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STAEBL -- STRUCTURAL TAILORING OF ENGINE BLADES (PHASE II)

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Structural Tailoring of Engine Blades (STAEBL)

The STAEBL program was initiated at NASA Lewis Research Center in 1980 to introduce optimal structural tailoring into the design process for aircraft gas turbine engine blades. As indicated in Figure 1, the standard procedure for blade design is highly iterative with the engineer directly providing most of the decisions that control the design process. The goal of the STAEBL program has been to develop an automated approach to generate structurally optimal blade designs.

The program has evolved as a three-phase effort with the developmental work being performed contractually by Pratt & Whitney Aircraft. Phase I was intended as a "proof of concept" in which two fan blades were structurally tailored to meet a full set of structural design constraints while minimizing DOC+I (direct operating cost plus interest) for a representative aircraft. This phase was successfully completed and was reported in references 1 and 2. Phase II has recently been completed and is the basis for this discussion. During this phase, three tasks were accomplished: (1) a nonproprietary structural tailoring computer code was developed; (2) a dedicated approximate finite-element analysis was developed; and (3) an approximate large-deflection analysis was developed to assess local foreign object damage. Phase III is just beginning and is designed to incorporate aerodynamic analyses directly into the structural tailoring system in order to relax current geometric constraints.

The Goal of STAEBL: Automated Engine Blade Design

- Current Design Procedure:

  The engineer performs design iterations manually

- STAEBL Procedure:

  Apply mathematical optimization to blade design

The Evolution of STAEBL

- Phase I (Completed): Proof of Concept

  Demonstrate the ability to realistically structurally tailor gas turbine engine blades

- Phase II (Completed): Develop Software System

  Develop a nonproprietary structural tailoring software system with dedicated structural analyses

- Phase III (Current): Aerodynamic Analysis

  Incorporate aerodynamic analyses into STAEBL to relax geometric constraints

Figure 1

STAEBL Procedure

The overall procedure developed for STAEBL during Phase I is shown in Figure 2. The tailoring process was divided into two stages: (1) approximate analysis; and (2) refined analysis. The first stage, outlined by the dotted line, uses approximate analyses for vibration, flutter, stress and FOD (foreign object damage) along with an optimizer to find a candidate optimal design. The COPES/CONMIN optimization code developed by G. N. Vanderplaats was selected as the optimizer for STAEBL [3, 4]. Once a candidate design is found, it is passed to the second stage where refined analyses are performed to evaluate the design against imposed constraints. If all constraints are met, the design is accepted as the optimal design. Otherwise, the constraints imposed during the approximate analyses are modified to reflect the differences between the two levels of analysis, and the structural tailoring procedure is repeated.

During Phase II the approximate analyses and the optimizer were incorporated into a nonproprietary computer code. Also, specialized approximate analyses were developed for basic structural analysis (stress and vibration) and for local FOD analysis.

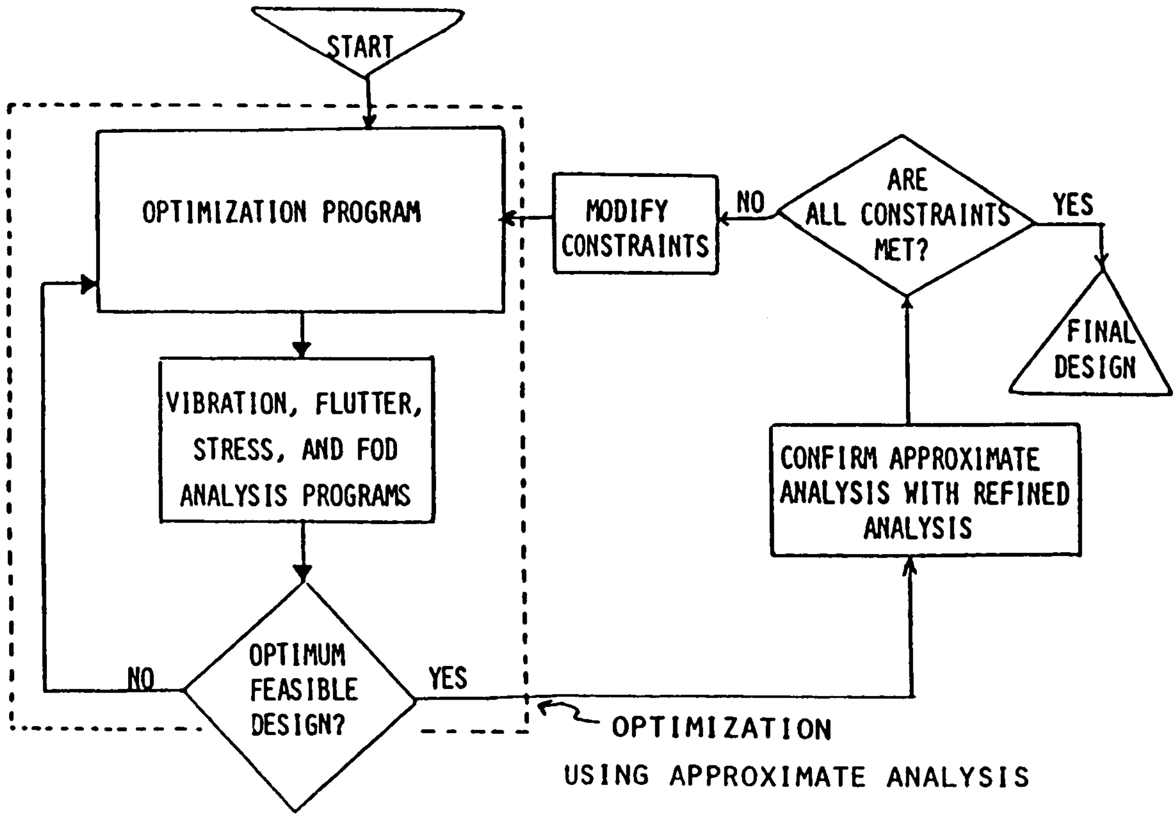


Figure 2

Demonstration Cases

During Phase I and II, two shroudless fan blade designs were used to demonstrate the effectiveness of STAEBL. These designs are a superhybrid composite fan blade and a hollow titanium fan blade with a composite inlay, shown in Figure 3. The starting point for these designs was a hollow, shroudless titanium fan blade designed by Pratt & Whitney Aircraft as part of the NASA-sponsored Energy Efficient Engine program. Also, during Phase II a solid titanium compressor blade was optimally tailored using STAEBL.

The fan blade cases were selected because of the difficulty in designing an acceptable shroudless blade relative to a shrouded blade. Typically, fan blades are designed with a mid-span shroud that ties neighboring blades together under normal operating conditions. The shroud acts as a connecting ring which greatly stiffens the blade in torsion and bending. Without the shroud the blade can be very susceptible to flutter due to a low torsional natural frequency and may undergo excessively large deflections as a result of a bird strike. However, shrouds add extra weight to the fan stage and result in unwanted aerodynamic blockage.

The independent design variables for the blades included root chord, thickness-to-chord ratio, material thickness, and composite fiber angle. In the case of the hollow blade, the cavity size and location could also be varied. The number of blades was not constant but varied inversely with the blade chord to maintain a fixed solidity.

STAEBL WAS DEMONSTRATED ON TWO FAN BLADES OF ADVANCED CONSTRUCTION

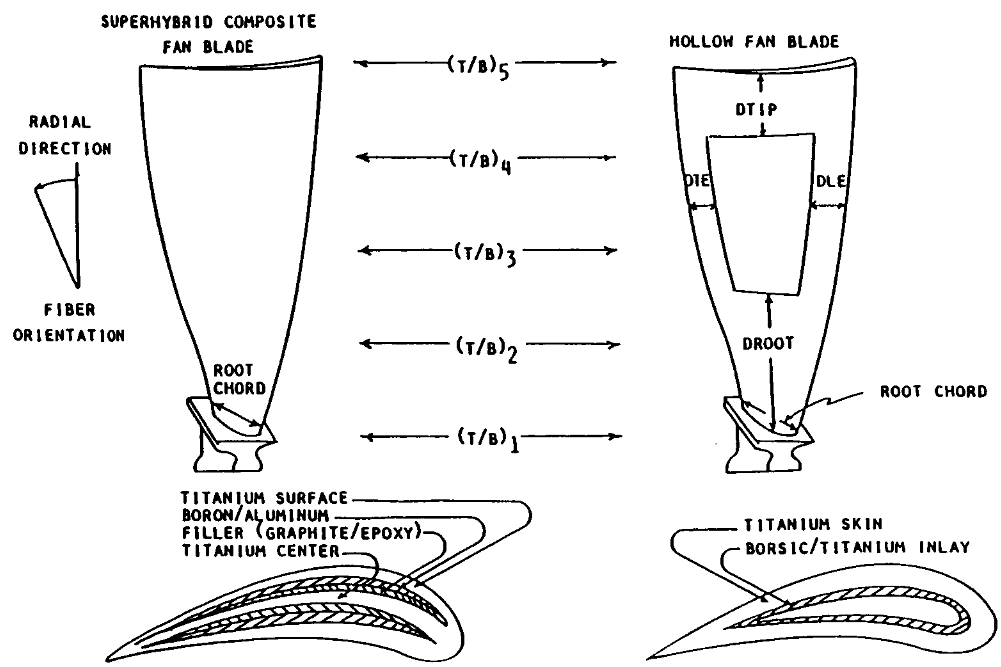


Figure 3

Design Constraints

In order for the STAEBL procedure to be demonstrated as a useful approach to design engine blades, realistic constraints were imposed on all candidate optional designs, as listed in Figure 4. Geometric constraints consisted of upper limits on thickness-to-chord ratio along the span, and minimum allowable titanium skin thickness and boundaries on the cavity for the hollow fan blade. Engine order resonances were avoided by requiring a frequency margin of 5% for critical engine order/mode combinations. Maintaining this margin over the normal operating range is accepted procedure for avoiding high-cycle fatigue failure. During Phase II an additional option was added to explicitly calculate the forced response of a blade subjected to specified loads of engine order frequencies. Aeroelastic stability was maintained by requiring aerodynamic excitations to be negatively damped in the first three modes (1st and 2nd bending and 1st torsion modes). A critical requirement for fan blades is that they survive a bird strike. During Phase I local damage was based on an empirical factor. This was replaced by an approximate large-deflection analysis during Phase II. A modal response was used in both phases for root bending. The final constraint, stress, was evaluated from a beam analysis during Phase I. During this phase, the beam analysis was also used for the modal analysis. This beam analysis was replaced by an approximate finite-element analysis during Phase II.

Thickness-to-Chord Ratio
Titanium Skin Thickness
Cavity Boundaries

Resonance Margins
- 1st Mode 2E (engine order)
- 2nd Mode 3E
- 2nd Mode 4E
- 3rd Mode 4E
- Tip Mode 10 E (compressor)

Flutter-log Decrement
- 1st Mode
- 2nd Mode
- 3rd Mode

F O D (Bird Ingestion)
- Local Severe Damage
- Root Bending

Stresses
- Steady
- Fatigue

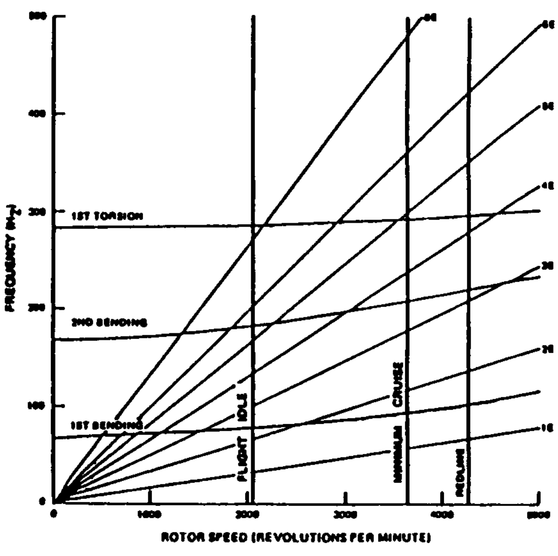


Figure 4

Structural Tailoring -- Phase I

The two demonstration cases run during Phase I of the STAEBL program were compared to a hollow shroudless titanium blade. In both cases two complete passes through the tailoring system were performed. The final results are shown in Figure 5. The hollow blade converged to an initial optimal blade after 13 iterations. Refined analysis showed stress and resonance constraints to be violated. Correction factors were applied to the constraints to reflect differences between refined and approximate analyses. After the second tailoring, requiring ten iterations, a resonance constraint was still violated. The cause of this violation was traced to incompatibilities between the approximate beam analysis of the blade and the refined finite-element analysis. No further tailoring was attempted. The near-optimal blade weighed 52% less than the reference blade and DOC+I was reduced by .45%. However, due to the 18% reduction in chord, more blades are needed for the stage. As such, the total blade weight per stage decreased by about 40%. The superhybrid blade required 15 iterations to converge to the first optimal candidate design. Refined analysis showed that one resonance and one flutter constraint were not satisfied. Correction factors were applied and a second tailoring requiring 13 iterations was performed. This design satisfied all constraints. The total blade weight for the stage was decreased by about 30% and DOC+I was reduced by .36%. While the reductions in DOC+I are small in absolute terms, engine component improvements which change DOC+I by a few tenths of a percent are considered to be significant.

	Reference Blade (Hollow Titanium)	Hollow Titanium Blade With Composite Inlays	Superhybrid Blade
Root Chord (in.)	9.12	7.46	8.32
Blade Weight (lb.)	19.2	9.3	12.1
△(DOC+I) (%)			
Engine Wt.	--	-.33	-.23
Engine Cost	--	-.15	-.18
Maintenance	--	+.03	+.05
Total	--	-.45	-.36
Active Constraints	2nd Mode 3E 1st Mode Flutter Local FOD	Min. Blade Thickness Cavity Location 2nd Mode 3E* 2nd Mode Flutter	Min. Blade Thick. 1st Mode Flutter Local FOD

* This constraint was not met completely when the tailoring was terminated

Figure 5

Specialized Finite-Element Analysis

During Phase I of the STAEBL program a beam model was used for approximate structural analyses. During Phase II a specialized coarse mesh finite-element analysis was developed and incorporated into STAEBL. The analysis utilizes variable thickness triangular plate elements to model the blade and Guyan reduction to reduce the size of the assembled mass and stiffness matrices. Lamination theory is used to model the different material layers through the thickness of the blade including the hollow cavity which is considered to be a layer with very small mass and stiffness. Guyan reduction is used to eliminate selected degrees of freedom and to condense the model into three sparse columns of nodes: one near the leading edge of the blade, one near the trailing edge, and one at mid-chord. The accuracy of this analysis was demonstrated on a model of the hollow titanium reference fan blade as shown in Figure 6. The data in the figure compares the natural frequencies of an equivalent beam model used during Phase I and a specialized plate model with a refined plate model. The error between the beam model and the refined model is about 9%, 3%, and 4.5% for the first, second, and third mode, respectively, while the corresponding error for the approximate plate model is uniformly about one-tenth as large. Also, the computer analysis time for the plate analysis, including model generation and reduction, is about the same as the solution time for the simpler beam analysis and only about 6% of the solution time for the refined analysis.

E^3 FAN BLADE NATURAL FREQUENCIES (CPS)

	APPROXIMATE BEAM MODE 66 DOF	SPECIALIZED PLATE MODEL 24 DOF.*	NASTRAN PLATE MODEL 1260 DOF
1ST MODE	101.0	92.9	93.0
2ND MODE	216.3	209.8	209.2
3RD MODE	288.7	274.6	276.1
COMPUTER TIME (CPU SEC)	6.0	6.2**	109

* REDUCED FROM 330 DOF
** INCLUDES MODEL GENERATION AND DOF REDUCTION

Figure 6

Approximate Severe FOD Analysis

One of the fundamental constraints imposed on turbine engine fan blades is the ability to survive a bird strike. This takes the form of surviving strong bending moments at the blade root and resisting severe local damage in the impact zone. Modal analysis of the blade with an impulsive impact load can be used adequately to estimate root bending. However, local damage analysis typically requires a fully nonlinear large-deflection analysis with an interacting impactor model. This involves too much computational effort to be useful for design iterations and, as such, empirical parameters are usually used as was done during Phase I of the STAEBL program. During Phase II an approximate large-deflection finite-element analysis was developed with an interactive representative loading model, depicted in Figure 7. The finite-element analysis models the impact region by retaining standard linear elastic bending in the chordwise direction but uses fully yielded large-deflection membrane action in the spanwise direction. This results in a model with linear mass and stiffness matrices which can be analyzed by conventional means. The bird is modeled by a representative loading profile which interacts with the blade to determine relative impact velocity and angle of impact which is used to identify the loaded nodes, peak pressure, and load duration. The approach taken is to use the first 10 natural modes to expand the deflections and loads in the impact region. The equations are then integrated numerically to determine structural response.

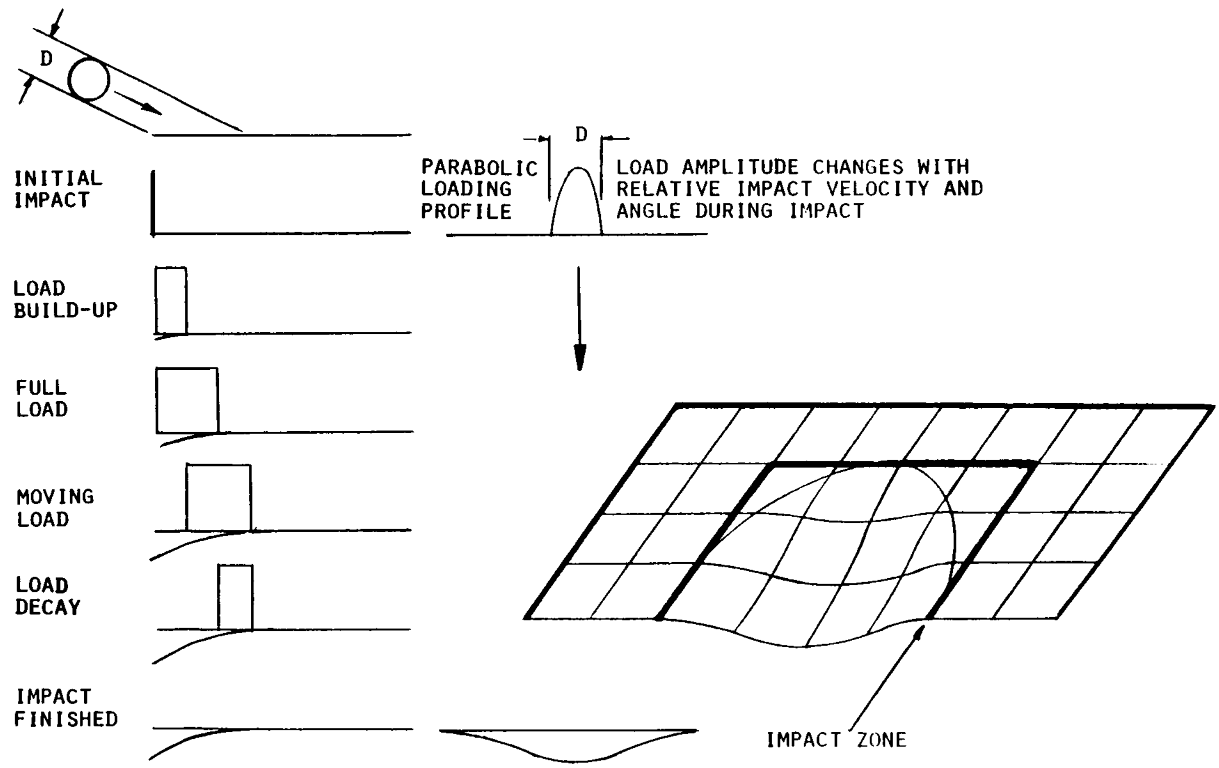


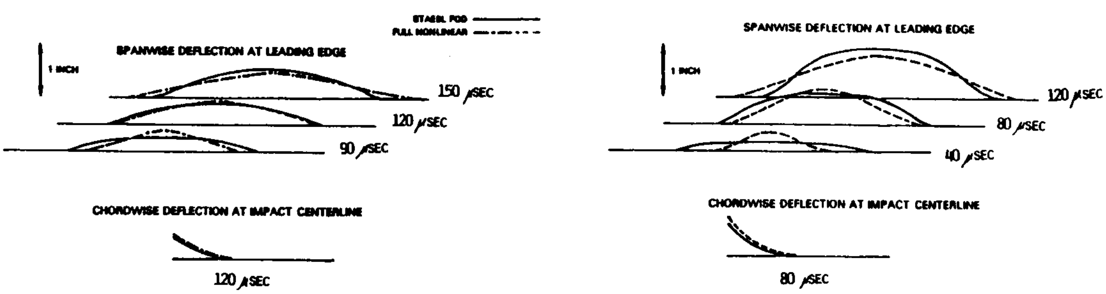
Figure 7

Impact Analysis Demonstration Cases

The accuracy of the approximate severe FOD analysis was demonstrated by comparison with a refined, fully nonlinear, large-deflection finite-element analysis using a nonlinear interacting fluid impactor model. The refined analysis was calibrated against experimental data in which a 1" diameter gelatin ball was fired at a thin titanium plate clamped on three sides [5]. Two experimental cases were run: a "light" impact with an impact velocity of 12,400 in/sec. and a "severe" impact with a velocity of 19,000 in/sec. In both cases the angle of impact was 30^{o}. The plate was 6" x 3" x .067" for the light impact and was tapered from mid-chord toward the free edge. For the severe impact, the maximum plate thickness was .126". The results from the approximate and refined analyses are shown in Figure 8. Note that in both impact cases the average strains for the two levels of analysis agree very well and the overall final deflection shapes are in good agreement. Differences between the peak strains for the two analyses are large. However, the approximate average strains can be scaled uniformly to agree with the refined analysis peak strains for the two cases shown. Finally, the computer time for the approximate analysis was only about .6% of the time required for the refined analysis. As such, the approximate severe FOD analysis can provide a good estimate of the degree of local damage, or possible failure, resulting from a bird strike at the expense of very little computer time.

EXAMPLE -- IMPACT OF A SPHERE ONTO TITANIUM PLATE
(APPROXIMATED BIRD STRIKE)

LIGHT IMPACT | SEVERE IMPACT



ANALYTICAL COMPARISON

	AVG. STRAIN (%)		MAX. STRAIN (%)			COMPUTER TIME (SEC)	
	STAEBL	FULL N. L.	STAEBL	SCALED STABEL*	FULL N. L.	STAEBL	FULL N.L.
LIGHT	1.02	1.00	4.7	5.1	5.8	1.8	300
SEVERE	4.0	4.0	11.0	20.0	19.5	1.8	300

* AVG. STAEBL x 5.0

Figure 8

Structural Tailoring - Phase II - Fan Blades

During Phase II of the STAEBL program, a hollow shroudless titanium fan blade with composite inlays and a superhybrid fan blade were structurally tailored, as was done during Phase I. The results are shown in Figure 9. Again, the reference blade was the hollow shroudless titanium Energy Efficient Engine fan blade designed by Pratt & Whitney Aircraft for NASA.

The initial design for the hollow blade was very similar to the reference blade. However, no appreciable improvement could be made after three optimization iterations. A new initial design was selected similar to the optimal hollow blade found during Phase I. A new optimal design was then found after ten iterations. Refined analysis showed no constraints were violated but that the design could be further improved. New calibration factors were calculated and the blade was re-optimized. The second tailoring converged after seven iterations. After the first pass through STAEBL, DOC+I was reduced by .53%. The second pass resulted in a further improvement to .61%.

The initial design for the superhybrid blade was the same initial design used during Phase I. After 15 iterations, STAEBL converged to an optimal design which was shown by refined analysis to violate a resonance and a flutter constraint. New approximate analysis calibration factors were calculated and a second tailoring was performed. This design converged in 19 iterations. It did not violate any constraints and reduced DOC+I by .48%.

	Reference Blade (Hollow Titanium)	Hollow Titanium Blade with Composite Inlays	Superhybrid Blade
Root Chord (in)	9.12	7.81	7.89
Blade Weight (lb)	19.2	8.86	9.73
Stage Weight (lb)	460.8	248.3	269.9
Δ(DOC+I) (%)			
Engine Wt.	--	-.16	-.35
Engine Cost	--	-.38	-.19
Maintenance Cost	--	-.07	+.06
TOTAL	-	-.61	-.48
Active Constraints	2nd Mode 3E 1st Mode Flutter Local FOD	1st Mode Flutter Max.Blade Thickness Cavity Location	Min.& Max.Blade Thickness 1st Mode Flutter Local FOD

Figure 9

Structural Tailoring - Phase II - Compressor Blade

During Phase II, a solid titanium sixth-stage compressor blade from the Energy Efficient Engine was also optimally tailored. This blade had an added constraint that the "tip" mode must avoid resonance with the 10th engine order excitation. This mode was identified by STAEBL during the tailoring procedure by comparing the tip deflection of leading and trailing edges of the blade with the tip mid-chord deflection for all modes calculated. Also, for this case the objective was changed to minimizing stage weight. A candidate optimal design was found by STAEBL after nine iterations. Refined analysis showed that no constraints were violated. The results are summarized in Figure 10. The individual blade weight was reduced by 56% and total stage weight was reduced by 28%. While the initial design had no active constraints, a resonance constraint was active for the tailored blade.

	Reference Blade	Tailored Blade
Root Chord (in.)	2.807	1.710
Blade Weight (lb.)	.431	.191
Stage Weight (lb.)	11.2	8.02
Active Constraints	None	1st Mode 2E

Figure 10

STAEBL Computer Code

STAEBL has been prepared as a nonproprietary computer code which includes a central executive, an optimizer, and all approximate analyses. The code has been delivered to NASA and is being prepared for public release. The general program architecture is shown in Figure 11. The code was designed in a modular form with separate modules for all key functions. The interfacing module functions as the executive and provides the communication links between the optimizer and the approximate analyses. Currently, the optimizer in STAEBL is COPES/CONMIN. However, during Phase III of the STAEBL program, the structural tailoring procedure will be augmented by adding an enhanced optimizer, ADS (Automated Design System) [6]. Since this system allows numerous optimization strategies and techniques to be used, part of the effort will be directed toward finding the most intelligent path for the structural tailoring of engine blades.

Also, during Phase III, the STAEBL procedure will be extended to include an aerodynamic analysis. At the present time, geometric constraints are imposed to maintain an aerodynamic design similar to a specified initial design. By incorporating an aerodynamic analysis capability into STAEBL those constraints can be relaxed and a true structurally optimal blade design can be found.

Due to the success of the STAEBL program, Pratt & Whitney Aircraft considers optimal structural tailoring to be an accepted element of the overall procedure to design new engine blades.

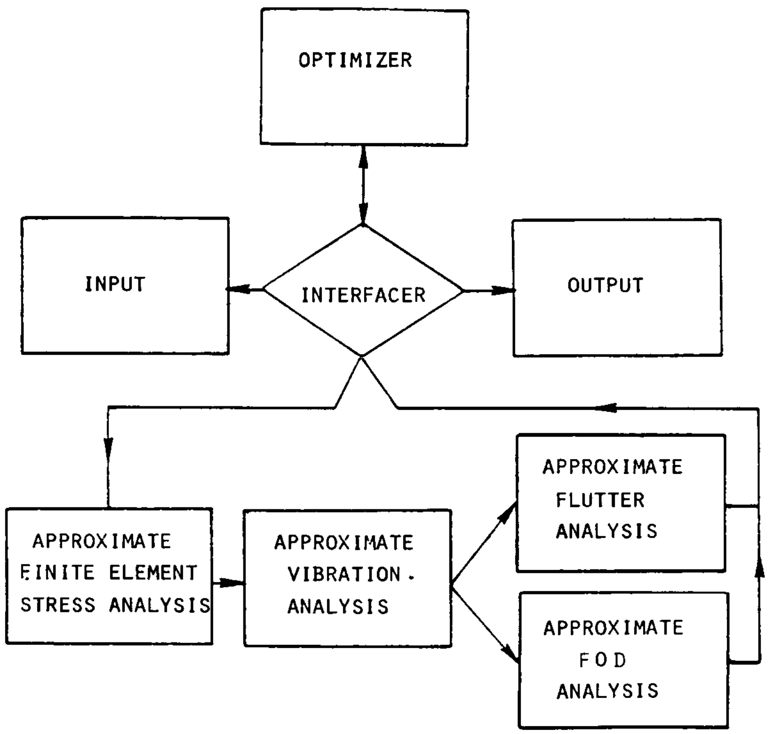


Figure 11

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