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STRUCTURAL TAILORING OF HIGH-SPEED TURBINE BLADES (SSME/STAEBL)*

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ABSTRACT

Space shuttle main engine (SSME) blades are subject to severe thermal, pressure, and forced vibration environments. An SSME blade design must meet tight clearance, fatigue life, and stress limit constraints. Because of the large number of potentially conflicting constraints, a "manual" design procedure may require many time-consuming iterations. Structural optimization provides an automated alternative. Any number of analyses, design variables, and constraints can be incorporated in a structural optimization computer code. This idea has been applied to develop the code SSME/STAEBL, which is a stand-alone code suitable for automated design of SSME turbopump blades.

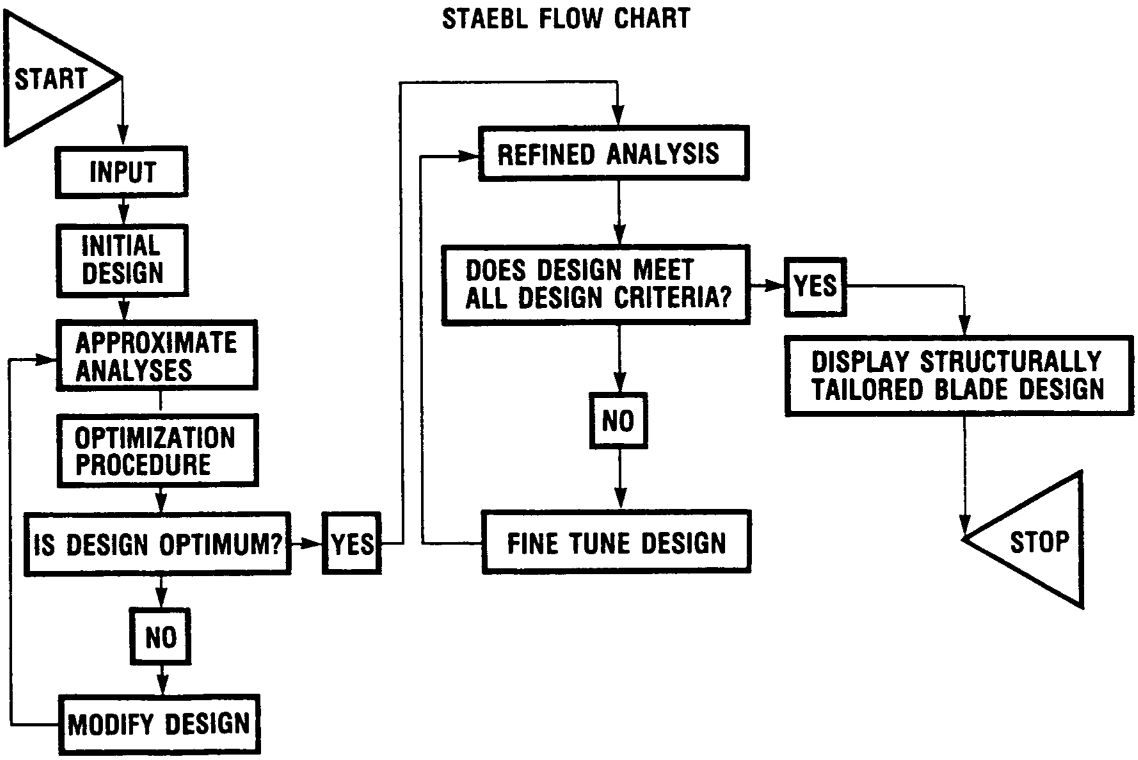
Additions and modifications of STAEBL included in SSME/STAEBL include the following: (1) thermal stress analysis, (2) gas dynamic (pressure) loads, (3) temperature-dependent material and thermal properties, (4) forced vibrations, (5) tip displacement constraints, (6) single crystal material analysis, (7) blade cross-section stacking offsets, and (8) direct time integration algorithm for transient dynamic response. Capabilities are also included which permit data transfer from finite element models and stand-alone analysis. Descriptions of preliminary probabilistic enhancements of SSME/STAEBL will be given.

*Work performed on-site at the Lewis Research Center for the Structural Mechanics Branch.

STRUCTURAL TAILORING OF ENGINE BLADES (STAEBL)

SSME/STAEBL was developed by systematically modifying and enhancing the STAEBL (Structural Tailoring of Engine Blades) code developed by Pratt and Whitney under contract to NASA Lewis Research Center. STAEBL was designed for application to gas turbine blade design. Typical design variables include blade thickness distribution and root chord. Typical constraints include resonance margins, root stress, and root-to-chord ratios. In this program, the blade is loaded by centrifugal forces only.

STAEBL FLOW CHART



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OPTIMIZATION STUDIES FOR SSME BLADE

Several design optimization studies have been completed by using an SSME blade design to test these various capabilities. Optimization studies have been completed to test the influence of thermal and pressure loads and temperature-dependent properties on optimal blade design. Comparison between designs optimized under centrifugal loads only and under centrifugal, thermal, and pressure loads with temperature-dependent blade properties shows that the additional loads require additional weight to meet all design constraints. The difference between the designs can be attributed to material property temperature dependence which, in this case, forces a much tighter root stress constraint.

CENTRIFUGAL LOADS ONLY; TEMPERATURE-INDEPENDENT PROPERTIES

SPAN, percent	THICKNESS, in	CHORD, in
0	.224	.890
50	.082	.681
100	.065	.650

REPRESENTATIVE THERMAL AND PRESSURE LOADS; TEMPERATURE-DEPENDENT PROPERTIES

SPAN, percent	THICKNESS, in	CHORD, in
0	.228	.890
50	.082	.681
100	.077	.650

	CENTRIFUGAL LOADS ONLY; TEMPERATURE-INDEPENDENT PROPERTIES	REPRESENTATIVE THERMAL AND PRESSURE LOADS; TEMPERATURE-DEPENDENT PROPERTIES
NATURAL FREQUENCY, cps:		
MODE 1	3454	3174
MODE 2	4868	4438
MODE 3	7069	6635
ROOT STRESS, ksi:	108	65
TIP DISPLACEMENTS:		
UNTWIST, deg	2.8	2.9
UNCAMBER, deg	0.7	1.5
TIP EXT, in	0.0027	0.0209
FORCED RESPONSE MARGINS:		
MODE 1	.000	.592
MODE 2	.000	.557
MODE 3	.000	.010
BLADE WEIGHT, lb:	.043	.044
NUMBER OF BLADES:	73	73
STAGE WEIGHT, lb:	3.14	3.18

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OPTIMIZATION STUDY INCLUDING BLADE-STACKING DESIGN VARIABLES

Optimization studies were undertaken to assess the influence of blade cross-section offsets on optimal design. These offsets are defined as the differences between the blade cross-section centers of gravity and a straight line perpendicular to the engine axis. Blade designers use these variables to balance centrifugal and pressure loads. In a typical optimization study, the initial design violated the root stress constraint. Root stress is extremely sensitive to offset variables, and the optimized design recommended a significant change in stacking.

INITIAL DESIGN			FINAL DESIGN		
SPAN, percent	THICKNESS, in	CHORD, in	SPAN, percent	THICKNESS, in	CHORD, in
0.	.233	1.041	0.	.226	.890
—50.	.138	.804	50.	.134	.688
100.	.092	.761	100.	.091	.650

BLADE STACKING:

	INITIAL DESIGN		FINAL DESIGN	
	A = 0.	B = 0.	A = – .0012	B = .0078
	C = 0.	D = 0.	C = .0013	D = .0095

ROOT STRESS, ksi: Initial design 82; final design 74

(z AXIS ALONG SPAN, BLADE LENGTH = L; x = x DISPLACEMENT FROM CENTER OF GRAVITY; AND y = y DISPLACEMENT FROM CENTER OF GRAVITY.)

$$x = A\,(z/L) + B\,(z/L)^2$$
$$y = C\,(z/L) + D\,(z/L)^2$$

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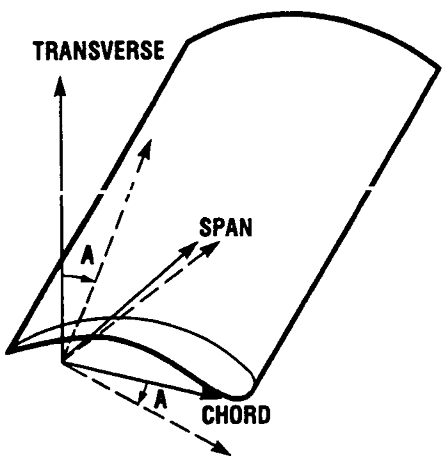
SINGLE CRYSTAL BLADE OPTIMIZATION STUDY

Design optimization studies for a blade made of a typical single crystal material showed relatively little effect on crystal axis orientation. This study was dominated by a root stress constraint which was violated by the initial design. It was found that root stress is influenced much less by crystal orientation than by the geometric design variables. The result is that the optimized design is found by adjusting the blade geometry significantly, but the crystal axis orientation insignificantly. Of course, in blade designs dominated by natural frequency constraints in particular, a different conclusion could be obtained.



	CRYSTAL ALIGNED WITH ROOT CHORD		CRYSTAL ALIGNED TO ROOT CHORD 45°	
SPAN, percent	THICKNESS, in	CHORD, in	THICKNESS, in	CHORD, in
0	.23	.89	.23	.89
50	.11	.69	.08	.69
100	.06	.65	.06	.65

	CRYSTAL ALIGNED WITH ROOT CHORD	CRYSTAL ALIGNED TO ROOT CHORD 45°
FREQUENCY, cps:		
	5110.	5079
	6851.	6847.
	13540.	13870.
ROOT STRESS, ksi:	63.	65.
STAGE WEIGHT, lb:	3.26	3.15
CRYSTAL ORIENTATION EULER ANGLES:		
	.89 E-3	45.00
	.57 E-2	−.20 E-1
	−.51 E-3	.48 E-2

——→ COORDINATE AXIS
– – –→ CRYSTAL AXIS

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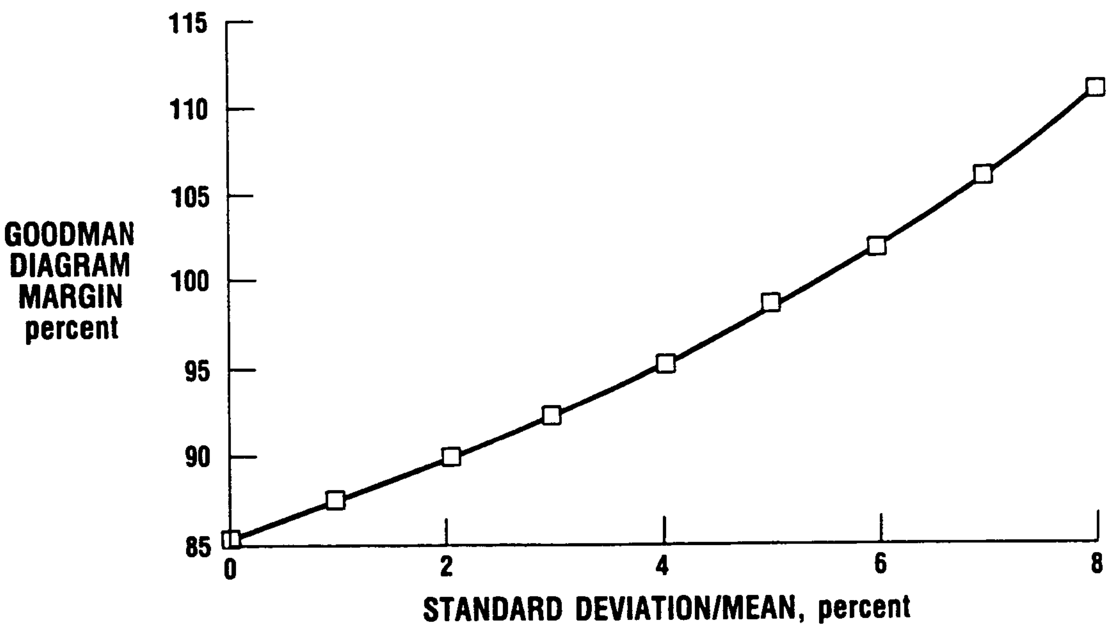
PROBABILISTIC ENHANCEMENTS

Preliminary capabilities have been developed to compute resonance margins, fatigue life, and stress levels probabilistically. Simple models are assumed for geometric imperfections to incorporate effects of imperfect offset stacking and twist on blade response. Probabilistic models are also assumed for strength as a function of number of cycles, stress level, and temperature. The graph shows the effect of uncertainties in material properties on Goodman fatigue strength diagram margins. As these uncertainties increase, the probability increases that the Goodman diagram margin will exceed 100 percent despite the fact that a deterministic calculation will indicate that the margin is about 85 percent.



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