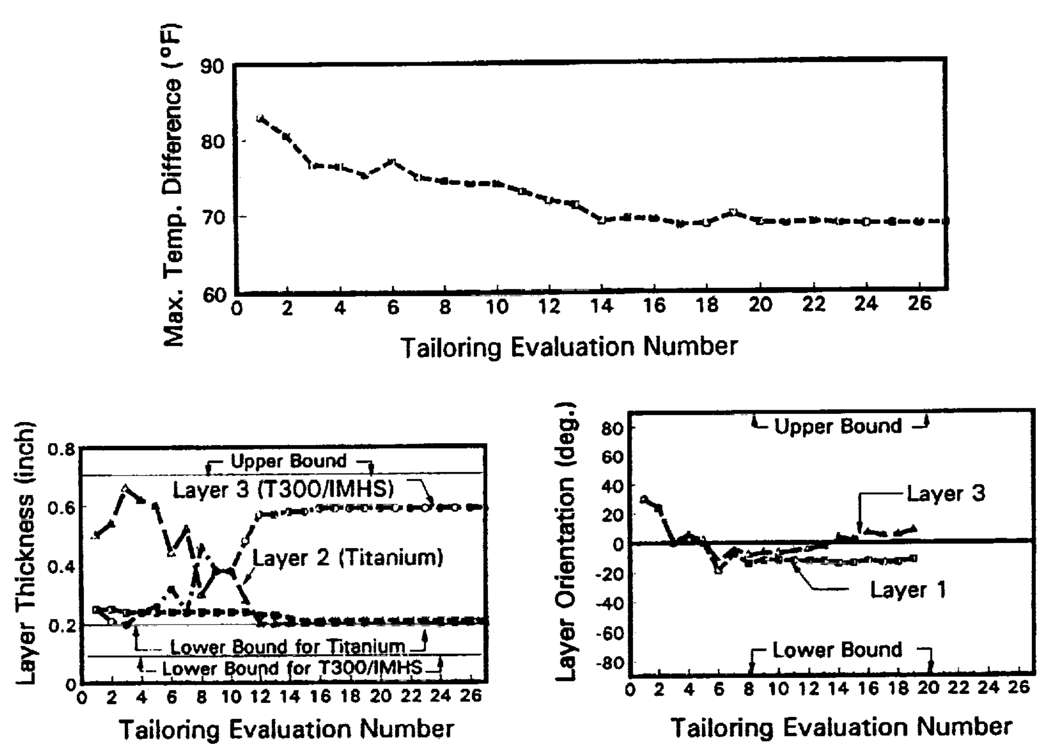


Fig. 10: Thermal Tailoring of Composite Fan Blade: Tailoring Path

Objective: Maximize Fundamental Vibration Frequency

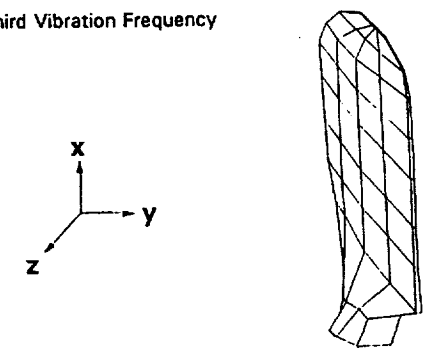
Design Variables: T300/IMHS Layer Orientations (-90 deg. < Layer Orientation < 90 deg.)

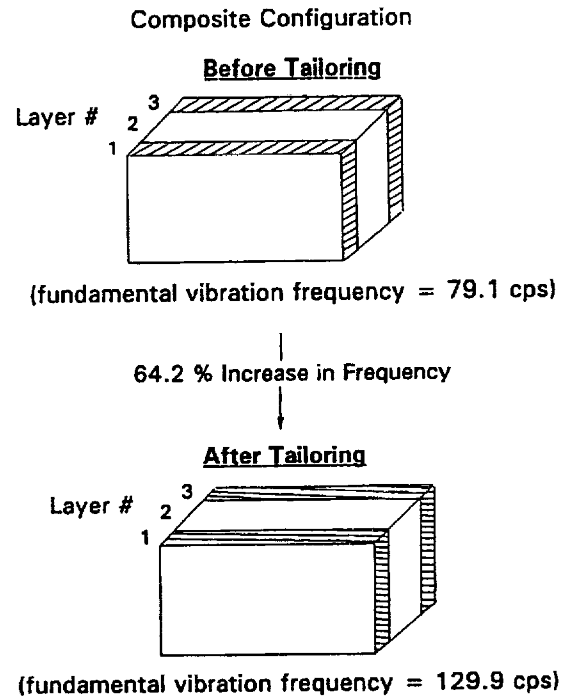
Constraint: Constant Total Thickness

$20 \text{ cps} < f_2, f_3 < 500 \text{ cps}$

f_2 : Second Vibration Frequency

f_3 : Third Vibration Frequency





Design Before & After Tailoring

Layer #	Material	Orientation w.r.t. x-axis (deg.)		Thickness (fraction)
		Before	After	
1	T300/IMHS	30	-4.7	0.25
2	Titanium	0	0	0.5
3	T300/IMHS	30	-3.5	0.25

Fig. 11: Vibration of Composite Fan Blade: Design Before and After Tailoring

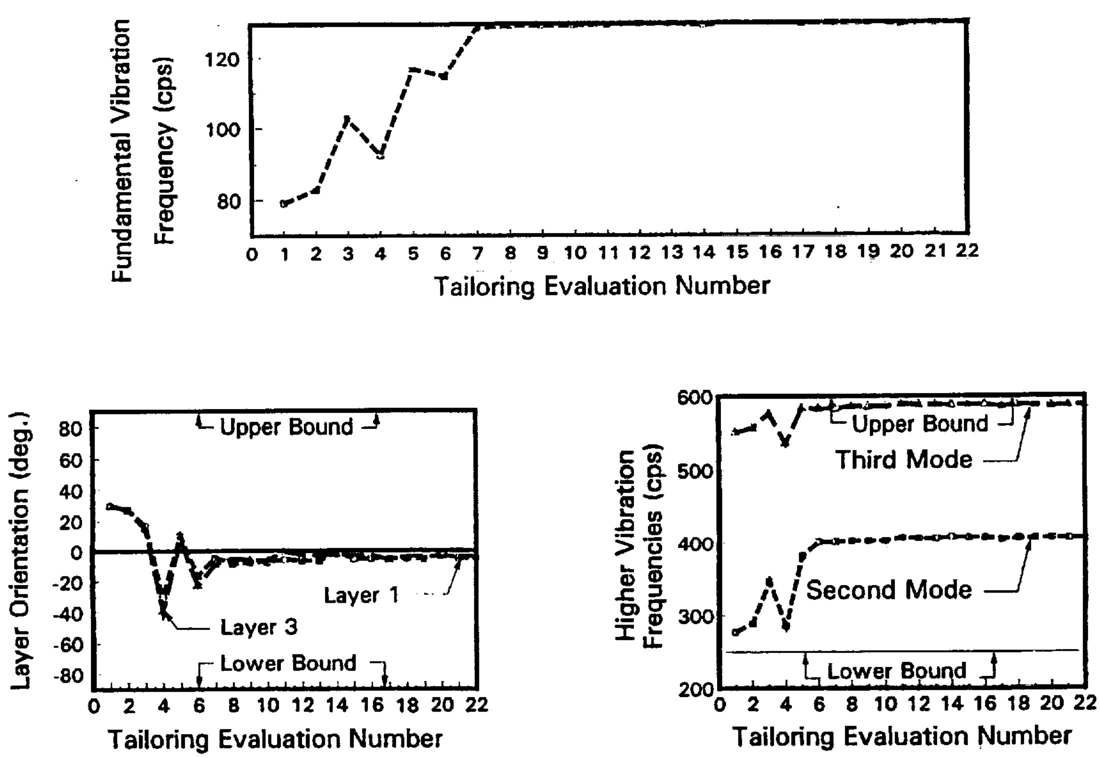
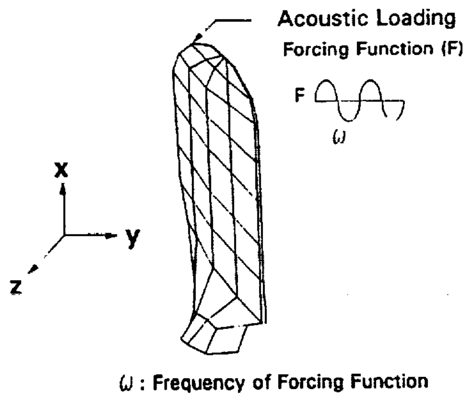


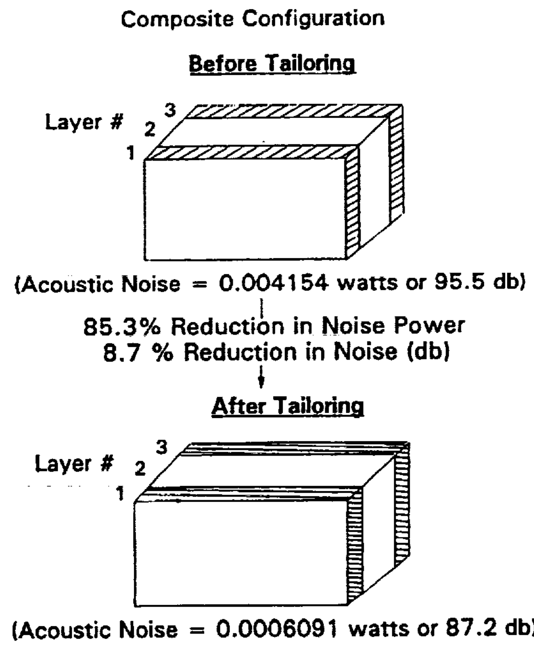
Fig. 12: Vibration of Composite Fan Blade: Tailoring Path

Objective: Minimize Acoustic Noise

Design Variables: T300/IMHS Layer Orientations (-90 deg. < Layer Orientation < 90 deg.)

Constraint: Constant Total Thickness





Design Before & After Tailoring

Layer #	Material	Orientation w.r.t. x-axis (deg.)		Thickness (fraction)
		Before	After	
1	T300/IMHS	30	-3.7	0.25
2	Titanium	0	0	0.5
3	T300/IMHS	30	-1.7	0.25

Fig. 13 Acoustic Tailoring of Composite Fan Blade: Design before and AfterTailoring

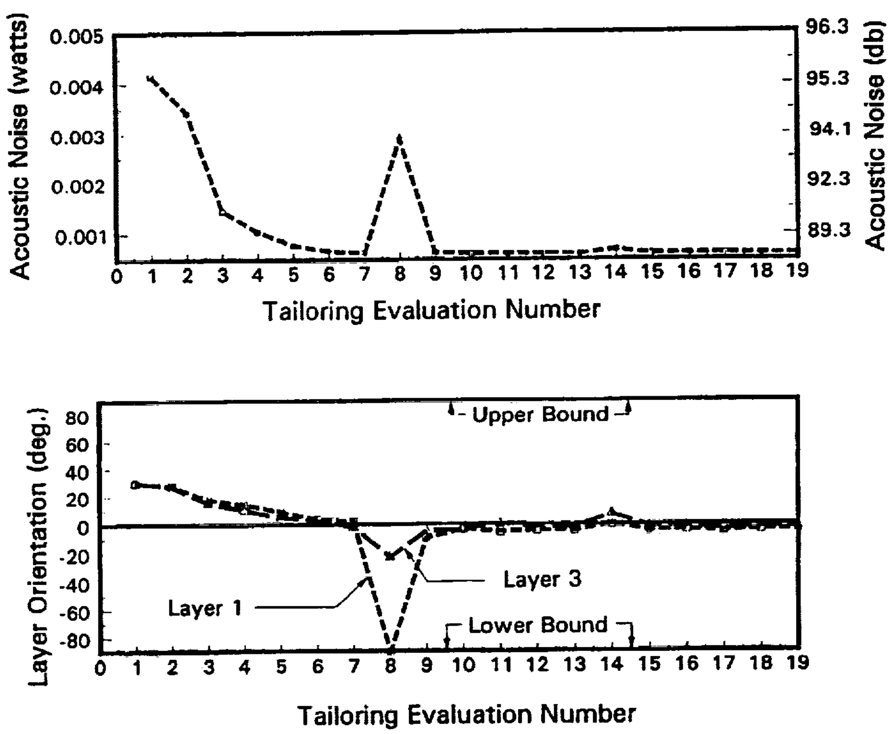
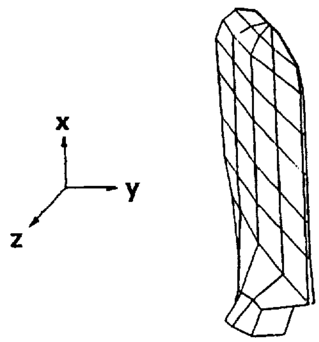


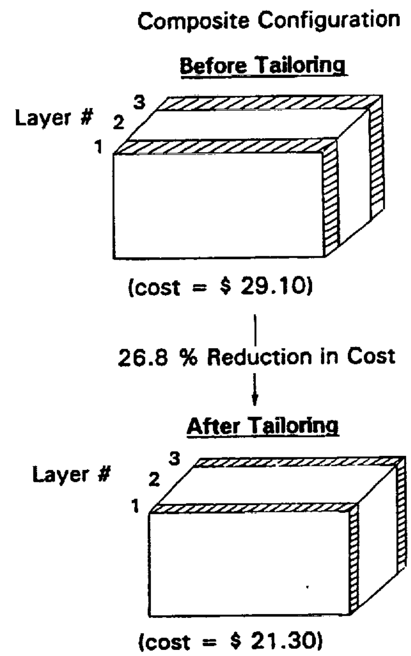
Fig. 14: Acoustic Tailoring of Composite Fan Blade: Tailoring Path

Objective: Minimize Material Cost

Design Variables: Layer Thicknesses (0.1 < Layer Thickness < 0.7) for T300/IMHS
(0.2 < Layer Thickness < 0.7) for Titanium

Constraint: Constant Total Thickness





Design Before & After Tailoring

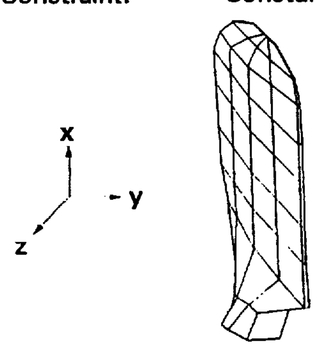
Layer #	Material	Cost ($/lb)	Thickness (fraction) Before	Thickness (fraction) After	Orientation w.r.t. x-axis (deg.)
1	T300/IMHS	20	0.25	0.15	30
2	Titanium	4	0.5	0.7	0
3	T300/IMHS	20	0.25	0.15	30

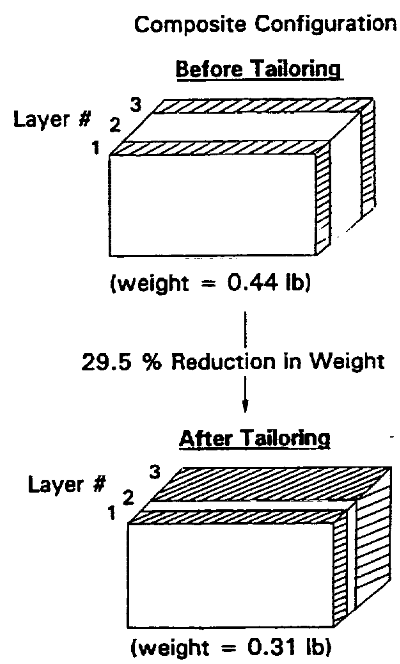
Fig. 15: Cost Tailoring of Composite Fan Blade: Design Before and After Tailoring

Objective: Minimize Structure Weight

Design Variables: Layer Thicknesses (0.1 < Layer Thickness < 0.7) for T300/IMHS
(0.2 < Layer Thickness < 0.7) for Titanium

Constraint: Constant Total Thickness





Design Before & After Tailoring

Layer #	Material	Density (lb/in^3)	Thickness (fraction) Before	Thickness (fraction) After	Orientation w.r.t. x-axis (deg.)
1	T300/IMHS	0.056	0.25	0.25	30
2	Titanium	0.161	0.5	0.2	0
3	T300/IMHS	0.056	0.25	0.55	30

Fig. 16 Weight of Composite Fan Blade: Design Before and After Tailoring

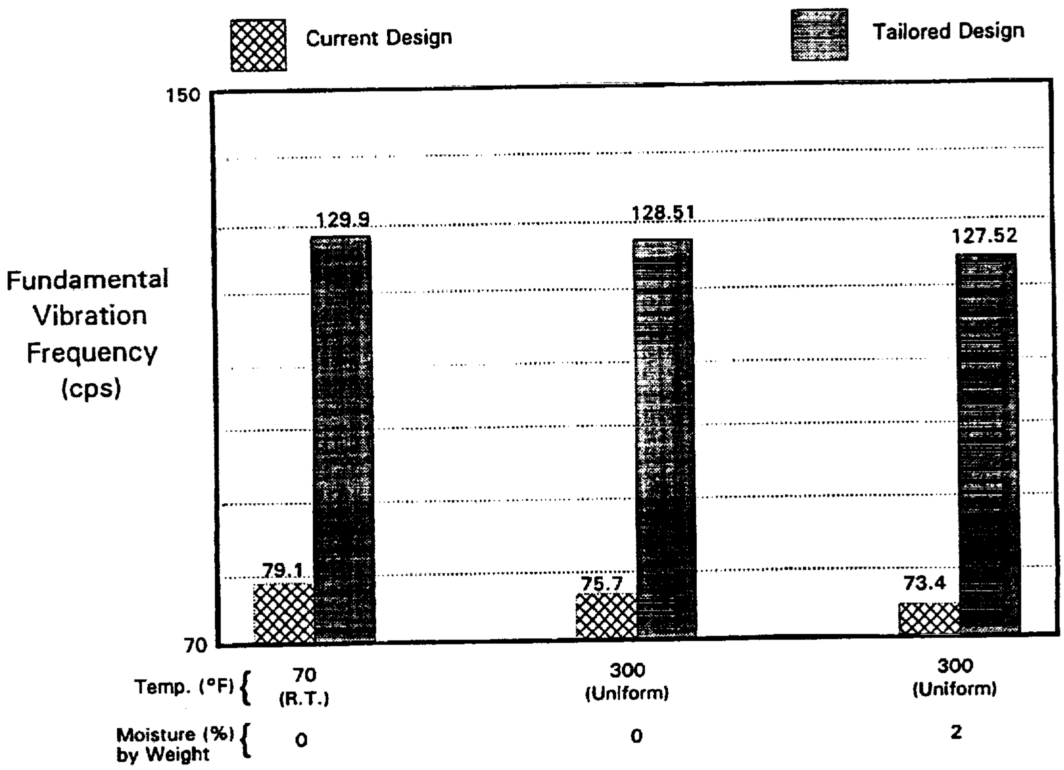


Fig. 17: Vibration Tailoring of Composite Fan Blade-Effect of Environments

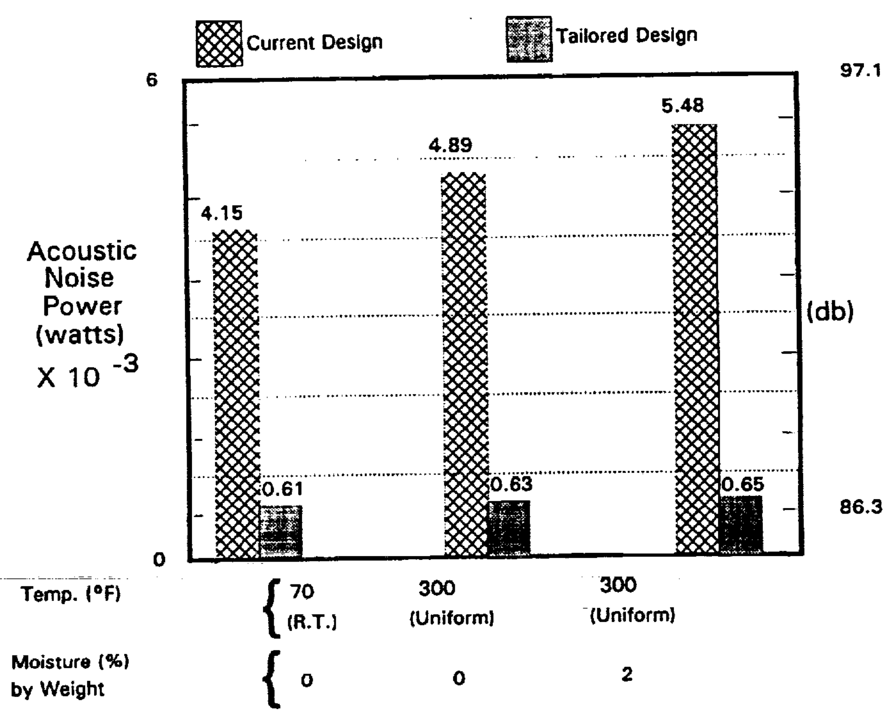


Fig. 18: Acoustic Tailoring of Composite Fan Blade - Effect of Environments

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Surendra N. Singhal and Christos C. Chamis

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2001 Aerospace Parkway
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13. ABSTRACT ***(Maximum 200 words)***
A computational simulation procedure is described for multidisciplinary analysis and tailoring of layered multi-material hot composite engine structural components subjected to simultaneous multiple discipline-specific thermal, structural, vibration, and acoustic loads. The effect of aggressive environments is also simulated. The simulation is based on a three-dimensional finite element analysis technique in conjunction with structural mechanics codes, thermal/acoustic analysis methods, and tailoring procedures. The integrated multidisciplinary simulation procedure is general-purpose including the coupled effects of nonlinearities in structure geometry, material, loading, and environmental complexities. The composite material behavior is assessed at all composite scales, i.e., laminate/ply/constituents (fiber/matrix), via a nonlinear material characterization hygro-thermo-mechanical model. Sample tailoring cases exhibiting nonlinear material/loading/environmental behavior of aircraft engine fan blades, are presented. The various multidisciplinary loads lead to different tailored designs, even those competing with each other, as in the case of minimum material cost versus minimum structure weight and in the case of minimum vibration frequency versus minimum acoustic noise.

14. SUBJECT TERMS
Acoustic excitation; Acoustic noise; Composites; Cost; Environmental effect; Heat transfer; Hygro-thermo-mechanics; Multidisciplinary analysis; Multidisciplinary tailoring; Nonlinear geometry; Nonlinear material; Nonlinear loading; Nonlinear environmental effects; Optimization; Polymer matrix composites; Simulation; Structural analysis; Tailoring; Thermal response; Vibration; Weight

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