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STRUCTURAL TAILORING OF ENGINE BLADES (STAEBL)

User's Manual

K. Brown

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NASA-Lewis Research Center
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ABS: This User's Manual contains instructions and demonstration case to prepare input data, run, and modify the Structural Tailoring of Engine Blades (STAEBL) computer code. STAEBL was developed to perform engine fan and compressor blade numerical optimizations. This blade optimization seeks a minimum weight or cost design that satisfies realistic blade design constraints, by tuning one to twenty design variables. The STAEBL constraint analyses include blade stresses, vibratory response, flutter, and foreign object damage. Blade design variables include airfoil thickness at several locations, blade chord, and construction variables:

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June 23, 1986

To: National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Attention: Mr. Chris Chamis, Program Manager
Bldg. 49 Room 211
Mail Stop 49-6

Subject: User's Manual for the Structural Tailoring of Engine Blades (STAEBL) Program

Reference: Contract NAS3-22525

Mr. Chamis:

We are pleased to submit six copies of the User's Manual in fulfillment of the terms of the referenced contract.

Sincerely yours,

UNITED TECHNOLOGIES CORPORATION
Pratt & Whitney Group
Engineering Division

Kenneth W Brown

Kenneth W. Brown
Program Manager

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16. Abstract

This User's Manual contains instructions and demonstration case to prepare input data, run, and modify the Structural Tailoring of Engine Blades (STAEBL) computer code. STAEBL was developed to perform engine fan and compressor blade numerical optimizations. This blade optimization seeks a minimum weight or cost design that satisfies realistic blade design constraints, by tuning one to twenty design variables. The STAEBL constraint analyses include blade stresses, vibratory response, flutter, and foreign object damage. Blade design variables include airfoil thickness at several locations, blade chord, and construction variables: hole size for hollow blades, and composite material layup for composite blades.

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STRUCTURAL TAILORING OF ENGINE BLADES (STAEBL)
USER'S MANUAL

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SECTION 1.0

STAEBL PROGRAM DESCRIPTION

The Structural Tailoring of Engine Blades (STAEBL) computer program was developed to perform engine fan and compressor blade numerical optimizations. These blade optimizations seek a minimum weight or cost design that satisfies realistic blade design constraints, by tuning one to twenty design variables.

The STAEBL constraint analyses include blade stresses, vibratory response, flutter, and foreign object damage. Blade design variables include airfoil thickness at several locations, blade chord, and construction variables: hole size for hollow blades, and composite material layup for composite blades.

To perform a blade optimization, three component analysis categories are required: an optimization algorithm; approximate analysis procedures for objective function and constraint evaluation; and refined analysis procedures for optimum design validation. The STAEBL computer program contains an executive control module, an optimizer and all approximate analyses. The optimization algorithm of STAEBL is the COPES/CONMIN (Control Program for Engineering Synthesis/Constrained Minimization) optimization package, which is a proven tool for optimizations with a small to medium (1-20) number of design variables.

The approximate analyses of STAEBL utilize an efficient, coarse mesh, plate finite element blade vibration analysis procedure. The finite element analysis provides blade natural frequencies and mode shapes, stress under centrifugal loads, and blade weight. Additional constraint evaluations, including flutter and foreign object damage calculations, utilize outputs from the finite element analysis.

Once a candidate optimal design has been found, the design should be verified by applying refined analyses to assure that all constraints are satisfied. This level of analysis is not automatically performed by STAEBL, but is left to the user's existing design/analysis system. STAEBL experience has shown that a first optimal candidate design satisfies most constraints, and does not severely violate the remaining constraints. If a constraint is found to be violated, the allowable constraint value must be modified to reflect the differences between approximate and refined analysis. For each of the cases studied during the STAEBL development effort, a fully satisfactory design was found on the second optimal blade design.

To use the blade optimization system, a coordinate description of the initial blade design is required. From that point, STAEBL will change the blade design according to the available blade design variables. Typically, blade geometry variables have consisted of maximum section thickness at five spanwise locations, and blade chord. For the composite blades optimized by STAEBL, additional construction variables are also available. These variables include composite material thickness and orientation, and/or hollow size and location.

The STAEBL system has been applied to several stages of the Energy Efficient Engine, which was designed under NASA Contract NAS3-20646. Fan blades of superhybrid and inlaid hollow construction have been tailored, showing significant potential for design improvements through the application of numerical optimization and these composite constructions. A solid all titanium compressor blade was also tailored using STAEBL, demonstrating significant blade weight reduction even for a relatively "simple" blade design application.

SECTION 2.0

STAEBL FLOWCHART

Figure 1 illustrates the STAEBL optimization process by which an optimum blade design is derived and verified.

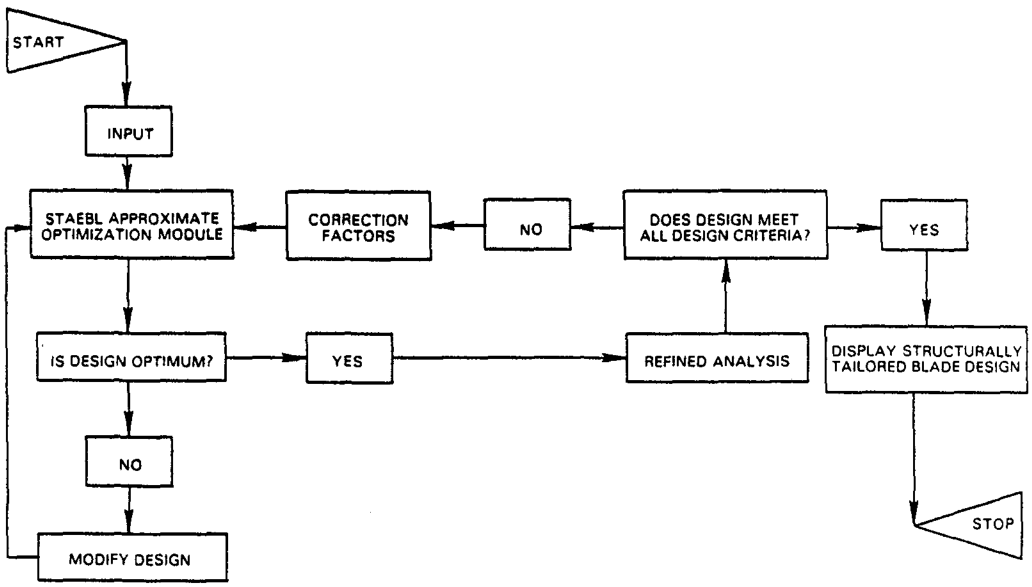


Figure 1 Flowchart for the STAEBL Optimization Process

SECTION 3.0

APPROXIMATE ANALYSIS FLOWCHART

Figure 2 illustrates the approximate analysis module flowchart. Details and additional information with regard to the approximate analysis module are provided in Section 9.0.

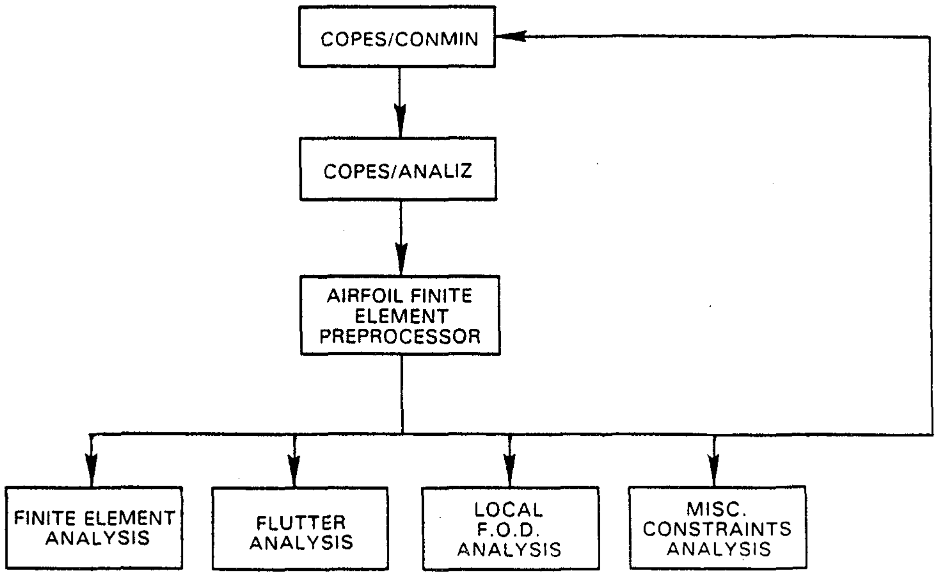


Figure 2 Approximate Analysis Flowchart

SECTION 4.0

DETAILED INPUT INSTRUCTIONS

Due to the modular construction of the STAEBL program, data input has been broken into three separate data blocks: 1) input to the COPES/CONMIN optimizer, 2) airfoil description, and 3) constraint calculation control. The three data blocks, designated as data blocks A, B and C, currently follow individual input procedures. Consistent data input procedures will be utilized in future releases of STAEBL. The three data blocks are input and are defined as follows:

DATA BLOCK A . . . COPES/CONMIN input. Further details can be found in Appendix A and/or the COPES/CONMIN user manual (NASA Report No. NPS69-81-003).

DATA BLOCK B . . . Airfoil coordinate data and other airfoil information, analysis speed, etc.

DATA BLOCK C . . . Additional approximate model input, scaling factors for geometry, etc.

Note: Any analysis options flagged in DATA BLOCK C that are to be used for optimization purposes must have the appropriate global variable included in DATA BLOCK A. Otherwise, the correct analysis will be made but will not be considered an optimization constraint. Similarly, if a global variable is called out as a constraint in DATA BLOCK A, DATA BLOCK C must have the appropriate flags and analysis information input.

Cards of DATA BLOCK A and Card C1a may be input using unformatted data input. For these cards, data entries may be separated by commas or by one or more blanks. If exponentiated numbers such as 1.+5 are read on an unformatted card, there must be no embedded blanks within the number being input. Unformatted cards may be intermingled with formatted cards. Real numbers on an unformatted card should have a decimal point. In DATA BLOCK A, if more than one number is contained on an unformatted data card, a comma must appear somewhere on the card.

4.1 Data Block A

CARD A1 (COPES DATA BLOCK A)

Contents: Title

1	2	3	4	5	6	7	8
←			TITLE				→

Field	Item	Format	Description
1-8	TITLE	20A4	Any 80 character title.

CARD A2 (COPES DATA BLOCK B)

Contents: COPES Control Parameters

1	2	3	4	5	6	7	8
NCALC	NDV				IPNPUT		
10	20				60		

Field	Item	Format	Description
1	NCALC	I	0 = Read input and stop. 1 = One cycle through program. 2 = Optimization.
2	NDV	I	Number of independent design variables in optimization.
6	IPNPUT	I	Input print control. 0 = Print card images of data plus formatted print of input data. 1 = Formatted print only of input data. 2 = No print of input data.

CARD A3 (COPES DATA BLOCK C. OMIT IF NDV = 0 ON CARD A2)

Contents: Optimization Control Parameters

1	2	3	4	5	6	7	8
IPRINT	ITMAX	ICNDIR	NSCAL	ITRM	LINOBJ	NACMX1	
10	20	30	40	50	60	70	80

Field	Item	Format	Description
1	IPRINT	I	Print control used in optimization. 0 = No print during optimization. 1 = Print initial and final optimization information. 2 = Print above plus objective function value and design variable values at each iteration. 3 = Print above plus constraint values, direction vector and move parameter at each iteration. 4 = Print above plus gradient information. 5 = Print above plus each proposed design vector, objective function and constraint values during the one-dimensional search.

CARD A3 (continued)

Field	Item	Format	Description
2	ITMAX	I	Maximum number of optimization iterations allowed. DEFAULT = 20.
3	ICNDIR	I	Conjugate direction restart parameter. DEFAULT = NDV + 1. For blade optimization, set ICNDIR equal to zero.
4	NSCAL	I	Scaling parameter. Suggested values are 0 or NDV + 1. When design variables differ largely in magnitude, internal scaling every NSCAL times will improve the optimization procedure. NDV + 1 is recommended for blade optimization. GT.0 = Scale design variable to order of magnitude one every NSCAL iterations. LT.0 = Scale design variables according to user-input scaling values.
5	ITRM	I	Number of consecutive iterations which must satisfy relative or absolute convergence criterion before optimization process is terminated. DEFAULT = 3.
6	LINOBJ	I	Linear objective function identifier. If the optimization objective is known to be a linear function of the design variables, set LINOBJ = 1. DEFAULT = Nonlinear.
7	NACMX1	I	One plus the maximum number of active constraints anticipated. DEFAULT = NDV + 2. If CONMIN writes an error message that the number of active and violated constraints exceeds N3-1, then NACMX1 must be increased (note that NACMX1 = N3).

CARD A4a (COPES DATA BLOCK D. OMIT IF NDV = 0 ON CARD A2)

Contents: Optimization Program Parameters (continued)

1	2	3	4	5	6	7	8
FDCH	FDCHM	CT	CTMIN	CTL	CTLMIN	THETA	
10	20	30	40	50	60	70	80

Field	Item	Format	Description
1	FDCH	F	Relative change in design variables in calculating finite difference gradients. DEFAULT = 0.01. (Note: Default value is suggested for blade optimization.)
2	FDCHM	F	Minimum absolute step in finite difference gradient calculations. DEFAULT = 0.01. (Note: Default value is suggested for blade optimization.)
3	CT	F	Constraint thickness parameter. DEFAULT = -0.1.
4	CTMIN	F	Minimum absolute value of CT considered in the optimization process. DEFAULT = 0.004. (Note: Default value is suggested for blade optimization.)
5	CTL	F	Constraint thickness parameter for linear constraints. DEFAULT = -0.01. (Note: Default value is suggested for blade optimization.)
6	CTLMIN	F	Minimum absolute value of CTL considered in the optimization process. DEFAULT = 0.001. (Note: Default value is suggested for blade optimization.)
7	THETA	F	Mean value of the push-off factor in the Method of Feasible Directions. DEFAULT = 1.0. (Note: 0.3 is suggested for blade optimization.)

CARD A4b (COPES DATA BLOCK D, SECOND CARD. OMIT IF NDV = 0 ON CARD A2)

Contents: Optimization Program Parameters (continued)

1	2	3	4	
DELFUN	DABFUN	ALPHAX	ABOBJI	
10	20	30	40	

Field	Item	Format	Description
1	DELFUN	F	Minimum relative change in objective function to indicate convergence of the optimization process. DEFAULT = 0.001. (Note: .005 is suggested for blade optimization.)
2	DABFUN	F	Minimum absolute change in objective function to indicate convergence of the optimization process. DEFAULT = 0.001 times the initial objective value. (Note: Default value is suggested for blade optimization.)
3	ALPHAX	F	Maximum fractional change in any design variable for first estimate of the step in the one-dimensional search. DEFAULT = 0.1. (Note: Default value is suggested for blade optimization.)
4	ABOBJI	F	Expected fractional change in the objective function for first estimate of the step in the one-dimensional search. DEFAULT = 0.1. (Note: Default value is suggested for blade optimization.)

Remarks:

The DEFAULT values for these parameters usually work well.

CARD A5 (COPES DATA BLOCK E. OMIT IF NDV = 0 ON CARD A2)

Contents: Total Number of Design Variables, Design Objective Identification and Sign

1	2	3	
NDVTOT	IOBJ	SGNOPT	
10	20	30	

Field	Item	Format	Description
1	NDVTOT	I	Total number of variables, including variables which are linked to the design variables. Thus, two or more variables may be assigned to a single design decision variable. The value of each parameter is the design variable value multiplied by a scalar, to be input on Card A7. Each parameter may employ a different multiplier value. DEFAULT = NDV. (Note: For STAEBL blade optimization, the default value is recommended.)
2	IOBJ	I	Global variable number associated with the objective function in optimization. (Refer to the Global Variable Code listing below. Usually variables 90 or 102 are used.)
3	SGNOPT	F	Sign used to identify whether function is to be maximized or minimized. +1.0 indicates maximization. -1.0 indicates minimization. If SGNOPT is not unity in magnitude, it acts as a multiplier as well, to scale the magnitude of the objective.

STAEBL GLOBAL VARIABLE CODE

VAR. NO.	VARIABLE	DEFINITION
1	OBJF	Blade weight
2-6	FN(5)	Frequency of first 5 roots
7-11	DLAR(5)	Flutter log. decrement for first 5 roots
12-32	THKVAL(21)	Design variable - thickness (e.g., for 5 thicknesses, use 12-16)
33-57	RF(5, 5)	Resonance margin for order number (ORDN) and root - RF(ORDN,ROOT) 33 - RF(1, 1) 34 - RF(2, 1) 38 - RF(1, 2) 45 - RF(3, 3)

STAEBL GLOBAL VARIABLE CODE (continued)

VAR. NO.	VARIABLE	DEFINITION
58	BRCC	Design variable - root chord
59	STRN	Foreign object damage parameter - leading edge strain
60-80	TOVB(21)	Thickness to chord ratio
81	DLE	Location of hole from leading edge
82	DTE	Location of hole from trailing edge
83	DROOT	Location of hole from root
84	DTIP	Location of hole from tip
85	TTI	Titanium skin thickness for a hollow blade
86	TLT	Inlay thickness
87	TIS	Titanium skin thickness for a superhybrid blade
88	TIC	Titanium center thickness
89	PCBA	Percent of boron aluminum
90	OBJFUN	Object function - cost and weight function
91	BTA	Borsic (registered trademark of Avco Corporation) titanium fiber angle
92	BAA	Boron aluminum fiber angle
93	GEA	Graphite epoxy fiber angle
94	SROOT	Maximum root static stress
97	TSWU	Maximum root foreign object damage
98	TSRT(1)	Maximum root TSAI-WU stress for a solid or hollow blade
99	TSRT(2)	Maximum root TSAI-WU stress for a superhybrid blade
100	TSRT(3)	Maximum root TSAI-WU stress for a superhybrid blade or maximum hole TSAI-WU stress for a hollow blade
101	TSRT(4)	Maximum root TSAI-WU stress for a superhybrid blade or maximum hole TSAI-WU stress for a hollow blade
102	STGWT	Stage weight
103	TPMRG	Tip mode frequency margin
104	FLTSLD	Bending flutter constraint - solid blade, FLTSLD = 1000 / $f_1 b_{75\%}$ where f_1 is the first bending mode frequency, cps, and $b_{75\%}$ is the chord at the 75% span location
105-109	GDMAX	Forced response margins
111	AMPA	Mass/unit area for local increased density
112	ADLE	Location of local increased density area from leading edge
113	ADTE	Location of local increased density area from trailing edge
114	ADROOT	Location of local increased density area from root
115	ADTIP	Location of local increased density area from tip

CARD A6 (COPES DATA BLOCK F. OMIT IF NDV = 0 ON CARD A2)

Contents: Design Variable Bounds, Initial Values and Scaling Factors. NDV cards are read.

1	2	3	4	
VLB	VUB	X	SCAL	
10	20	30	40	

Field	Item	Format	Description
1	VLB	F	Lower bound on the design variable. If VLB.LT.-1.0E+15, no lower bound.
2	VUB	F	Upper bound on the design variable. If VUB.GT.1.0E+15, no upper bound.
3	X	F	Initial value of the design variable. If X is non-zero, this will supersede the value initialized by the STAEBL-supplied subroutine ANALIZ.
4	SCAL	F	Design variable scale factor. Not used if NSCAL.GE.0 in Block C.

CARD A7 (COPES DATA BLOCK G. OMIT IF NDV = 0 ON CARD A2)

Contents: Design Variable Identification. NDVTOT cards are read.

1	2	3	
NDSGN	IDSGN	AMULT	
10	20	30	

Field	Item	Format	Description
1	NDSGN	I	Design variable number associated with this parameter. (NDSGN = 1, 2, 3, ..., NDVTOT)
2	IDSGN	I	Global variable number associated with this parameter. (Refer to the Global Variable Code listing under Card A5 input instructions.)
3	AMULT	F	Constant multiplier on this parameter. The value of the parameter will be the value of the design parameter, NDSGN, times AMULT. DEFAULT = 1.0.

(Note: NDVTOT = NDV for blade optimization.)

CARD A8 (COPES DATA BLOCK H. OMIT IF NDV = 0 ON CARD A2)

Contents: Number of Constraint Sets

1	
NCONS	
10	

Field	Item	Format	Description
1	NCONS	I	Number of constraint sets in the optimization problem.

CARD A9a (COPES DATA BLOCK I. OMIT IF NDV = 0 ON CARD A2 OR IF NCONS = 0 ON CARD A8)

Contents: Constraint Identification and Constraint Bounds. NCONS pairs of Card A9a and Card A9b are read.

1	2	3	
ICON	JCON	LCON	
10	20	30	

Field	Item	Format	Description
1	ICON	I	First global variable number corresponding to the constraint set.
2	JCON	I	Last global variable number corresponding to the constraint set. DEFAULT = ICON.
3	LCON	I	Linear constraint identifier for this constraint set. LCON = 1 indicates linear constraints. (In blade optimization, constraints are usually nonlinear. Therefore, LCON in most cases will be equal to 0.)

Remark:

Each Card A9a identifies a set of consecutively numbered global variables (ICON through JCON) to be constrained, with the constraint limits specified on the subsequent data card, Card A9b.

CARD A9b (INCLUDE FOR EVERY CARD A9a USED)

Contents: Constraint Identification and Constraint Bounds (continued)

1	2	3	4	
BL	SCAL1	BU	SCAL2	
10	20	30	40	

Field	Item	Format	Description
1	BL	F	Lower bound on the constrained variables. If BL.LT.-1.0E+15, no lower bound.
2	SCAL1	F	Normalization factor on lower bound. DEFAULT = MAX of ABS(BL), 0.1.
3	BU	F	Upper bound on the constrained variables. If BU.GT.1.0E+15, no upper bound.
4	SCAL2	F	Normalization factor on upper bound. DEFAULT = MAX OF ABS(BU), 0.1.

Remarks

1. The normalization factor should usually be defaulted.
2. Each constrained parameter is converted to two constraints in CONMIN unless ABS(BL) or ABS(BU) exceeds 1.0E+15, in which case no constraint is created for that bound.

CARD A10 (COPES DATA BLOCK V)

Contents: COPES Data 'END' Card

1	
END	
3	

Field	Item	Format	Description
1	--	--	The word 'END' in columns 1-3.

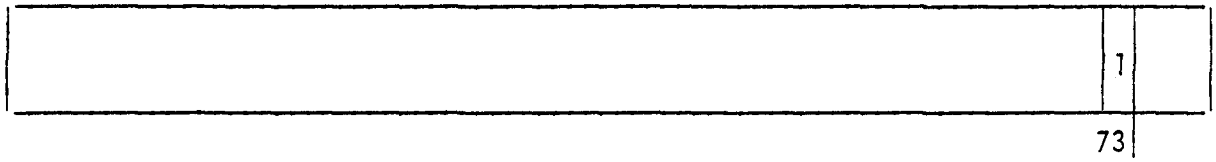
Remarks

1. This card MUST appear at the end of the COPES data.
2. This ends the COPES input data.
3. Data for the STAEBL airfoil processor follows this data set.

4.2 Data Block B

CARD B1

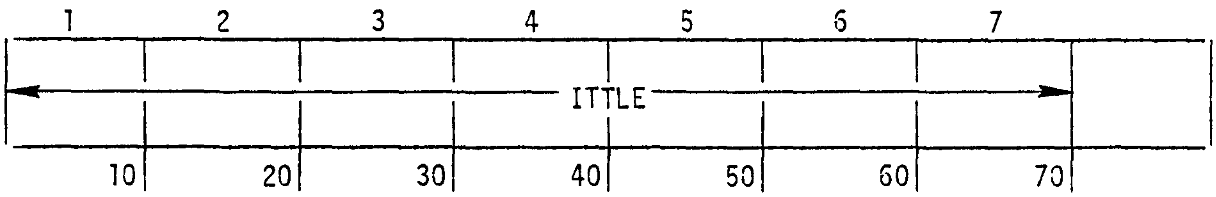
Contents: Case Control



Field	Item	Format	Description
Col. 73	NTEST	I	Insert '1' (one) in column 73 to indicate start of blade data.

CARD B2

Contents: Title



Field	Item	Format	Description
1-7	ITTLE	A	Descriptive title.

CARD B3

Contents: RPM Increment

1	2	3	4	5	6	7	8	9	10
RPM				ROOT	DRPM				
8				40	48				

Field	Item	Format	Description
1	RPM	F	Analysis speed, RPM. This is the speed desired for flutter stability evaluation.
5	ROOT	F	Number of frequencies desired, maximum of 5.
6	DRPM	F	Delta RPM. This RPM increment is added to the input RPM and another frequency is calculated at the higher speed for the purpose of computing the sensitivity of the natural frequencies to speed. 1000.0 is suggested.

CARD B4

Contents: Blade Station Definition

1	2	3	4	5	6	7	8	9	10
NSTA									
2									

Field	Item	Format	Description
1	NSTA	I	Number of spanwise coordinate input stations for blade geometry input description, maximum of 21. Suggested value is 11.

CARD B5

Contents: Blade Station Radius, Chord Angle, Coordinate Instruction. Input One Card B5 for Each Blade Station from ID to OD.

1	2	3	4	5	6	7	8	9	10
R				ALPHA					NO
8				40				73	77

Field	Item	Format	Description
1	R	F	Distance from the engine center line to the blade station, inches. The first input station should be the blade attachment, the last the tip station. (See Figure 5.)
5	ALPHA	F	Angle between plane of rotation of rotor stage and chord normal (y=0), degrees.
10	NO	F	The number of coordinate stations along the chord used to describe the airfoil profile. Maximum of 53 points. Thirty to fifty points are recommended.

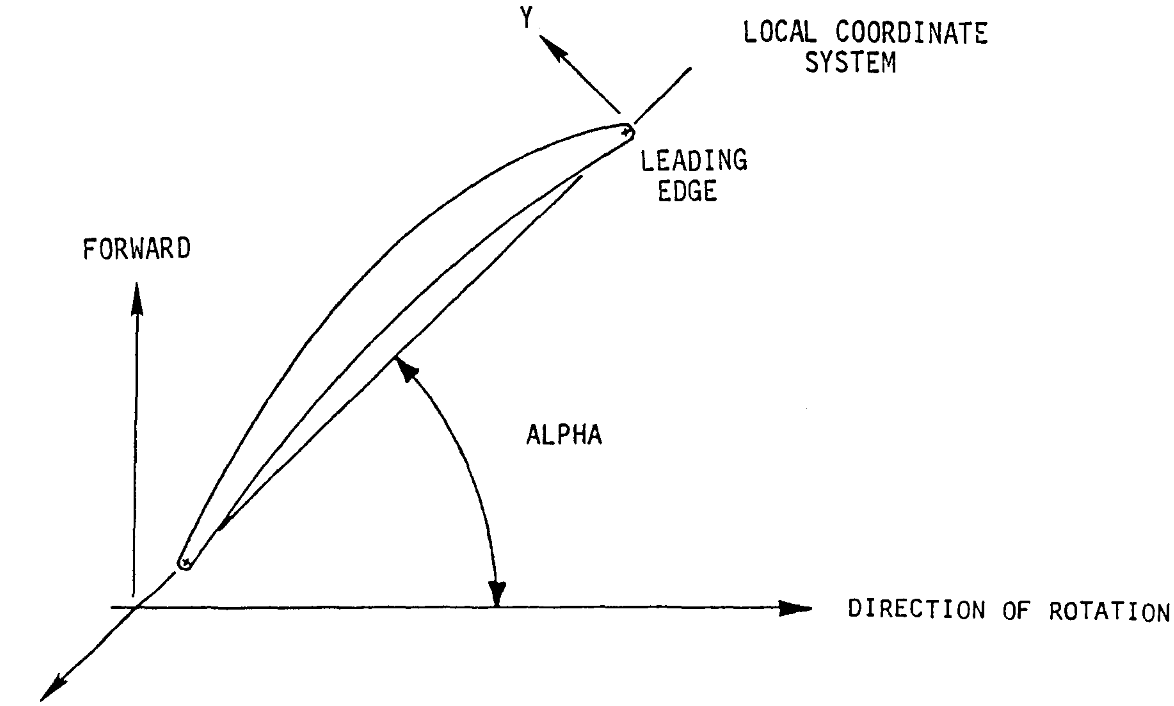


Figure 3 Definition of Angle ALPHA

CARDS B6, B7, AND B8

Contents: Airfoil Coordinates

These cards follow Cards B5 at each station. Input x values first, then upper y's, then lower y's. For a solid or hollow airfoil with a conventional parallelogram neck geometry to serve as the transition between airfoil root and dovetail attachment, the coordinates of the first station will be ignored. The coordinates for station 1 must be input, however, usually using the station 2 coordinates. STAEBL will build a model of the neck, shown in Figure 5, from information included on Card B9. For an airfoil with no platform and a contoured neck, such as the superhybrid blade, the neck is treated as an extension of the airfoil, and thus proper section 1 coordinates are required.

B6:	X(1)	X(2)	X(3)	...						
B7:	YU(1)	YU(2)	YU(3)	...						
B8:	YL(1)	YL(2)	YL(3)	...						

Field	Item	Format	Description
9 values per card. Fields of 8.	X	F	The x coordinates of the blade cross section given in ascending order for NO points, inches.
Start each set on a card.	YU	F	The upper y coordinates of the blade cross section corresponding to the x coordinates, inches.
	YL	F	The lower y coordinates of the blade cross section corresponding to the x coordinates, inches.

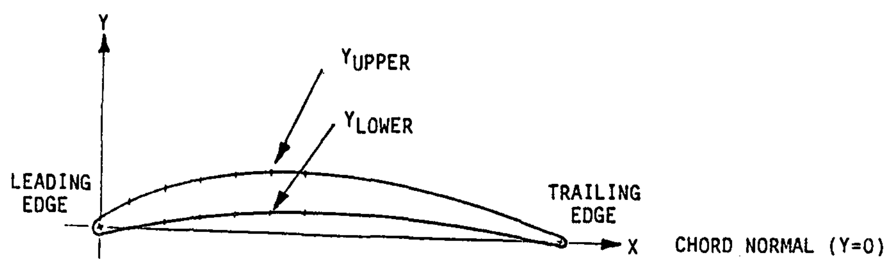


Figure 4 1X2Y Airfoil Section Coordinate Input

CARD B9

Contents: Blade Root Angle. Neck Description.

1	2	3	4	5	
	THER	TROOT	RROOT	BRANG	
8	16	24	32	40	

Field	Item	Format	Description
2	THER	F	Blade root angle, degrees. This is the angle between the blade platform and the engine center line. Positive counterclockwise.
3	TROOT	F	Thickness of blade neck, inches.
4	RROOT	F	Radius of first airfoil station, inches. This radius is the radius at the half-chord point of the airfoil root. RROOT does not have to correspond to an airfoil 1X2Y coordinate input station radius, but must lie between R(1) and R(NSTA).
5	BRANG	F	Broach angle, the angle between the center line of the broach slot and an axial plane, degrees.

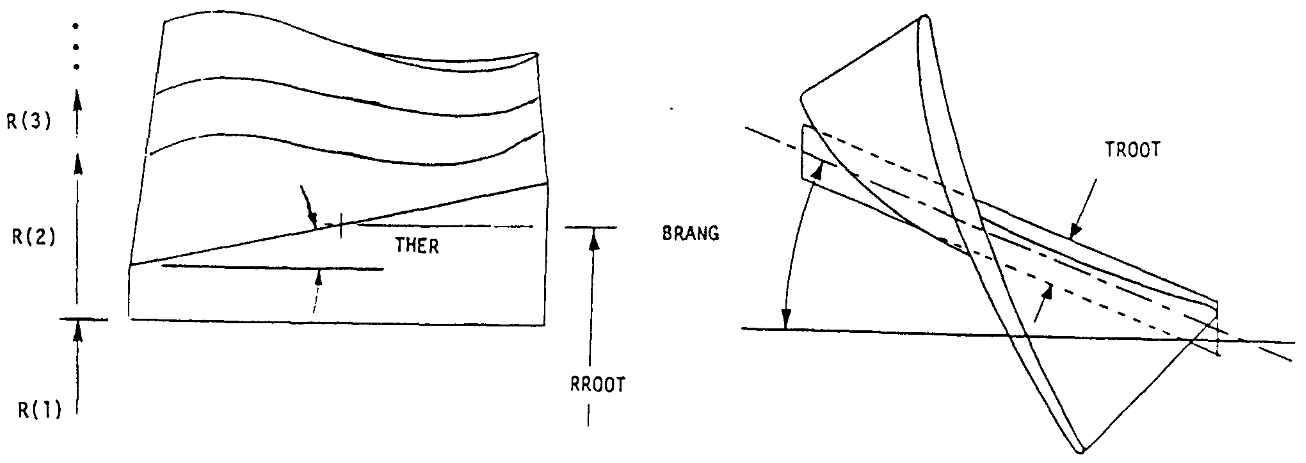


Figure 5 Blade Root Angle and Neck Description

CARD B10

Contents: Number of Blades

1	2	3	4	5	6	7	
						BLADES	
					48	56	

Field	Item	Format	Description
7	BLADES	F	Number of blades in initial stage. The number of blades will be varied inversely with chord during optimization in order to preserve solidity.

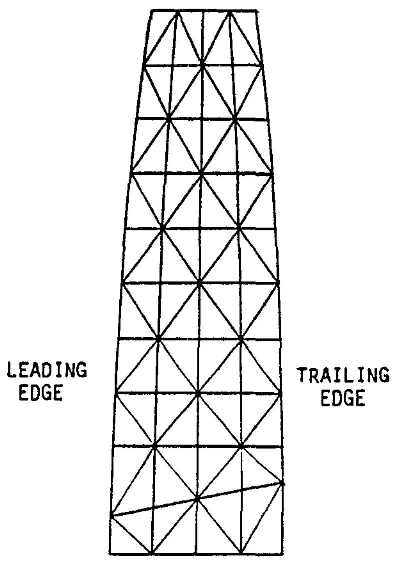


Figure 6 Blade Model With Attachment and Flowpath Angle After Blade Preprocessing

4.3 Data Block C

CARD C1a

Contents: Problem Definition

1	2	3	4	5	6	7	8	9	
NTIS	NRF	NRFOD	NCD	NLAYER	NRTFOD	NRESFF	NTIPMD	BRSV	
5	10	15	20	25	30	35	40	50	

Field	Item	Format	Description
1	NTIS	I	Number of thickness input stations, maximum of 21, minimum of 2. Suggested value is 5.
2	NRF	I	Number of roots calculated by flutter analysis, maximum of 5.
3	NRFOD	I	Number of roots for both local and root foreign object damage (FOD) analysis. Suggested value is 5. If = 0, FOD analysis is not made.
4	NCD	I	Defines the airfoil type: 0 = solid 1 = hollow 2 = superhybrid
5	NLAYER	I	Number of layers for blade. If NCD=0: use 1 or -1; If NCD=1: use 5 or -5; If NCD=2: use 7 or -7. Note: If NLAYER is positive, the program uses preset limits (see Card C11 for the preset TSAI-WU limits). If NLAYER is negative, TSAI-WU limits will be input on Card C11.
6	NRTFOD	I	Root foreign object damage option: 0 = not calculated 1 = calculated

CARD C1a (continued)

Field	Item	Format	Description
7	NRESFF	I	Resonance margin criteria: 0 = resonance margins calculated 1 = forcing function calculated. STAEBL-provided forcing functions are applicable to the Energy Efficient fan blade only. User-supplied forcing functions may be incorporated by updating Subroutine FRCFNC. 2 = both of the above Notes: 1. Excitation orders for which margins are calculated are input on Card C5. 2. When resonance margin is specified as a constraint in Data Block A and if NRESFF=0, minimum resonance margin will be as specified on Card A9b. If NRESFF=1, minimum resonance margin will be based on maximum permissible vibratory and steady stress combination on the blade which satisfies the Modified Goodman Diagram. STAEBL assumes titanium for Goodman Diagram construction. To change material, Subroutine GOODMN may be updated. When NRESFF=2, the limiting case (either the specified resonance margin or maximum permissible blade stress) will govern.
8	NTIPMD	I	Tipmode search (required if a tip plate vibratory mode constraint is desired): 0 = no search ≥ 1 = number of modes tested for tip (5 maximum) Note: if NTIPMD $>$ 0 and no tipmodes are found, tipmode defaults to fifth mode.
9	BRSV	F	Root chord length for which optimization will begin, inches. All coordinate input will be scaled by BRSV/coordinate input root chord.

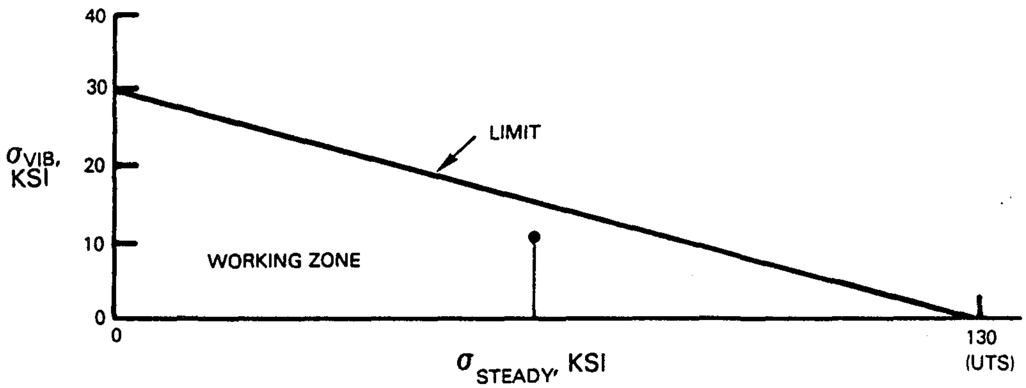


Figure 7 Location of the Worst Vibratory and Steady Stress Combination on the Modified Goodman Diagram - STAEBL

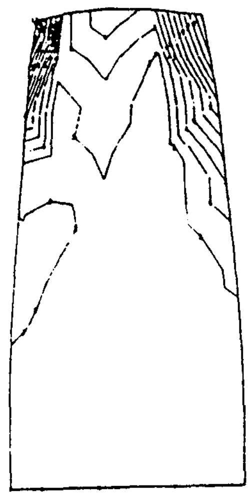


Figure 8 Contour Plot of Tip Mode

CARD C1b

Contents: Frequency Correction Factors

1	2	3	4	5	6	
CF1	CF2	CF3	CF4	CF5	CFT	
5	10	15	20	25	30	

Field	Item	Format	Description
1	CF1	F	First mode correction factor. DEFAULT = 1.0. $CF = \frac{\text{Refined Analysis Frequency}}{\text{Approximate Analysis Frequency}}$
2	CF2	F	Second mode correction factor. DEFAULT = 1.0.
3	CF3	F	Third mode correction factor. DEFAULT = 1.0.
4	CF4	F	Fourth mode correction factor. DEFAULT = 1.0.
5	CF5	F	Fifth mode correction factor. DEFAULT = 1.0.
6	CFT	F	Tipmode correction factor. DEFAULT = 1.0.

CARD C2

Contents: Airfoil Coordinate Input in Section B Will be Scaled to Reflect These Starting Values of Maximum Thickness.

1	2	3	4	
IST(1)	VALT(1)	IST(2)	VALT(2)	... NTIS TIMES
2	10	12	20	

Field	Item	Format	Description
1	IST(1)	I	Station number (as referenced to Section B).
2	VALT(1)	F	Thickness, inches.

ALTERNATE NTIS TIMES

Remark:

IST(NTIS) must correspond to the blade tip.

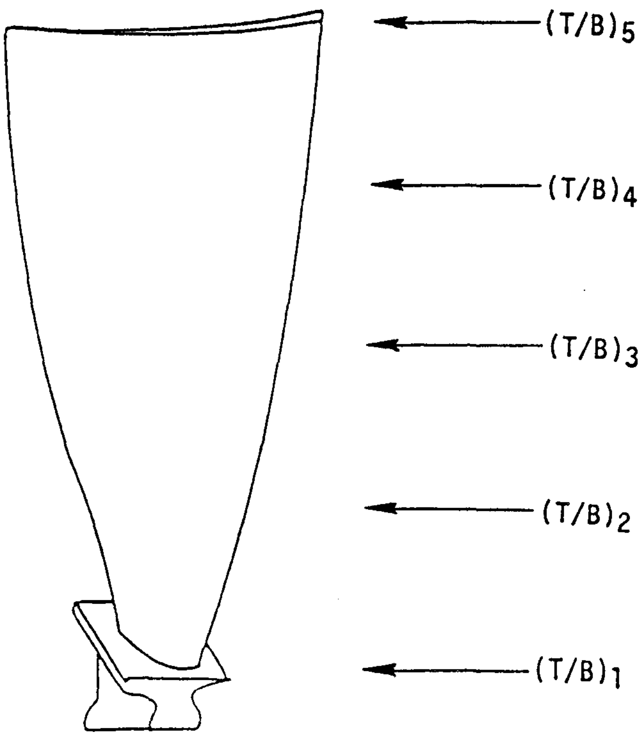


Figure 9 Typical Station Locations for Airfoil Maximum Thickness Starting Values

CARD C3 (REQUIRED IF NRF > 0 ON CARD C1a)

Contents: Supersonic flutter analysis input control.

1	2	3	4	
	TEMPST		NAC	
10	20	30	40	

Field	Item	Format	Description
2	TEMPST	F	Inlet static temperature, °F.
4	NAC	I	Number of aerodynamic stations. Note: At present, only one station is allowed.

CARD C4 (REQUIRED IF NRF > 0 ON CARD C1a)

Contents: Aerodynamic Data for Flutter Calculation. Input NAC Times.

1	2	3	4	
VOM(I)	ARAD(I)		STPRS(I)	
10	20	30	40	

Field	Item	Format	Description
1	VOM(I)	F	Relative inlet Mach Number.
2	ARAD(I)	F	Corresponding radius in inches.
4	STPRS(I)	F	Inlet static pressure, lbf/ft^2.

CARD C5

Contents: Speed and Excitation Orders for Resonance Margin Calculation

1	2	3	4	5	
SPDRL	SPDMC	NORD	IORD (1)	IORD (2)	... NORD TIMES
10	20	30	35	40	

Field	Item	Format	Description
1	SPDRL	F	Redline speed, RPM.
2	SPDMC	F	Minimum cruise speed, RPM.
3	NORD	I	Number of excitation orders input, maximum of 5.
4	IORD(I)	I	Order number.
	I = 1, NORD		

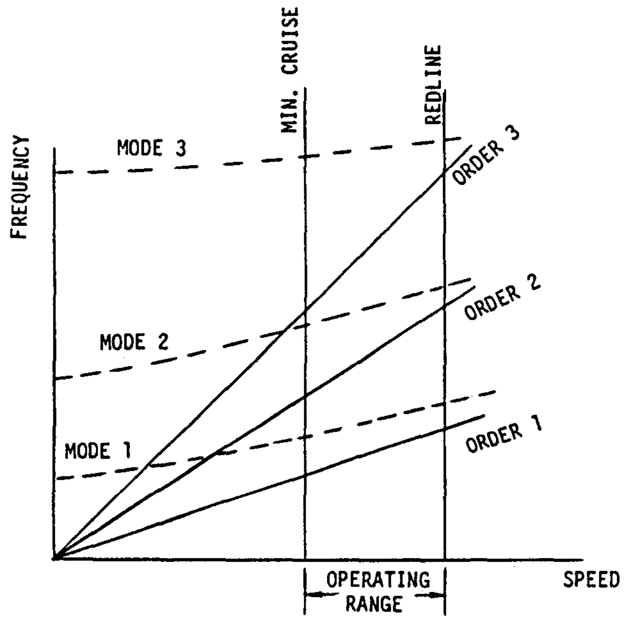


Figure 10 Resonance Diagram for a Successfully Tuned Blade (No Response Crossings Within 5 Percent of the Speed Operating Range)

CARD C6 (REQUIRED IF NRFOD > 1 ON CARD C1a)

Contents: Local Foreign Object Damage Input

1	2	3	4	5	6	
R	VP	THETA	RHO	TSTEP	BETA	
10	20	30	40	50	60	

Field	Item	Format	Description
1	R	F	Bird radius, inches.
2	VP	F	Bird velocity, inches/sec.
3	THETA	F	Impact angle relative to ALPHA on Card B5, radians (see Figure 11). THETA can be calculated as follows: $THETA = ALPHA \text{ (at impact radius)} - \phi$ where $\phi = TAN^{-1}((60 \cdot V_p)/(2\pi \cdot \text{blade impact radius} \cdot RPM))$
4	RHO	F	Bird density, lb sec^2/in^4
5	TSTEP	F	Timestep, seconds. 1×10^{-5} recommended.
6	BETA	F	Modal damping, 0.0 is recommended.

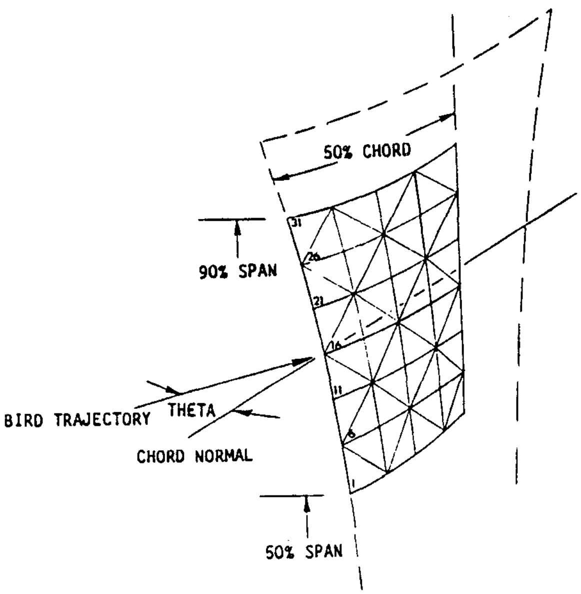


Figure 11 Local Foreign Object Damage Model

CARD C7 (REQUIRED IF NRFOD > 0 ON CARD C1a)

Contents: Foreign Object Damage Input (continued)

1	2	
NREF	NSTEP	
5	10	

Field	Item	Format	Description
1	NREF	I	Leading edge impact node for local foreign object damage. Normally use 16 (see Figure 11).
2	NSTEP	I	Number of timesteps required. 40 is suggested.

CARD C8

Contents: Material Properties (Input NLAYER Values)

1	2	3	4	5	
E11(I)	E22(I)	V12(I)	G12(I)	RH(I)	
10	20	30	40	50	

Field	Item	Format	Description
1	E11(I)	E	Youngs modulus in primary (1-1) direction, psi.
2	E22(I)	E	Youngs modulus in secondary (2-2) direction, psi.
3	V12(I)	F	Poissons ratio.
4	G12(I)	E	Shear modulus, psi.
5	RH(I)	F	Mass density, lb sec^2/in^4.

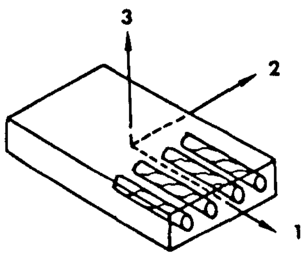


Figure 12 Unidirectionally Reinforced Lamina

CARD C9 (REQUIRED IF NCD = 1 ON CARD C1a)

Contents: Data Associated With a Hollow Blade Design

1	2	3	4	5	6	7	
DLE	DTE	DROOT	DTIP	TTI	TLT	BTA	
10	20	30	40	50	60	70	

Field	Item	Format	Description
1	DLE	F	Distance to hole from leading edge, inches.
2	DTE	F	Distance to hole from trailing edge, inches.
3	DROOT	F	Distance to hole from airfoil root, inches.
4	DTIP	F	Distance to hole from airfoil tip, inches.
5	TTI	F	Thickness of skin, inches.
6	TLT	F	Thickness of inlay, inches.
7	BTA	F	Inlay fiber angle, degrees.

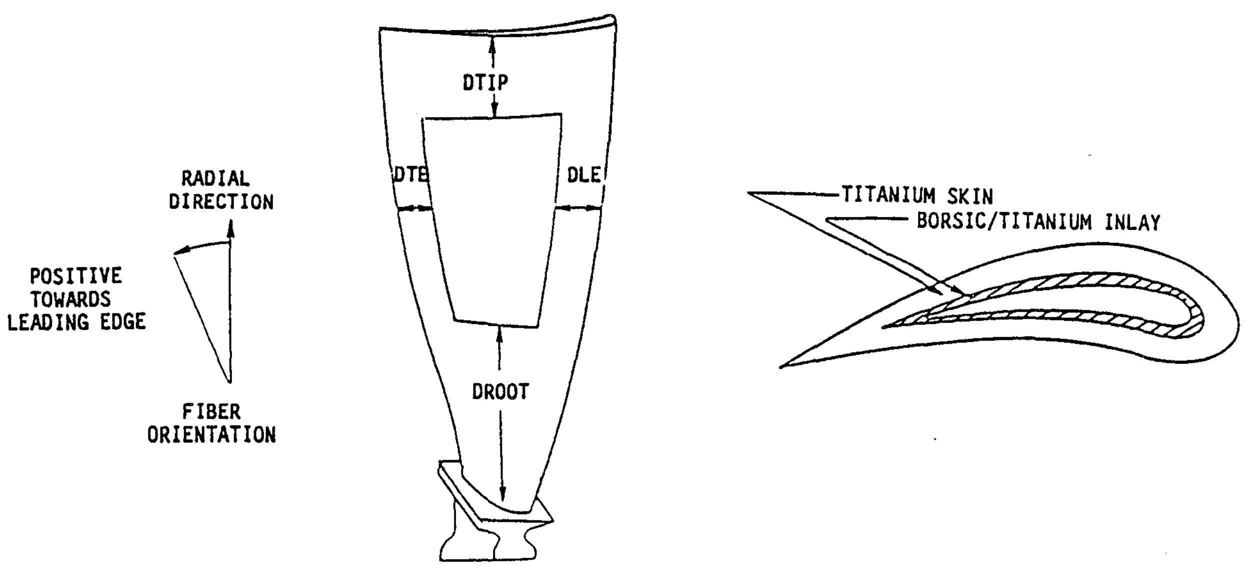


Figure 13 Dimensions and Layup Associated With a Hollow Blade Design

CARD C9a (REQUIRED IF NCD = 2 ON CARD C1a)

Contents: Data Associated With a Superhybrid Blade Design

1	2	3	4	5	6	
TIS	TIC	PCBA	BAA	GEA	AMPA	
10	20	30	40	50	60	

Field	Item	Format	Description
1	TIS	F	Skin thickness, inches.
2	TIC	F	Center thickness, inches.
3	PCBA	F	Outer composite percent (remaining is inner composite).
4	BAA	F	Outer composite fiber angle, degrees.
5	GEA	F	Inner composite fiber angle, degrees.
6	AMPA	F	Added mass patch option. If AMPA = 0: No added mass. If AMPA > 0: Added mass option active, and AMPA reflects mass per inch^2, lb sec^2/in^4.

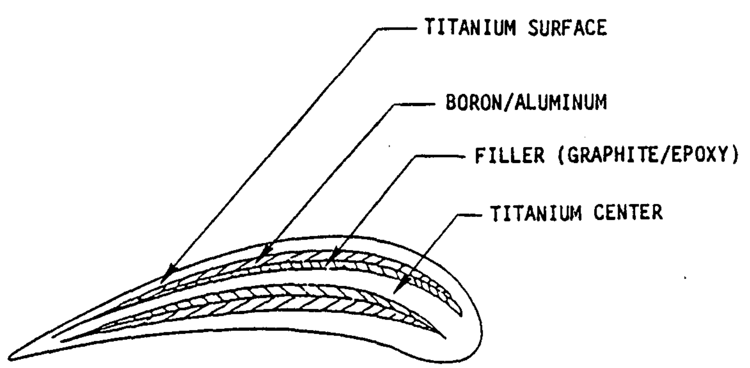


Figure 14 Layup Associated With a Superhybrid Blade Design

CARD C10 (REQUIRED IF AMPA $\neq$ 0 ON CARD C9a)

Contents: Local Increased Density Input

1	2	3	4	
ADLE	ADTE	ADROOT	ADTIP	
10	20	30	40	

Field	Item	Format	Description
1	ADLE	F	Distance to patch from leading edge, inches.
2	ADTE	F	Distance to patch from trailing edge, inches.
3	ADROOT	F	Distance to patch from blade root, inches.
4	ADTIP	F	Distance to patch from blade tip, inches.

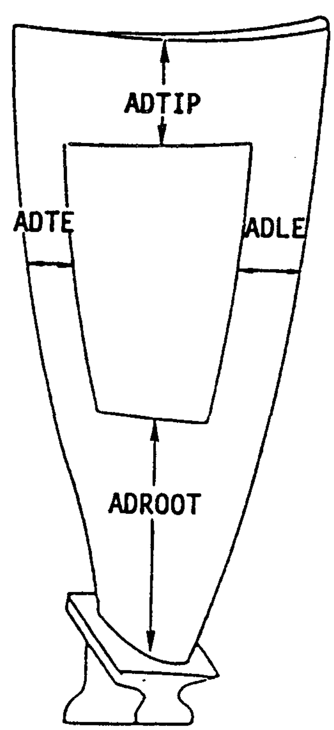


Figure 15 Dimensions Associated With a Local Increased Density Blade

CARD C11 (REQUIRED ONLY IF NLAYER < 0 ON CARD C1a)

Contents: TSAI-WU Failure Limits. Input NLAYER Values.

1	2	3	4	5	6	
X1T(I)	X1C(I)	X2T(I)	X2C(I)	S6P(I)	S6M(I)	
10	20	30	40	50	60	

Field	Item	Format	Description
1	X1T	E	Ultimate tensile strength in fiber direction, psi.
2	X1C	E	Ultimate compressive strength in fiber direction, psi.
3	X2T	E	Ultimate tensile strength perpendicular to fiber direction, psi.
4	X2C	E	Ultimate compressive strength perpendicular to fiber direction, psi.
5	S6P	E	Ultimate shear strength in x-y direction, psi.
6	S6M	E	Ultimate shear strength in y-x direction, psi.

Notes:

Input all strengths with positive value.

S6P and S6M are usually equal.

If NLAYER on Card C1a is positive, the following preset values for TSAI-WU limits will be used:

X1T = 110,000 psi
X1C = 110,000 psi
X2T = 110,000 psi
X2C = 110,000 psi
S6P = 63,470 psi
S6M = 63,470 psi

These values correspond to the values required to calculate a Von Mises equivalent yield limit in titanium.

SECTION 5.0

DETAILED OUTPUT DESCRIPTION

A description of the STAEBL output is summarized in the following sections, including each variable name, the writing element, and, if the output message is not self evident, an explanation follows.

5.1 COPES/CONMIN

Refer to Appendix A and/or the COPES/CONMIN manual (NASA Report No. NPS69-81-003).

5.2 Approximate Analysis

5.2.1 Global Variable Definition

Write routine for global variable description: MESAGE

5.2.2 Analysis Information

Output Message	Var. Name	Subroutine	Remark
Iteration Number	ITER	CNSTAV	Analysis iteration counter.
INFOG	INFOG	↓	Gradient calc. flag: 0 = nongradient 1 = gradient
IFREQ	IFREQ	↓	Frequency calc. flag: 0 = no 1 = yes
IFLT	IFLT	↓	Flutter calc. flag: 0 = no 1 = yes
IFOD	IFOD	↓	Foreign object damage calc. flag: 0 = no 1 = yes
ISTR	ISTR	↓	Stress calc. flag: 0 = no 1 = yes
IRTF	IRTF	↓	Root foreign object damage calc. flag: 0 = no 1 = yes

5.2.3 Airfoil Geometry

Output Message	Var. Name	Subroutine	Remark
NCD	NCD	CALCTH	Airfoil type: 0 = solid 1 = hollow 2 = superhybrid
DLE	DLE	↓	Hollow blade: distance from leading edge to hole.
DTE	DTE		Hollow blade: distance from trailing edge to hole.
DROOT	DROOT		Hollow blade: distance from blade root to hole.
DTIP	DTIP		Hollow blade: distance from blade tip to hole.
TTI	TTI		Hollow blade: skin thickness.
TLT	TLT		Hollow blade: inlay thickness.
B/T ANG	BTA		Hollow blade: inlay angle.
TIS	TIS		Superhybrid blade: skin thickness.
TIC	TIC		Superhybrid blade: center thickness.
PCBA	PCBA		Superhybrid blade: percent thickness of remaining for outer composite.
B/A ANG	BAA		Superhybrid blade: outer composite angle.
G/E ANG	GEA		Superhybrid blade: inner composite angle.
MASS PER UNIT AREA	AMPA		
ADLE	ADLE		Location of patch from leading edge.
ADTE	ADTE	↓	Location of patch from trailing edge.

Output Message	Var. Name	Subroutine	Remark
ADROOT	ADROOT	CALCTH	Location of added mass patch from root.
ADTIP	ADTIP	↓	Location of added mass patch from tip.
STA.	I	↓	Design station number.
RADIUS (IN.)	R	↓	Design station radius.
PCT. SPAN	PC	↓	Airfoil percent span.
THICKNESS (IN.)	TCC	↓	Airfoil maximum thickness.
CHORD (IN.)	BCC	↓	Airfoil chord length.
THK/CHD	TOB	↓	Airfoil thickness to chord ratio (t/b).

5.2.4 Resonance Margin Information

Output Message	Var. Name	Subroutine	Remark
FREQUENCIES AT RPM	SPD1	RESMRG	Initial analysis speed.
(#1)	FN1(1)	↓	1st mode frequency (Calculated frequencies (not corrected))
.	.		.
.	.		.
(n)	FN1(n)	↓	nth mode frequency (Calculated frequencies (not corrected))
FREQUENCIES AT RPM	SPD2	↓	Incremented speed. (Calculated frequencies (not corrected))
(#1)	FN2(1)	↓	1st mode frequency (Calculated frequencies (not corrected))
.	.		.
.	.		.
(n)	FN2(n)	↓	nth mode frequency (Calculated frequencies (not corrected))
REDLINE SPEED-RPM	SPDRL	↓	
MIN CRUISE SPEED RPM	SPDMC	↓	
FREQUENCY-CPS (REDLINE)	FRL	↓	Corrected frequencies
FREQUENCY-CPS (MIN CRUISE)	FMC	↓	Corrected frequencies
MARGIN (REDLINE)	RRL	↓	Positive margin at redline indicates a frequency above an order.
MARGIN (MIN CRUISE)	RMC	↓	Positive margin at min cruise indicates a frequency below an order.

Output Message	Var. Name	Subroutine	Remark
MARGIN (MAX)	RF	RESMRG	
ORDER	IORD	↓	
ORDER NUMBER	I	↓	
ROOT NUMBER	J	↓	

5.2.5 Resonance Margin Information, Forced Response

Output Message	Var. Name	Subroutine	Remark
MODE	I	GOODMN	
ORDER	IORD	↓	Order number.
SPEED	SPRL	↓	Redline speed.
PC MARGIN	PMGDRL	↓	Percent margin at redline speed.
SPEED	SPMC	↓	Min cruise speed.
PC MARGIN	PMGDMC	↓	Percent margin at min cruise speed.
MODE	I	↓	
MARGIN	GDMAX	↓	Max response margin.

5.2.6 Flutter Output

Output Message	Var. Name	Subroutine	Remark
FLUTTER CONSTRAINT	FLTSLD	ANALIZ	Bending flutter evaluation used for solid blade optimization.
AERO DAMPING COEF.	DELSAV	ITW751	Minimum aero. log. decrement found.
CRIT. NODAL DIA	NSAV	↓	Nodal diameter associated with minimum aero. log. decrement.

5.2.7 Tip Mode Information

Output Message	Var. Name	Subroutine	Remark
FREQUENCY-CPS AT # RPM	SPD1	FRQTIP	Analysis RPM.
(#)	FN1	↓	Tipmode frequency (raw).
FREQUENCY-CPS AT # RPM	SPD2		Incremented analysis RPM.
(#)	FN2		Tipmode frequency (raw).
REDLINE SPEED-RPM	SPDRL		
FREQUENCY-CPS	FRL		Corrected tipmode frequency at redline.
MARGIN	TPRL		Redline margin.
MIN CRUISE SPEED-RPM	SPDMC		
FREQUENCY-CPS	FMC		Corrected tipmode frequency at minimum cruise.
MARGIN	TPMC		Minimum cruise margin.
TIPMODE FREQUENCY MARGIN	TPMRG		Limiting margin.
ON #E	NRD		Order for limiting margin.
MODE	NM	↓	Tipmode mode number.

5.2.8 Stress Output

Output Message	Var. Name	Subroutine	Remark
ROOT STRESS	SROOT	ANALIZ	Maximum root stress as output from finite element analysis. (First two rows of element are searched.)
TSAI-WU STRESS	TSRT	STRCON	Maximum TSAI-WU stress.
FOR ELEMENT NUMBER	NELRT		
AND LAYER	NLYRT		

5.2.9 Object Function Information

Output Message	Var. Name	Subroutine	Remark
BLADE WEIGHT	WGHT	ANALIZ	
NUMBER OF BLADES	BLDGPC		BLOGIC is changed during the optimization process to keep the gap/chord ratio a constant.
STAGE WEIGHT	STGWT		
OBJECT FUNCTION	OBJFUN	OBJTV	

5.2.10 Local Foreign Object Damage Output

Output Message	Var. Name	Subroutine	Remark
STRAIN	STRN	ANALIZ	Average leading edge strain.
AT TIME	TMXA		Time of maximum average leading edge strain.

5.2.11 Root Foreign Object Damage Output

Output Message	Var. Name	Subroutine	Remark
ROOT FOD	TSWU	ANALIZ	
FOR ELEMENT NUMBER	NELM		
AND LAYER	NLAY		

SECTION 6.0

PROGRAMMED ERROR MESSAGES

This section contains programmed error messages found in STAEBL's approximate analysis. The COPES/CONMIN (Control Program for Engineering Synthesis/Constrained Minimization) manual and/or Appendix A should be referred to for any additional messages encountered.

6.1 COPES/CONMIN

Refer to Appendix A and/or the COPES/CONMIN manual, NASA Report Number NPS69-81-003.

6.2 COPES/ANALIZ

Message	Problem	Routine	Write Unit
N EXCEEDS NTIS	Number of thickness input stations not equal to the specified amount. See NTIS, IST on card C1a and C2.	CALCTH	26
NCD=__NOT A VALID OPTION	Bad NCD on card C1a.	CALCTH	26
NLAYER=__MUST BE BETWEEN 1&7	Bad number of layers specified on card C1a.	RDDATA	26
NLAYER=__ NLAYER MUST EQUAL 1, 5, OR 7 WHEN ITFL EQUALS 0. EXECUTION HALTED.	Self explanatory.	TSWUFL	26
INDEPENDENT VARIABLE WHICH IS__, IS OUT OF X RANGE	Beam fit routine is faltering. Check flutter aero. input stations.	BMEVAL	6
ROOT NUMBER=__ A ROOT NUMBER OTHER THAN 1, 2, OR 3 IS NOT SUPPORTED. ANALYSIS STOPPED.	Forcing functions for Energy Efficient Engine fan blades beyond third mode are not supported.	FRCFNC	26

6.3 Finite Element Preprocessor

Message	Problem	Routine	Write Unit
NSPAN=__ THE MAXIMUM IS 8. ANOTHER SPC1 CARD IS REQUIRED.	Self explanatory.	BC	6
NCHORD=__ THE MINIMUM IS 3. NSPAN=__ THE MINIMUM=5.	Self explanatory.	BC	6
THE NUMBER OF DATA POINTS IS LESS THAN 2. N=__	Inadequate subroutine input.	BMFIT2	6
THICKNESS CHECK IN LAMINA FAILURE CHECK=__	Remaining percentage thickness check has failed.	LAMINA	26
THE SUM OF LAMINA THICKNESSES DOESNT EQUAL THE INPUT TOTAL THICKNESS FOR THIS LAMINATE. SUM OF LAMINA THICKNESSES=__ INPUT LAMINA THICKNESS=__	Thicknesses of element in question are bad. Check layer thickness input.	LAMIN8	26

6.4 Finite Element Analysis

Note: Error messages from this module will probably never be seen unless the user has made changes to or replaced the existing preprocessor module.

Message	Problem	Routine	Write Unit
BANDED MATRIX SIZE LIMIT EXCEEDED.	Self explanatory.	MNU808	6
ERROR IN DATA,IER=__	If IER=1: element property card ID problem. If IER= 2, 3, 4: element grid point ID problem.	EMGG	6
***USER FATAL MESSAGE 4298. A CORNER POINT MEMBRANE THICKNESS HAS NOT BEEN SPECIFIED FOR ELEMENT WITH ID=__ AND THERE IS NO DEFAULT VALUE ON THE ASSOCIATED PROPERTY CARD.	Self explanatory.	ETR3D, STR31D	6
***USER FATAL MESSAGE 4301. FOR ELEMENT WITH ID A=__ THE MATERIAL ROUTINE -MAT- RETURNS A 3X3 G-MATRIX WITH EITHER OR BOTH OF BOTH TERMS G11 AND G22 EQUAL ZERO. MATERIAL ID CONCERNED EQUALS__.	Self explanatory.	ETR3D, STR31D	6

Message	Problem	Routine	Write Unit
***USER FATAL MESSAGE 4558. INAPPROPRIATE GEOMETRY OR INCORRECT MATERIAL DATA SPECIFIED FOR ELEMENT WITH ID=__.	Self explanatory.	ETR3D, STR31D	6
INAPPROPRIATE -TRIA3- GEOMETRY.	Self explanatory.	ETR3D, STR31D	6
MID2 MATERIAL -G- 3X3 MATRIX INSUFFICIENT, MATERIAL ID=__.	Self explanatory.	ETR3D, STR31D	6
ZERO MOMENT OF INERTIA COMPUTED.	Self explanatory.	ETR3D, STR31D	6
SINGULAR TRANSVERSE SHEAR MATRIX -Z-.	Self explanatory.	ETR3D, STR31D	6
INCOMPATABLE MATRIX MULTIPLICATION.	Bad subroutine input.	GMMATD	6
UNKNOWN BULK DATA CARD.	An unrecognizable name encountered during read for F.E. input.	INPUT	6
NO.OF GRIDS ELE PSHELL MAT CORD RFOR MAX. 80 120 120 240 80 1 THIS RUN THIS RUN STOPPED BECAUSE ONE OF THE ABOVE LIMITS HAS BEEN EXCEEDED.	Self explanatory.	INPUT	6
FAILED TO FIND LOCAL COORDINATE SYSTEM----IDENTITY MATRIX SUBSTITUTED.	Self explanatory.	TRANSD	6

SECTION 7.0

EXAMPLES: VALIDATION TEST CASES

7.1 Energy Efficient Engine Fan Hollow Blade With Borsic Inlay

7.1.1 Input

Card:	Data:
A1	E3 TEST CASE (HOLLOW BLADE)
A2	2,13
A3	5,10,0,14
A4a	0.0,0.0,-.05,0.0,0.0,0.0,.3
A4b	.005
A5	0,90,-1.0
A6	0.0,1.E+15
↓	0.0,1.E+15
	0.0,1.E+15
	0.0,1.E+15
	3.0,20.0
	0.05,4.5
	0.05,4.5
	2.42,16.4
	0.05,13.0
	.002,1.0
	0.0,0.3
	-90.0,90.0
A7	1,12,1.0
↓	2,13,1.0
	3,14,1.0
	4,15,1.0
	5,16,1.0
	6,58,1.0
	7,81,1.0
	8,82,1.0
	9,83,1.0
	10,84,1.0
	11,85,1.0
	12,86,1.0
	13,91,1.0
A8	13
A9a	33,35
A9b	.05,0.0,1.E+15
↓	38,40
	.05,0.0,1.E+15
	43,45
	.05,0.0,1.E+15
	60,61
	.02,0.0,.15
	62,63
	.02,0.0,.12
	64
	.02,0.0,.09
	7
	-.00786,0.0,1.E15
	8,9
	0.0,0.0,1.E15
	94
	0.0,0.0,47340.
	59
	-1.0E+15,0.0,.165
	98
	-1.0E+15,0.0,.2269

```
Card:     Data:

A9a       100
A9b       -1.0E+15,0.0,.2254
          101
          -1.0E+15,0.0,1.0
          97
          -1.0E+15,0.0,28.9
A10       END
B1                                                                                       1
B2         E3 TEST CASE
B3          3988.0                                3.0  1000.0
B4        19
B5        13.50000                              86.259                                    34.
B6          0.0      0.03053 0.29415 0.58829 0.88244 1.17659 1.47073 1.76488 2.05902
          2.35317 2.64732 2.94146 3.23561 3.52976 3.82390 4.11805 4.41220 4.70634
          5.00049 5.29463 5.58878 5.88293 6.17707 6.47122 6.76537 7.05951 7.35366
          7.64781 7.94195 8.23610 8.53025 8.82439 9.09154 9.11854
B7        0.04844 0.07751 0.32854 0.59306 0.84106 1.07337 1.29103 1.49489 1.68168
          1.85026 1.99982 2.13126 2.24482 2.34106 2.41926 2.47904 2.52126 2.54577
          2.55287 2.54231 2.51273 2.46329 2.39262 2.29955 2.18224 2.03889 1.86715
          1.66456 1.42809 1.15503 0.84095 0.48090 0.10566 0.06774
B8        -0.04022-0.02154 0.13972 0.31228 0.47586 0.63044 0.77619 0.91305 1.04078
          1.15895 1.26610 1.36224 1.44688 1.51962 1.57913 1.62503 1.65783 1.67747
          1.68450 1.67814 1.65746 1.62181 1.57046 1.50239 1.41662 1.31222 1.18824
          1.04298 0.87521 0.68361 0.46697 0.22348-0.02522-0.05036
B5        15.91800        -1.00000              86.259                                    34.
B6          0.0      0.03053 0.29415 0.58829 0.88244 1.17659 1.47073 1.76488 2.059[illegible]
 .        2.35317 2.64732 2.94146 3.23561 3.52976 3.82390 4.11805 4.4[illegible]
 .        5.00049 5.29463 5.58878 5.88293 6.17707 6.4712[illegible]
 .        7.64781 7.94195 8.23610 8.53025 8.8[illegible]
          0.04844 0.07751 0.32854 [illegible]
          1.85026 1.9998[illegible]
          2.55[illegible]

                                     .
                                     .
                                     .
                                                                                          34.
                                                                        [illegible].56851 2.99660
                                                               5.99320 6.42129 6.84937
                                                [illegible]80 9.41789 9.8459810.2740610.70215
                                       [illegible].4144912.8425813.2509713.27066
                          [illegible] 0.02314 0.02300 0.02118 0.01777 0.01268 0.00627-0.00083
                  [illegible]52-0.01674-0.02528-0.03481-0.04446-0.05146-0.05257-0.04596-0.03170
          -0.01084 0.01444 0.03705 0.05534 0.06935 0.07932 0.08548 0.08801 0.08716
           0.08315 0.07598 0.06591 0.05324 0.03823 0.02116 0.02034
          -0.01979-0.02145-0.05291-0.08597-0.11857-0.15068-0.18216-0.21274-0.24184
          -0.26915-0.29461-0.31809-0.34082-0.36058-0.37516-0.38205-0.37939-0.36572
          -0.34232-0.31474-0.28587-0.25866-0.23292-0.20856-0.18517-0.16264-0.14090
          -0.11987-0.09924-0.07883-0.05841-0.03807-0.01837-0.01742
B9                24.3000  1.283   15.844    10.0
B10                                                             24.00
C1a          5     3     5     1     5     1     0    08.16064
C1b        .937 .920 .931              0.0
C2         2.77128   61.20216 10.59455  15.25854  19.26292
C3        0.0        -45.0                        12
C4         0.768      13.500                496.6
           0.834      15.844                491.0
           0.903      18.301                485.1
           0.988      20.758                477.9
           1.080      23.215                467.5
           1.172      25.672                457.5
           1.268      28.130                448.4
           1.360      30.587                441.8
           1.450      33.044                438.2
           1.530      35.501                439.8
           1.610      37.958                445.0
           1.692      40.491                449.5
C5        4267.0      3625.0        3     2    3    4
C6        2.225       14075.0    .4122      .0000841   .000010   0.0
C7           16     35
C8        16.1      E616.1    E6.33       6.05      E60.000414
          27.9      E618.0    E6.27       7.65      E60.000226
          00.0      E600.0    E6.00       0.00      E60.000000
          27.9      E618.0    E6.27       7.65      E60.000226
          16.1      E616.1    E6.33       6.05      E60.000414
C9        .74685     1.1914     2.4200      .2494      .018385   .060076   -.0129
```

7.1.2 Output

```
* * * * ANALYSIS INFORMATION * * * *

ITERATION NUMBER  7
INFOG = 0(INFOG = 0 - NON-GRADIENT CALCULATION , = 1 - GRADIENT CALCULATION)

ANALYSIS NOT PERFORMED FOR A ZERO INDICATOR (GRADIENT CALCULATION ONLY)
(IFRQ-FREQUENCY ANALYSIS , IFLT-FLUTTER ANALYSIS , IFOD-FOD ANALYSIS , ISTR-STRESS ANALYSIS , IRTF-ROOT FOD)
IFRQ = 1  IFLT = 1  IFOD = 1  ISTR = 1  IRTF = 1

* * * * AIRFOIL GEOMETRY * * * *

NCD = 1  (HOLLOW FOIL)
DLE =  0.90077E+00  DTE =  0.10476E+01  DROOT =  0.24200E+01  DTIP =  0.24884E+00
TTI =  0.15210E-01  TLT =  0.46733E-01  B/T ANG = -0.12899E-01

$ - INDICATES A DESIGN VARIABLE STATION

   STA.   RADIUS   PCT. SPAN  THICKNESS   CHORD     THK/CHD
           (IN.)                (IN.)     (IN.)
$   2   15.91800     0.0     0.76344    7.80949   0.09776
    3   17.36340     5.88    0.91237    8.05830   0.11322
    4   18.80881    11.76    1.06130    8.40903   0.12621
    5   20.25421    17.65    1.21024    8.77593   0.13790
$   6   21.69962    23.53    1.35917    9.07369   0.14979
    7   23.14502    29.41    1.18392    9.30773   0.12720
    8   24.59042    35.29    1.00868    9.49244   0.10626
    9   26.03583    41.18    0.83343    9.64939   0.08637
$  10   27.48123    47.06    0.65818    9.83029   0.06695
   11   28.92664    52.94    0.57759   10.00858   0.05771
   12   30.37204    58.82    0.49699   10.18422   0.04880
   13   31.81744    64.71    0.41639   10.35054   0.04023
   14   33.26285    70.59    0.33580   10.52599   0.03190
$  15   34.70825    76.47    0.25520   10.70728   0.02383
   16   36.15366    82.35    0.25294   10.88196   0.02324
   17   37.59906    88.23    0.25069   11.07183   0.02264
   18   39.04446    94.12    0.24843   11.24325   0.02210
$  19   40.49001   100.00    0.24617   11.36554   0.02166

* * * * RESONANCE MARGIN INFORMATION * * * *

FREQUENCIES AT  3988.2 RPM     115.11     258.12     319.41
FREQUENCIES AT  4988.4 RPM     130.83     284.88     326.29

RED LINE SPEED-RPM =  4267.0    MIN CRUISE SPEED-RPM =  3625.0

FREQUENCY-CPS  FREQUENCY-CPS    MARGIN         MARGIN        MARGIN        EXCITATION    ROOT
 (RED LINE)    (MIN CRUISE)    (RED LINE)   (MIN CRUISE)     (MAX)           ORDER      NUMBER
0.11182E+03    0.10290E+03   -0.21384E+00   0.14845E+00   0.14845E+00        2          1
0.11182E+03    0.10290E+03   -0.47590E+00   0.43230E+00   0.43230E+00        3          1
0.11182E+03    0.10290E+03   -0.60692E+00   0.57422E+00   0.57422E+00        4          1
0.24402E+03    0.22936E+03    0.71561E+00  -0.89813E+00   0.71561E+00        2          2
0.24402E+03    0.22936E+03    0.14374E+00  -0.26542E+00   0.14374E+00        3          2
0.24402E+03    0.22936E+03   -0.14220E+00   0.50935E-01   0.50935E-01        4          2
0.29902E+03    0.29537E+03    0.11023E+01  -0.14444E+01   0.11023E+01        2          3
0.29902E+03    0.29537E+03    0.40156E+00  -0.62962E+00   0.40156E+00        3          3
0.29902E+03    0.29537E+03    0.51171E-01  -0.22221E+00   0.51171E-01        4          3
```

* * * * FLUTTER OUTPUT * * * *

P&W FLUTTER ANALYSIS

MODE	CRIT. NODAL DIA	AERO DAMPING COEF.
1	2	-0.78906E-02
2	-2	0.26567E-01
3	2	0.51978E-01

* * * * STRESS OUTPUT * * * *

ROOT STRESS (PSI) = 0.20653E+05

ROOT TSAI-WU STRESS = 0.15801E+00 FOR ELEMENT NUMBER 14 AND LAYER 5

HOLE TSAI-WU STRESS (TI) = 0.22297E+00 FOR ELEMENT NUMBER 21 AND LAYER 1

HOLE TSAI-WU STRESS (B/T) = 0.67622E+00 FOR ELEMENT NUMBER 21 AND LAYER 2

* * * * OBJECT FUNCTION INFORMATION * * * *

BLADE WEIGHT (LBS) = 0.88612D+01

NUMBER OF BLADES = 0.28023E+02

STAGE WEIGHT (LBS) = 0.24832E+03

OBJECT FUNCTION = 0.10785E+01

* * * * LOCAL FOD OUTPUT - AVE. PERCENT STRAIN,TIME,LOCATION * * * *

STRAIN = 0.130921E+00 AT TIME = 0.320000D-03

* * * * ROOT FOD OUTPUT * * * *

ROOT FOD = 0.60347E+01 FOR ELEMENT NUMBER 16 AND LAYER 5

7.2 Energy Efficient Engine Fan Superhybrid Blade

7.2.1 Input

Card:	Data:
A1	E3 TEST CASE
A2	2,11
A3	5,10,0,12
A4a	0.0,0.0,-.00928,0.0,0.0,0.0,.3
A4b	.005
A5	0,90,-1.0
A6	0.0,1.E+15
	0.0,1.E+15
	0.0,1.E+15
	0.0,1.E+15
	0.0,1.E+15
	3.0,20.0
	.010,5.0
	0.0,5.0
	0.0,1.0
	-90.0,90.0
	-90.0,90.0
A7	1,12,1.0
	2,13,1.0
	3,14,1.0
	4,15,1.0
	5,16,1.0
	6,58,1.0
	7,87,1.0
	8,88,1.0
	9,89,1.0
	10,92,1.0
	11,93,1.0
A8	14
A9a	33,35
A9b	.05,0.0,1.E+15
	38,40
	.05,0.0,1.E+15
	43,45
	.05,0.0,1.E+15
	60,61
	.02,0.0,.15
	62,63
	.02,0.0,.12
	64
	.02,0.0,.09
	7
	-.00714,0.0,1.E15
	8,9
	0.0,0.0,1.E15
	94
	0.0,0.0,47340.
	59
	-1.0E+15,0.0,.165
	97
	-1.0E+15,0.0,28.9
	99
	-1.0E+15,0.0,.2269

```
Card:   Data:

A9a     100
A9b     -1.0E+15,0.0,1.0
A9a     101
A9b     -1.0E+15,0.0,1.0
A10     END
B1                                                                              1
B2       E3 TEST CASE
B3        3988.0                                    3.0   1000.0
B4      19
B5      13.50000 0.0                        86.259                                  34.
B6       0.0      0.03053 0.29415 0.58829 0.88244 1.17659 1.47073 1.76488 2.05902
 |       2.35317 2.64732 2.94146 3.23561 3.52976 3.82390 4.11805 4.41220 4.70634
 |       5.00049 5.29463 5.58878 5.88293 6.17707 6.47122 6.76537 7.05951 7.35366
 v       7.64781 7.94195 8.23610 8.53025 8.82439 9.09154 9.11854
B7       0.04844 0.07751 0.32854 0.59306 0.84106 1.07337 1.29103 1.49489 1.68168
 |       1.85026 1.99982 2.13126 2.24482 2.34106 2.41926 2.47904 2.52126 2.54577
 |       2.55287 2.54231 2.51273 2.46329 2.39262 2.29955 2.18224 2.03889 1.86715
 v       1.66456 1.42809 1.15503 0.84095 0.48090 0.10566 0.06774
B8      -0.04022-0.02154 0.13972 0.31228 0.47586 0.63044 0.77619 0.91305 1.04078
 |       1.15895 1.26610 1.36224 1.44688 1.51962 1.57913 1.62503 1.65783 1.67747
 |       1.68450 1.67814 1.65746 1.62181 1.57046 1.50239 1.41662 1.31222 1.18824
 v       1.04298 0.87521 0.68361 0.46697 0.22348-0.02522-0.05036
B5      15.91800         -1.00000           86.259                                  34
B6       0.0      0.03053 0.29415 0.58829 0.88244 1.17659 1.47073 1.76488
 |       2.35317 2.64732 2.94146 3.23561 3.52976 3.82390 4.118
 |       5.00049 5.29463 5.58878 5.88293 6.17707 6.4
 v       7.64781 7.94195 8.23610 8.53025
B7       0.04844 0.07751 0.328
 .       1.85026 1.9
 .
 .
                                      .
                                      .
                                      .

                                                                                    34.
                                                                  2.56851 2.99660
                                                          5.99320 6.42129 6.84937
                                                 .98980 9.41789 9.8459810.2740610.70215
                                    12.4144912.8425813.2509713.27066
                           .02162 0.02314 0.02300 0.02118 0.01777 0.01268 0.00627-0.00083
        .00852-0.01674-0.02528-0.03481-0.04446-0.05146-0.05257-0.04596-0.03170
        -0.01084 0.01444 0.03705 0.05534 0.06935 0.07932 0.08548 0.08801 0.08716
         0.08315 0.07598 0.06591 0.05324 0.03823 0.02116 0.02034
        -0.01979-0.02145-0.05291-0.08597-0.11857-0.15068-0.18216-0.21274-0.24184
        -0.26915-0.29461-0.31809-0.34802-0.36058-0.37516-0.38205-0.37939-0.36572
        -0.34232-0.31474-0.28587-0.25866-0.23292-0.20856-0.18517-0.16264-0.14090
        -0.11987-0.09924-0.07883-0.05841-0.03807-0.01837-0.01742
B9               24.3000  1.283    15.844     10.0
B10                                                            24.00
C1a        5    3    5    2    7    1    0   011.1147
C1b      .996 .9861.033                0.0
C2      21.0736    6.8019    10.8693    15.44780   19.3754
C3      0.0        -45.0                          12
C4       0.768      13.500                496.6
 |       0.834      15.844                491.0
 |       0.903      18.301                485.1
 |       0.988      20.758                477.9
 |       1.080      23.215                467.5
 |       1.172      25.672                457.5
 |       1.268      28.130                448.4
 |       1.360      30.587                441.8
 |       1.450      33.044                438.2
 |       1.530      35.501                439.8
 |       1.610      37.958                445.0
 v       1.692      40.491                449.5
C5      4267.0     3625.0        3     2     3     4
C6      2.225      14075.0   .4122       .0000841  .000010  0.0
C7         16    35
C8      16.1     E616.1     E6.33        6.05     E60.000414
 |      27.9     E618.0     E6.27        7.65     E60.000226
 |      18.5     E61.54     E6.30        0.85     E60.000115
 |      16.1     E616.1     E6.33        6.05     E60.000414
 |      18.5     E61.54     E6.30        0.85     E60.000115
 |      27.9     E618.0     E6.27        7.65     E60.000226
 v      16.1     E616.1     E6.33        6.05     E60.000414
C9a     .042700     .023200    0.72330     -.00205    -.00712
```

7.2.2 Output

```
* * * * ANALYSIS INFORMATION * * * *

ITERATION NUMBER  9
INFOG = 0(INFOG = 0 - NON-GRADIENT CALCULATION , = 1 - GRADIENT CALCULATION)

ANALYSIS NOT PERFORMED FOR A ZERO INDICATOR (GRADIENT CALCULATION ONLY)
(IFRQ-FREQUENCY ANALYSIS , IFLT-FLUTTER ANALYSIS , IFOD-FOD ANALYSIS , ISTR-STRESS ANALYSIS , IRTF-ROOT FOD)
IFRQ = 1  IFLT = 1  IFOD = 1  ISTR = 1  IRTF = 1

* * * * AIRFOIL GEOMETRY * * * *

NCD = 2  (COMPOSITE FOIL)
TIS =  0.20587E-01  TIC =  0.20291E-01  PCBA =  0.59084E+00
B/A ANG = -0.20500E-02  G/E ANG = -0.71201E-02

$ - INDICATES A DESIGN VARIABLE STATION

  STA.   RADIUS   PCT. SPAN  THICKNESS   CHORD     THK/CHD
          (IN.)               (IN.)      (IN.)
$   2   15.91800     0.0     1.18092    7.89029   0.14967
    3   17.36340     5.88    1.11082    8.14167   0.13644
    4   18.80881    11.76    1.04071    8.49603   0.12249
    5   20.25421    17.65    0.97061    8.86673   0.10947
$   6   21.69962    23.53    0.90050    9.16757   0.09823
    7   23.14502    29.41    0.93836    9.40402   0.09978
    8   24.59042    35.29    0.97622    9.59065   0.10179
    9   26.03583    41.18    1.01408    9.74922   0.10402
$  10   27.48123    47.06    1.05194    9.93199   0.10591
   11   28.92664    52.94    0.93722   10.11212   0.09268
   12   30.37204    58.82    0.82249   10.28958   0.07993
   13   31.81744    64.71    0.70777   10.45762   0.06768
   14   33.26285    70.59    0.59305   10.63489   0.05576
$  15   34.70825    76.47    0.47832   10.81806   0.04422
   16   36.15366    82.35    0.42921   10.99454   0.03904
   17   37.59906    88.23    0.38010   11.18638   0.03398
   18   39.04446    94.12    0.33098   11.35957   0.02914
$  19   40.49001   100.00    0.28186   11.48312   0.02455

* * * * RESONANCE MARGIN INFORMATION * * * *

FREQUENCIES AT  3988.2 RPM      119.85    299.23    411.66
FREQUENCIES AT  4988.4 RPM      133.76    318.47    415.83

RED LINE SPEED-RPM =  4267.0    MIN CRUISE SPEED-RPM =  3625.0

FREQUENCY-CPS  FREQUENCY-CPS    MARGIN          MARGIN          MARGIN        EXCITATION    ROOT
 (RED LINE)    (MIN CRUISE)   (RED LINE)     (MIN CRUISE)       (MAX)           ORDER      NUMBER
0.12307E+03     0.11476E+03  -0.13475E+00    0.50257E-01    0.50257E-01          2           1
0.12307E+03     0.11476E+03  -0.42316E+00    0.36684E+00    0.36684E+00          3           1
0.12307E+03     0.11476E+03  -0.56737E+00    0.52513E+00    0.52513E+00          4           1
0.30002E+03     0.28895E+03   0.11093E+01   -0.13913E+01    0.11093E+01          2           2
0.30002E+03     0.28895E+03   0.40623E+00   -0.59421E+00    0.40623E+00          3           2
0.30002E+03     0.28895E+03   0.54668E-01   -0.19566E+00    0.54668E-01          4           2
0.42635E+03     0.42391E+03   0.19976E+01   -0.25082E+01    0.19976E+01          2           3
0.42635E+03     0.42391E+03   0.99837E+00   -0.13388E+01    0.99837E+00          3           3
0.42635E+03     0.42391E+03   0.49878E+00   -0.75411E+00    0.49878E+00          4           3
```

* * * * FLUTTER OUTPUT * * * *

P&W FLUTTER ANALYSIS

MODE	CRIT. NODAL DIA	AERO DAMPING COEF.
1	2	-0.71425E-02
2	-2	0.15013E-01
3	-2	0.56323E-01

* * * * STRESS OUTPUT * * * *

ROOT STRESS (PSI) = 0.31434E+05

ROOT TSAI-WU STRESS (TI) = 0.76245E-01 FOR ELEMENT NUMBER 12 AND LAYER 1

ROOT TSAI-WU STRESS (B/A) = 0.99606E+00 FOR ELEMENT NUMBER 13 AND LAYER 6

ROOT TSAI-WU STRESS (G/E) = 0.41773E-01 FOR ELEMENT NUMBER 9 AND LAYER 3

* * * * OBJECT FUNCTION INFORMATION * * * *

BLADE WEIGHT (LBS) = 0.97301D+01

NUMBER OF BLADES = 0.27736E+02

STAGE WEIGHT (LBS) = 0.26987E+03

OBJECT FUNCTION = 0.12105E+01

* * * * LOCAL FOD OUTPUT - AVE. PERCENT STRAIN,TIME,LOCATION * * * *

STRAIN = 0.102622E+00 AT TIME = 0.230000D-03

* * * * ROOT FOD OUTPUT * * * *

ROOT FOD = 0.49362E+01 FOR ELEMENT NUMBER 16 AND LAYER 6

7.3 Energy Efficient Engine Fan Superhybrid With Local Increased Density

7.3.1 Input

Card:	Data:
A1	E3 TEST CASE (L.I.D.)
A2	2,16
A3	5,13,0,16
A4a	0.0,.0001,-.02154,0.0,0.0,0.0,.3
A4b	.005
A5	0,90,-1.0
A6	0.0,1.E+15
↓	0.0,1.E+15
	0.0,1.E+15
	0.0,1.E+15
	0.0,1.E+15
	3.0,20.0
	.010,5.0
	0.0,5.0
	0.0,1.0
	-90.0,90.0
	-90.0,90.0
	0.0,.2
	.05,4.5
	.05,4.5
	2.42,16.4
	.05,13.0
A7	1,12,1.0
↓	2,13,1.0
	3,14,1.0
	4,15,1.0
	5,16,1.0
	6,58,1.0
	7,87,1.0
	8,88,1.0
	9,89,1.0
	10,92,1.0
	11,93,1.0
	12,111,1.0
	13,112,1.0
	14,113,1.0
	15,114,1.0
	16,115,1.0
A8	14
A9a	33,35
A9b	.05,0.0,1.E+15
↓	38,40
	.05,0.0,1.E+15
	43,45
	.05,0.0,1.E+15
	60,61
	.02,0.0,.15
	62,63
	.02,0.0,.12
	64
	.02,0.0,.09
	7
	-.00714,0.0,1.E15
	8,9
	0.0,0.0,1.E15

```
Card:   Data:

A9a     94
A9b     0.0,0.0,47340.
        59
        -1.0E+15,0.0,.165
        97
        -1.0E+15,0.0,28.9
        99
        -1.0E+15,0.0,.2269
        100
        -1.0E+15,0.0,1.0
        101
        -1.0E+15,0.0,1.0
A10     END
B1                                                                                    I
B2       E3 TEST CASE
B3        3988.0                              3.0  1000.0
B4      19
B5      13.50000                           86.259                                        34.
B6       0.0     0.03053 0.29415 0.58829 0.88244 1.17659 1.47073 1.76488 2.05902
         2.35317 2.64732 2.94146 3.23561 3.52976 3.82390 4.11805 4.41220 4.70634
         5.00049 5.29463 5.58878 5.88293 6.17707 6.47122 6.76537 7.05951 7.35366
         7.64781 7.94195 8.23610 8.53025 8.82439 9.09154 9.11854
B7       0.04844 0.07751 0.32854 0.59306 0.84106 1.07337 1.29103 1.49489 1.68168
         1.85026 1.99982 2.13126 2.24482 2.34106 2.41926 2.47904 2.52126 2.54577
         2.55287 2.54231 2.51273 2.46329 2.39262 2.29955 2.18224 2.03889 1.86715
         1.66456 1.42809 1.15503 0.84095 0.48090 0.10566 0.06774
B8      -0.04022-0.02154 0.13972 0.31228 0.47586 0.63044 0.77619 0.91305 1.04078
         1.15895 1.26610 1.36224 1.44688 1.51962 1.57913 1.62503 1.65783 1.67747
         1.68450 1.67814 1.65746 1.62181 1.57046 1.50239 1.41662 1.31222 1.18824
         1.04298 0.87521 0.68361 0.46697 0.22348-0.02522-0.05036
B5      15.91800        -1.00000           86.259
B6       0.0     0.03053 0.29415 0.58829 0.882
 •       2.35317 2.64732 2.94146 3.
 •       5.00049 5.294                                                                   34.
 •       7.
                                                                   2.56851 2.99660
                                                           5.99320 6.42129 6.84937
                                           980 9.41789 9.8459810.2740610.70215
                                     4144912.8425813.2509713.27066
                              0.02314 0.02300 0.02118 0.01777 0.01268 0.00627-0.00083
                       -0.01674-0.02528-0.03481-0.04446-0.05146-0.05257-0.04596-0.03170
        -0.01084 0.01444 0.03705 0.05534 0.06935 0.07932 0.08548 0.08801 0.08716
         0.08315 0.07598 0.06591 0.05324 0.03823 0.02116 0.02034
        -0.01979-0.02145-0.05291-0.08597-0.11857-0.15068-0.18216-0.21274-0.24184
        -0.26915-0.29461-0.31809-0.34082-0.36058-0.37516-0.38205-0.37939-0.36572
        -0.34232-0.31474-0.28587-0.25866-0.23292-0.20856-0.18517-0.16264-0.14090
        -0.11987-0.09924-0.07883-0.05841-0.03807-0.01837-0.01742
B9              24.3000  1.283   15.844    10.0
B10                                                            24.00
C1a        5    3    5    2    7    1    0    08.1664
C1b     .996 .9861.033               0.0
C2      21.2001   6.8993    101.1023   15.5123   19.2634
C3      0.0       -45.0                          12
C4      0.768     13.500               496.6
        0.834     15.844               491.0
        0.903     18.301               485.1
        0.988     20.758               477.9
        1.080     23.215               467.5
        1.172     25.672               457.5
        1.268     28.130               448.4
        1.360     30.587               441.8
        1.450     33.044               438.2
        1.530     35.501               439.8
        1.610     37.958               445.0
        1.692     40.491               449.5
C5      4267.0    3625.0       3    2    3    4
C6      2.225     14075.0   .4122      .0000841  .000010  0.0
C7         16    35
C8      16.1     E616.1    E6.33       6.05      E60.000414
        27.9     E618.0    E6.27       7.65      E60.000226
        18.5     E61.54    E6.30       0.85      E60.000115
        16.1     E616.1    E6.33       6.05      E60.000414
        18.5     E61.54    E6.30       0.85      E60.000115
        27.9     E618.0    E6.27       7.65      E60.000226
        16.1     E616.1    E6.33       6.05      E60.000414
C9a     .017400   .019800   0.67260    -.00205    -.00711  .0000165
C10     .9567     .9631     10.979     .2004
```

7.3.2 Output

* * * * ANALYSIS INFORMATION * * * *

ITERATION NUMBER 8
INFOG = 0(INFOG = 0 - NON-GRADIENT CALCULATION , = 1 - GRADIENT CALCULATION)

ANALYSIS NOT PERFORMED FOR A ZERO INDICATOR (GRADIENT CALCULATION ONLY)
(IFRQ-FREQUENCY ANALYSIS , IFLT-FLUTTER ANALYSIS , IFOD-FOD ANALYSIS , ISTR-STRESS ANALYSIS , IRTF-ROOT FOD)
IFRQ = 1 IFLT = 1 IFOD = 1 ISTR = 1 IRTF = 1

* * * * AIRFOIL GEOMETRY * * * *

NCD = 2 (COMPOSITE FOIL)
TIS = 0.15233E-01 TIC = 0.18581E-01 PCBA = 0.64650E+00
B/A ANG = -0.20500E-02 G/E ANG = -0.71100E-02

ADDED MASS OPTION MASS PER UNIT AREA = 0.15162E-04

ADLE = 0.97570E+00 ADTE = 0.97286E+00 ADROOT = 0.11637E+02 ADTIP = 0.20065E+00

$ - INDICATES A DESIGN VARIABLE STATION

	STA.	RADIUS (IN.)	PCT. SPAN	THICKNESS (IN.)	CHORD (IN.)	THK/CHD
$	2	15.91800	0.0	1.17632	7.84335	0.14998
	3	17.36340	5.88	1.12544	8.09324	0.13906
	4	18.80881	11.76	1.07457	8.44548	0.12724
	5	20.25421	17.65	1.02369	8.81398	0.11614
$	6	21.69962	23.53	0.97281	9.11303	0.10675
	7	23.14502	29.41	1.00822	9.34808	0.10785
	8	24.59042	35.29	1.04362	9.53359	0.10947
	9	26.03583	41.18	1.07902	9.69123	0.11134
$	10	27.48123	47.06	1.11443	9.87291	0.11288
	11	28.92664	52.94	0.99271	10.05197	0.09876
	12	30.37204	58.82	0.87099	10.22837	0.08515
	13	31.81744	64.71	0.74927	10.39541	0.07208
	14	33.26285	70.59	0.62755	10.57162	0.05936
$	15	34.70825	76.47	0.50583	10.75370	0.04704
	16	36.15366	82.35	0.44029	10.92914	0.04029
	17	37.59906	88.23	0.37474	11.11983	0.03370
	18	39.04446	94.12	0.30920	11.29199	0.02738
$	19	40.49001	100.00	0.24365	11.41481	0.02135

* * * * RESONANCE MARGIN INFORMATION * * * *

FREQUENCIES AT 3988.2 RPM 118.91 297.98 404.91
FREQUENCIES AT 4988.4 RPM 132.62 316.87 409.15

RED LINE SPEED-RPM = 4267.0 MIN CRUISE SPEED-RPM = 3625.0

FREQUENCY-CPS (RED LINE)	FREQUENCY-CPS (MIN CRUISE)	MARGIN (RED LINE)	MARGIN (MIN CRUISE)	MARGIN (MAX)	EXCITATION ORDER	ROOT NUMBER
0.12208E+03	0.11390E+03	-0.14168E+00	0.57344E-01	0.57344E-01	2	1
0.12208E+03	0.11390E+03	-0.42778E+00	0.37156E+00	0.37156E+00	3	1
0.12208E+03	0.11390E+03	-0.57084E+00	0.52867E+00	0.52867E+00	4	1
0.29869E+03	0.28782E+03	0.11000E+01	-0.13820E+01	0.11000E+01	2	2
0.29869E+03	0.28782E+03	0.40000E+00	-0.58799E+00	0.40000E+00	3	2
0.29869E+03	0.28782E+03	0.49999E-01	-0.19099E+00	0.49999E-01	4	2
0.41940E+03	0.41691E+03	0.19487E+01	-0.24503E+01	0.19487E+01	2	3
0.41940E+03	0.41691E+03	0.96579E+00	-0.13002E+01	0.96579E+00	3	3
0.41940E+03	0.41691E+03	0.47434E+00	-0.72516E+00	0.47434E+00	4	3

* * * * FLUTTER OUTPUT * * * *

P&W FLUTTER ANALYSIS

MODE	CRIT. NODAL DIA	AERO DAMPING COEF.
1	2	-0.70173E-02
2	-2	0.13480E-01
3	-2	0.58687E-01

* * * * STRESS OUTPUT * * * *

ROOT STRESS (PSI) = 0.34400E+05

ROOT TSAI-WU STRESS (TI) = 0.83558E-01 FOR ELEMENT NUMBER 12 AND LAYER 1

ROOT TSAI-WU STRESS (B/A) = 0.99478E+00 FOR ELEMENT NUMBER 13 AND LAYER 6

ROOT TSAI-WU STRESS (G/E) = 0.45189E-01 FOR ELEMENT NUMBER 9 AND LAYER 3

* * * * OBJECT FUNCTION INFORMATION * * * *

BLADE WEIGHT (LBS) = 0.10544D+02

NUMBER OF BLADES = 0.27902E+02

STAGE WEIGHT (LBS) = 0.29421E+03

OBJECT FUNCTION = 0.12754E+01

* * * * LOCAL FOD OUTPUT - AVE. PERCENT STRAIN,TIME,LOCATION * * * *

STRAIN = 0.898786E-01 AT TIME = 0.220000D-03

* * * * ROOT FOD OUTPUT * * * *

ROOT FOD = 0.42661E+01 FOR ELEMENT NUMBER 16 AND LAYER 6

7.4 Energy Efficient Engine High-Pressure Compressor Rotor 6 Solid Blade

7.4.1 Input

Note: For this blade optimization, no analytical flutter evaluation was performed. To protect against possible bending flutter, the first mode reduced velocity (originally 2.3) was constrained to be no higher than 4.5, the reduced velocity of the seventh rotor of the Energy Efficient Engine high-pressure compressor. In constraint form, this flutter parameter is satisfied when $0 \leqslant 1000/b_{75\%}\omega \leqslant 1.0$. The reduced velocity constraint term is stored in global location 104 of COPES, and is handled by COPES as a standard constraint.

Card:	Data:
A1	E3 TEST CASE (SOLID BLADE)
A2	2,6
A3	5,10,0,7
A4a	0.0,0.0,-.05,0.0,0.0,0.0,0.3
A4b	.005
A5	0,102,-1.0
A6	0.0,1.E+15
↓	0.0,1.E+15
↓	0.0,1.E+15
↓	0.0,1.E+15
↓	0.0,1.E+15
↓	0.05,10.0
A7	1,12,1.0
↓	2,13,1.0
↓	3,14,1.0
↓	4,15,1.0
↓	5,16,1.0
↓	6,58,1.0
A8	9
A9a	33,36
A9b	0.05,0.0,1.E+15
↓	38,41
↓	0.05,0.0,1.E+15
↓	43,46
↓	0.05,0.0,1.E+15
↓	60,61
↓	0.02,0.0,.15
↓	62,63
↓	0.02,0.0,.12
↓	64
↓	0.02,0.0,.10
↓	94
↓	0.0,0.0,47340.
↓	103
↓	0.10,0.0,1.E+15
↓	104
↓	0.0,0.0,1.0
A10	END

```
Card:   Data:

B1                                                                                   1
B2       E3 HPC ROTOR 6
B3        14250.0                                3.0  1000.0
B4      16
B5      6.24132                             70.404                                      34.
B6      0.0       0.01090 0.09054 0.18108 0.27162 0.36217 0.45271 0.54325 0.63379
 |       0.72433 0.81487 0.90542 0.99596 1.08650 1.17704 1.26758 1.35812 1.44866
 |       1.53921 1.62975 1.72029 1.81083 1.90137 1.99191 2.08245 2.17300 2.26354
 V       2.35408 2.44462 2.53516 2.62570 2.71625 2.79768 2.80679
B7       0.01483 0.02328 0.08505 0.15171 0.21325 0.27039 0.32278 0.37128 0.41555
 |       0.45610 0.49286 0.52615 0.55590 0.58238 0.60514 0.62349 0.63730 0.64635
 |       0.65076 0.65051 0.64535 0.63514 0.61968 0.59866 0.57173 0.53833 0.49777
 V       0.44918 0.39133 0.32254 0.24040 0.14113 0.03177 0.01955
B8      -0.01183-0.00713 0.02720 0.06498 0.10051 0.13389 0.16510 0.19411 0.22095
 |       0.24558 0.26805 0.28831 0.30637 0.32223 0.33585 0.34701 0.35550 0.36124
 |       0.36415 0.36398 0.36066 0.35410 0.34410 0.33049 0.31303 0.29144 0.26539
 V       0.23448 0.19826 0.15614 0.10738 0.05103-0.00660-0.01304
B5      6.85000         -1.00000            70.404
B6      0.0       0.01090 0.09054 0.18108 0.27162 0.36217 0.4527
 •       0.72433 0.81487 0.90542 0.99596 1.08650 1.177
 •       1.53921 1.62975 1.72029 1.81083 1
 •       2.35408 2.44462 2.53516
         0.01483 0.023
         0.45

                                       •
                                       •
                                       •

                                                                                        34.
                                                    45958 0.57448 0.68937 0.80427
                                           1.37874 1.49364 1.60853 1.72343 1.83832
                                   2.29790 2.41280 2.52769 2.64259 2.75748 2.87238
                   217 3.21706 3.33196 3.44685 3.55206 3.56175
         0.00951 0.01046 0.02059 0.03096 0.04060 0.04951 0.05782 0.06549 0.07253
         0.07897 0.08485 0.09021 0.09513 0.09964 0.10378 0.10761 0.11120 0.11458
         0.11783 0.12096 0.12441 0.12771 0.13028 0.13098 0.12896 0.12411 0.11651
         0.10607 0.09279 0.07662 0.05749 0.03534 0.01184 0.00968
        -0.00952-0.00936-0.00771-0.00614-0.00476-0.00354-0.00247-0.00146-0.00052
         0.00036 0.00120 0.00205 0.00296 0.00396 0.00511 0.00646 0.00806 0.00995
         0.01219 0.01485 0.01794 0.02201 0.02566 0.02859 0.03009 0.03019 0.02881
         0.02606 0.02189 0.01633 0.00934 0.00095-0.00813-0.00897
B9                12.0    .438    6.85      15.00
B10                                                        26.00
C1a         5    0    0    0    1    0    0     52.80679
C1b      .976 .972 .912          1.138
C2       2.286      6.238      9.1955    13.120     16.106
C5      14250.0   12800.0       4    2    3    4   10
C8      16.2     E616.2     E60.35      6.0      E6.000409
```

7.4.2 Output

```
* * * * ANALYSIS INFORMATION * * * *

ITERATION NUMBER  9
INFOG = 0(INFOG = 0 - NON-GRADIENT CALCULATION , = 1 - GRADIENT CALCULATION)

ANALYSIS NOT PERFORMED FOR A ZERO INDICATOR (GRADIENT CALCULATION ONLY)
(IFRQ-FREQUENCY ANALYSIS , IFLT-FLUTTER ANALYSIS , IFOD-FOD ANALYSIS , ISTR-STRESS ANALYSIS , IRTF-ROOT FOD)
IFRQ = 1  IFLT = 1  IFOD = 1  ISTR = 1  IRTF = 1

* * * * AIRFOIL GEOMETRY * * * *

NCD = 0  (SOLID FOIL)

$ - INDICATES A DESIGN VARIABLE STATION
```

	STA.	RADIUS (IN.)	PCT. SPAN	THICKNESS (IN.)	CHORD (IN.)	THK/CHD
$	2	6.85000	0.0	0.23011	1.70967	0.13459
	3	7.19500	7.14	0.22360	1.73262	0.12905
	4	7.54000	14.29	0.21709	1.75660	0.12359
	5	7.88500	21.43	0.21058	1.78239	0.11814
$	6	8.23000	28.57	0.20407	1.80845	0.11284
	7	8.57500	35.71	0.18266	1.83354	0.09962
	8	8.92000	42.86	0.16125	1.85759	0.08681
$	9	9.26500	50.00	0.13984	1.88315	0.07426
	10	9.60999	57.14	0.12320	1.91112	0.06447
	11	9.95499	64.29	0.10657	1.94215	0.05487
	12	10.29999	71.43	0.08994	1.97715	0.04549
$	13	10.64499	78.57	0.07330	2.01664	0.03635
	14	10.98999	85.71	0.07518	2.06138	0.03647
	15	11.33498	92.86	0.07705	2.11377	0.03645
$	16	11.68000	100.00	0.07892	2.16952	0.03638

```
* * * * RESONANCE MARGIN INFORMATION * * * *

FREQUENCIES AT 14250.0 RPM     511.62   1114.05   1373.67
FREQUENCIES AT 15250.2 RPM     535.86   1145.97   1389.29

RED LINE SPEED-RPM = 14250.0   MIN CRUISE SPEED-RPM = 12800.0
```

FREQUENCY-CPS (RED LINE)	FREQUENCY-CPS (MIN CRUISE)	MARGIN (RED LINE)	MARGIN (MIN CRUISE)	MARGIN (MAX)	EXCITATION ORDER	ROOT NUMBER
0.49934E+03	0.46604E+03	0.51237E-01	-0.92270E-01	0.51237E-01	2	1
0.49934E+03	0.46604E+03	-0.29917E+00	0.27182E+00	0.27182E+00	3	1
0.49934E+03	0.46604E+03	-0.47438E+00	0.45387E+00	0.45387E+00	4	1
0.49934E+03	0.46604E+03	-0.78975E+00	0.78155E+00	0.78155E+00	10	1
0.10829E+04	0.10402E+04	0.12797E+01	-0.14379E+01	0.12797E+01	2	2
0.10829E+04	0.10402E+04	0.51980E+00	-0.62529E+00	0.51980E+00	3	2
0.10829E+04	0.10402E+04	0.13985E+00	-0.21897E+00	0.13985E+00	4	2
0.10829E+04	0.10402E+04	-0.54406E+00	0.51241E+00	0.51241E+00	10	2
0.12528E+04	0.12336E+04	0.16374E+01	-0.18912E+01	0.16374E+01	2	3
0.12528E+04	0.12336E+04	0.75829E+00	-0.92748E+00	0.75829E+00	3	3
0.12528E+04	0.12336E+04	0.31872E+00	-0.44561E+00	0.31872E+00	4	3
0.12528E+04	0.12336E+04	-0.47251E+00	0.42176E+00	0.42176E+00	10	3

FLUTTER CONSTRAINT = 0.99414E+00

* * * * TIP MODE INFORMATION * * * *

FREQUENCY-CPS AT 14250.0 RPM = 2375.10
FREQUENCY-CPS AT 15250.2 RPM = 2383.42

AT RED LINE SPEED-RPM = 14250.0 FREQUENCY-CPS = 2702.86 MARGIN = 0.13805E+00
AT MIN CRUISE SPEED-RPM = 12800.0 FREQUENCY-CPS = 2690.22 MARGIN = -0.26104E+00

TIP MODE FREQUENCY MARGIN = 0.13805E+00 ON 10 E MODE = 5

* * * * STRESS OUTPUT * * * *

ROOT STRESS (PSI) = 0.28467E+05

ROOT TSAI-WU STRESS = 0.62948E-01 FOR ELEMENT NUMBER 9 AND LAYER 1

* * * * OBJECT FUNCTION INFORMATION * * * *

BLADE WEIGHT (LBS) = 0.19073D+00

NUMBER OF BLADES = 0.42685E+02

STAGE WEIGHT (LBS) = 0.81413E+01

OPTIMIZATION RESULTS

OBJ = 0.81715E+01

SECTION 8.0

INSTRUCTIONS FOR PROGRAM MODIFICATIONS

8.1 Program Modifications

When it is required that a particular element of STAEBL be modified or replaced, it is important that data supplied by that element to other elements be provided. In most cases this information is brought through the common blocks. But in some cases, such as with the finite element preprocessor, output is transferred via external read and write units. In addition, these units may differ for any given element depending on iteration number, etc. Subroutine WTW137, for example, has several different write units. Section 8.1.1 provides a listing of the major elements in STAEBL and in what form data are transferred. Those elements with an asterisk have only common blocks associated with data transfer under that heading type. It should be noted that associated with the major elements listed are various supporting routines that must also be considered when program modifications are to be made.

8.1.1 Read/Write Units

Element	Input	Output
Finite Element Preprocessor	*	6,9
Finite Element Analysis	5,9	5,6
Postprocessing		
Laminate Stress	*	5,26
Forced Response	*	26
Tip Mode Detection	*	26
Flutter (W751)	5	6,26
Flutter (NASA)	*	5,26
Local Foreign Object Damage	5	6,26
Root Foreign Object Damage	*	26
COPES/CONMIN	25	26

Below is a listing of the read and write units used in STAEBL:

Unit No.	Unit Function	Additional Comments
5	Temporary read, write data	Used by RDW137, MNW751, MODES
6	Write for long printout	
7	Write for final geometry	Input data block B format
9	F.E. input data read, write	NASTRAN input data format
11,12,24	COPES/CONMIN requirements	
25	Input data, blocks A, B and C	
26	Write for short printout	See Output Description

8.1.2 Common Block Cross Reference

The following common block cross reference can be useful when program modifications are being made:

Table of Element Names Per Common Block

Common:	Element Names												
ANAL01:	RDW137	WTW137											
ANAL02:	RDW137	STAEBL	WTW137										
ANAL03:	ANALIZ	BC	FODSAV	MNU808	RDW137	WTW137	WT751						
ANAL04:	ANALIZ	CALCTH	FLTSAV	MATRL	MNW137	OBJTV	RDDATA	RDW137	STAEBL	TMAX	WTW137		
ANAL05:	ANALIZ	CALCTH	DK369	OBJTV	RDW137	STAEBL	STRCON	WTW137					
ANAL06:	RDW137	WTW137											
ANAL07:	DK369	RDW137	STAEBL	TMAX	WTW137								
ANAL08:	PSHEL	RDW137	STAEBL	TRIA3	WTW137								
ANAL09:	RDW137	WTW137											
ANAL10:	RDW137	WTW137											
ANAL11:	ANALIZ	CALCTH	FODSAV	ITW751	NASFLT	NDW751	RDW137	WTW137	WT751				
ANAL12:	RDW137	WTW137											
ANAL13:	RDW137	WTW137											
ANAL14:	RDW137	WTW137											
ANAL15:	RDW137	WTW137											
ANAL16:	RDW137	WTW137											
ANAL17:	ANALIZ	CALCTH	OBJTV	TMAX	WTW137								
ANAL30:	ANALIZ	CALCTH	ITW751	LAMINA	LYERAT	MNU808	NASFLT	OBJTV	PSHEL	RDDATA	STAEBL	STRCON	TRIA3
ANAL31:	ITW751	NASFLT	RDDATA	WT751									
ANAL32:	ANALIZ	FRQTIP	GOODMN	MNU808	RDDATA	RESMRG							
ANAL33:	ANALIZ	FODSAV	MNU808	RDDATA									
ANAL34:	ANALIZ	MODES											
ANAL40:	DK369	FLTSAV											
ANAL41:	FLTSAV	NASFLT	WT751										
ANAL54:	ANALIZ	ITW751	RDDATA										
ASET :	INPUT	MNU808											
BLK1 :	AKAPM	AKAPPA	AKP2	ALAMDA	ASYCON	DLKAPM	DRKAPM	SSCASC					
BLK1A :	AKAPM	ASYCON	DLKAPM	DRKAPM	SSCASC								
BLK2 :	AKAPM	ASYCON	DRKAPM	SSCASC									
BTF :	IMPCT	LOAD	MNFOD										
CNMN1 :	CNMN01	CNMN02	CNMN03	CNMN05	CNMN06	CNSTAV	CONMIN	COPE01	COPE02	COPE04	COPE09	MAIN	SIMCON
CNSTNT:	ANALIZ	CNSTAV	MNU808										
CNTIFO:	CNMN01	CNSTAV	CONMIN	COPE01									
CNVRG :	AKAPM	ASYCON	DLKAPM	DRKAPM	SSCASC								
COMPST:	HOLLOW	HOLLW2	LAMINA	LAMIN8	LYERAT	OBJTV	RDDATA	RTFOD	STRCON	STRES2			
CONDAD:	ETR3D	MNU808	PSTRSS	REORDR	STR31D	STR32D							
CONSAV:	CONMIN												
COPES1:	COPE01	COPE04	COPE06	MAIN									
COPES2:	COPE09	MAIN											
COPES3:	COPE01	COPE02	COPE03	COPE04	COPE06	COPE09	MAIN						
CORD :	CTMASS	GETVEC	GP6X6	GP6X6B	INPUT	MNU808	RLOAD	TRANSD					
CTRIA3:	BANDER	EMA	EMGG	IMPCT	INPUT	LOAD	MNFOD	MNU808	MODES	PROJ	STRESS		
DLTAR0:	ITW751	NASFLT	WORK										
ELCONT:	EMGG	EMGPOM	MNU808	STRESS									
EMAC :	EMA	GP6X6	GP6X6B	IMPCT	LOAD	MNFOD	MNU808	MODES	RLOAD				
EMACC :	GOODMN	IMPCT	LOAD	MNFOD	MNU808	PSTRSS	STRPRT						
EMG :	DK369	EMA	EMGPOM	ETRFOD	FGAB	GOODMN	GP6X6	GP6X6B	IMPCT	MNFOD	MNU808	MODES	PROJ
	STAEBL	STRESS	STRES2										
EMGDS1:	EMA	EMGG	ETR3D	MNU808	STRESS								
EMGEST:	EMGG	ETR3D	MNU808	PSTRSS	STRESS	STR31D	STR32D						
EMGPRM:	EMGG	ETR3D	MNU808	STRESS									
EMGXXX:	GETVEC	MNU808	STRESS										
FAIL :	TSAIWU	TSWUFL											
FODMEM:	ETRFOD	ETR3D											
GENMAS:	GOODMN	MNU808											
GLOBCM:	ANALIZ	CALCTH	COPE09	HOLLOW	HOLLW2	LAMINA	LYERAT	MAIN	OBJTV	RDDATA	STRCON	TRIA3	
GRD :	IMPCT	MNFOD	MODES										
GRID :	CTMASS	EMA	EMGG	FGAB	FODSAV	INPUT	LOAD	MNFOD	MNU808	MODES	RLOAD	STRCON	STRESS

Table of Element Names Per Common Block (continued)

Common:	Element Names												
IO :	BMEVAL	BMFIT	LINEAR	MAIN1	MAIN2	MAIN3	PLOTIT	WORK					
IOUNIT:	BANDER	BMADD	BRMPLY	CTMASS	DIAG	ECHO	EMA	EMGG	EMGPOM	ETR3D	FODSAV	GMMATD	GOSET
	IDENT	INPUT	MATCMP	MATPRT	MERGE	MNU808	MODPRT	PRTRED	REBAND	REORDR	RESTOR	RLOAD	SDR2WT
	SPC	SPCARR	STRESS	STRPRT	STR31D	STR32D	TRANSD						
IPARAM:	NSFLCL	SSCASC											
JMPCHK:	ITW751	NDW751											
KPR :	MATRL	MNU808	PSHEL										
MATIN :	ETR3D	MAT	MNU808	STRES2	STR31D								
MATOUT:	ETR3D	MAT	MNU808	STRES2	STR31D								
MAT1 :	FGAB	MNFOD	MODES	MODINT									
MAT12 :	INPUT	MAT	MNU808	STRES2									
MAXSIZ:	INPUT	MNU808											
MCPLX :	MAIN2	MAIN3											
MPLX :	MAIN1	MAIN2											
M12 :	MAIN1	MAIN2											
M123 :	MAIN1	MAIN2	MAIN3										
M13 :	MAIN1	MAIN3											
M23 :	MAIN2	MAIN3											
NFLT :	NASFLT	NSFLCL											
OPTMZ :	ANALIZ	MNU808											
PLOTSS:	MAIN3	PLOTIT	STABIL	WORK									
PLTBUF:	MAIN1	MAIN2	MAIN3	PLOTIT	WORK								
PRINT :	MAIN1	MAIN2	MAIN3	PLOTIT	WORK								
PSHELL:	EMGG	FGAB	INPUT	LOAD	MNFOD	MNU808	MODES	MODINT	STRESS	STRES2			
RFRC :	CTMASS	INPUT	MNU808	RLOAD									
ROTFOD:	MNU808	RTFOD											
SIZE :	ANALIZ	BANDER	CTMASS	EMA	EMGG	GETVEC	GP6X6	GP6X6B	INPUT	MAT	MNU808	RLOAD	SPCARR
	STRESS	STRES2	STRPRT	TRANSD									
SPDFRQ:	FRQTIP	GOODMN	MNU808	RESMRG									
STCSTR:	GOODMN	PSTRSS	RTFOD	STRES2	STRPRT								
STRMAX:	ANALIZ	STRPRT											
STRS :	SDR2WT	STRESS	STR31D	STR32D									
TITEL :	INPUT												
TSISIG:	LAMINA	RTFOD	STRCON	STRES2									
UIOS :	ANALIZ	BIRDF	CALCTH	CNMN03	CNMN05	CNMN06	CNSTAV	CONMIN	COPE01	COPE03	COPE05	COPE07	COPE09
	COPE14	COPE18	FRCFNC	FRQTIP	GOODMN	ITW751	MAIN	MESAGE	OBJTV	RDDATA	RDW137	RESMRG	RTFOD
	STRCON	TIPMOD	TMAX	TSWUFL	WTW137	WT751							
VALUES:	MAIN1	MAIN2	MAIN3	VALUES									
WIEGHT:	LAMINA	OBJTV	TRIA3										

SECTION 9.0

SUBROUTINE DICTIONARY

A programming description of the features in STAEBL follows. Elements are arranged by the parent module (generally like the flowchart described in Section 3.0).

9.1 COPES/ANALIZ; Miscellaneous Constraint Analysis

Routine	External Reference		Calling Element	Function
*ANALIZ	CALCTH CNSTAV FRQTIP GOODMN ITW751 LYERAT MESAGE MNFOD MNU808 MNW137 MYTIME	OBJTV RDDATA RDW137 RESMRG RTFOD STRCON TMAX WTW137	COPE03 COPE04 COPE06 COPE09 MAIN	Constraint calculation for COPES/CONMIN
BIRDF			RTFOD	Calculates local foreign object damage input
BMEVAL			MAIN2	Point evaluation from curve fit
BMFIT			FLTSAV MAIN2 NASFLT	Interpolation routine
CALCTH			ANALIZ	Input blade thickness calculation
CNSTAV			ANALIZ	Determines which constraints are active or violated
FLTSAV	BMEVAL BMFIT		MNU808	Writes flutter modeshape input data
FODSAV			MNU808	Writes foreign object damage input data
FRCFNC			GOODMN	Calculates forcing function for forced response

*Controlling routine for the module

COPES/ANALIZ; Miscellaneous Constraint Analysis (continued)

Routine	External Reference	Calling Element	Function
FRQTIP		ANALIZ	Determines tip mode frequency margin
GOODMN	FRCFNC	ANALIZ	Calculates blade forced response
ITW751	NASFLT NDW751 WT751	ANALIZ	Determines nodal diameters used for flutter calculation, writes input and calls appropriate flutter subroutine
LYERAT		ANALIZ	Sets layer angles and thicknesses into common block from COPES
MESAGE		ANALIZ	Prints global variable numbers, names
MULTZM		MNU808	Multiplies mass and modeshape elements
NASFLT	BMEVAL DIMAG BMFIT NSFLCL	ITW751	Generates NASA flutter input
NDW751		ITW751	Selects nodal diameter for flutter calculation
NSFLCL	DCONJG SSCASC	NASFLT	Routine calling NASA flutter code
OBJTV		ANALIZ	Calculates objective function
RDDATA	TSWUFL	ANALIZ	Reads input Data Block C
RDW137		ANALIZ	Reads input Data Block B
RESMRG		ANALIZ	Determines frequency margins
RFDSAV		MNU808	Saves specific finite element output data
RTFOD	BIRDF STRES2	ANALIZ	Root foreign object damage calculation
STRCON		ANALIZ	Finds maximum root and hole stress

COPES/ANALIZ; Miscellaneous Constraint Analysis (continued)

Routine	External Reference	Calling Element	Function
TMAX		ANALIZ	Determines airfoil section maximum thickness
TSWUFL		RDDATA	Sets TSAI-WU failure limits
WTW137		ANALIZ	Blade analysis output
WT751		ITW751	Flutter output routine

9.2 Airfoil Finite Element Preprocessor

Routine	External Reference	Calling Element	Function
BC		STAEBL	Generates RFORCE, SPC'S, ASET input for finite element analysis
BMFIT2		FLTSAV MAIN2	Curve fitting routine
CORD2R		STAEBL	Calculates CORD2R input for finite element analysis
CUBIC		STAEBL	Solves a cubic equation
DK369		MNW137	Airfoil section property calculator
HOLLOW		TRIA3	Calculates layer thickness for airfoil elements and checks for hollowness (cavities)
HOLLW2		TRIA3	Same as HOLLOW, but used when added mass option exercised
LAMINA	LAMIN8	TRIA3	Generates layer thicknesses, effective density
LAMIN8		LAMINA	Generates material property cards for finite element analysis

Airfoil Finite Element Preprocessor (continued)

Routine	External Reference	Calling Element	Function
*MNW137	DK369 STAEBL	ANALIZ	Controls finite element model generator
PBMFIT	BMFIT2	STAEBL	Geometric curve fitter
PSHEL		STAEBL	Generates property cards (PSHELL) for finite element analysis
STAEBL	BC PSHEL CORD2R TRIA3 CUBIC PBMFIT	MNW137	Generates grid locations, meanline thicknesses, and geometry for the finite element model
TRIA3	HOLLOW LAMINA XPROD	STAEBL	Element connectivity generator
XPROD		TRIA3	Calculates element area

9.3 Finite Element Analysis

Routine	External Reference	Calling Element	Function
APPEND		INPUT	Adds SPC's and/or ASETS to grid points
BANDER	MYTIME	MNU808	Finds bandwidth of matrix
BMADD	MYTIME	MNU808	Adds two banded matrices
BRMPLY	MYTIME	MNU808	Multiplies rect. and banded matrix
CTMASS		MNU808	Calculates centrifugal mass stiffening
DIAG	MYTIME	MNU808	Prints matrix diagonal
ECHO	MYTIME	MNU808	Prints input image
EMA	GP6X6 GP6X6B MYTIME	MNU808	Stiffness and mass matrix assembly

*Controlling routine for the module

Finite Element Analysis (continued)

Routine	External Reference	Calling Element	Function
EMGG	ETRFOD ETR3D MYTIME	MNU808	Driver to build element stiffness
EMGPOM		ETR3D	Outputs stiffness matrix for element
ETRFOD		EMGG	Calculates stiffness terms for certain foreign object damage model elements
ETR3D	EMGPOM GETVEC GMMATD MAT	EMGG	Generates element stiffnesses
FTRNSF	MATTMP	RLOAD	Performs load transformation, global to local
GETVEC	MATMPY	ETR3D	Transforms from local to basic coordinate system
GMMATD		ETR3D STR31D STR32D	General matrix multiplier
GOSET	MYTIME	MNU808	Matrix operator
GP6X6	TRNSFM	EMA	Inserts element stiffness into global stiffness
GP6X6B	TRNSFM	EMA	Inserts element stiffness into global stiffness
IDENT	MYTIME	MNU808 TRANSD	Generates identity matrix
INPUT	APPEND INTRPD INTRPI LAJA MYTIME ZEROI	MNU808	Reads finite element input

Finite Element Analysis (continued)

Routine	External Reference		Calling Element	Function
INTRPD			INPUT	Keyword reader for finite element input
INTRPI			INPUT	Keyword reader for finite element input
LEQUSL			STRES2	Linear equation solution
MADD			MNU808	Calculates matrix addition
MAT			ETR3D STRES2 STR31D	Generation of material property matrix
MATCMP	MYTIME		MNU808	Multiplies matrix by a constant
MATMPY			GETVEC MNU808 STRES2	Matrix multiplier
MATMP1			TRNSFM	Matrix multiplier
MATMP2			TRNSFM	Matrix multiplier
MATPRT	MYTIME		MNU808 SDR2WT	Prints a matrix
MATSTP			STRESS	Mode shape selection
MATTMP			FTRNSF MNU808	Multiplies matrix with transpose
MERGE	MYTIME		MNU808	Used to assemble deflection vector
*MNU808	BANDER BMADD BRMPLY CTMASS DIAG EBALAF EBBCKF ECHO EMBCKF EMESSF	MATMPY MATPRT MTTMP MERGE MODPRT MSUB MULTZM MYTIME PRTRED REBAND	ANALIZ	Finite element driver

*Controlling routine for the module

Routine	External Reference		Calling Element	Function
*MNU808 (cont)	EMA EMGG EQRH3F FLTSAV FODSAV GOSET IDENT INPUT LEQT1P LEQ1PB LUELPB MADD MATCMP	REORDR RESTOR RFDSAV RLOAD SAVE SCALE SPC SPCARR STRESS STRES2 STRPRT TIRMOD ZEROFE	ANALIZ	Finite element driver
MODPRT	MYTIME		MNU808	Print static disp. or mode shape
MSUB			MNU808	Calculates matrix difference
PRTRED	MYTIME		MNU808	Matrix partition reduction
PSTRESS			STR32D	Calculates principle stress
REBAND	MYTIME		MNU808	Reband matrix
REORDR	MYTIME		MNU808	Reorders eigenvalues from minimum to maximum
RESTOR	MYTIME		MNU808	Stores matrix in vector form
RLOAD	FTRNSF MYTIME		MNU808	Builds load vector
SAVE			MNU808	Stores matrix A into B
SCALE			MNU808	Scales modeshape
SPC	MYTIME		MNU808	Interprets SPC cards
SPCARR	MYTIME		MNU808	Arranges SPC cards in proper sequence
STRESS	MATSTP MYTIME STR31D STR32D		MNU808	Stress output driver

*Controlling routine for the module

Finite Element Analysis (continued)

Routine	External Reference	Calling Element	Function
STRES2	LEQUSL MAT MATMPY TSAIWU	MNU808	Laminate stress generator
STRPRT		MNU808	Print static or modal stress save maximum static stress
STR31D	AMMATD MAT TRANSD	STRESS	Stress recovery for finite elements
STR32D	AMMATD PSTRSS	STRESS	Stress recovery for finite elements
TIPMOD		MNU808	Tipmode selection
TSAIWU		STRES2	TSAI-WU failure criteria evaluation
TRANSD		STR31D	Displacement transforms to global
TRNSFM		CTMASS GP6X6 GP6X6B	Performs vector transformation
ZEROFE		INPUT	Array zeroing

9.4 Local Foreign Object Damage Analysis

Routine	External Reference	Calling Element	Function
FGAB		MODES	Calculates coefficients for modal integration
IMPCT		MODES	Calculates bird impact mass, squash up time and average total force
LOAD		MODES	Zeroes blade momentum, calculates nodal forces

Local Foreign Object Damage Analysis (continued)

Routine	External Reference		Calling Element	Function
MODES	FGAB IMPCT LOAD	MODINT MTMPYA MTTMPA	MNFOD	Reads foreign object damage (FOD) input, calls FOD subroutines, writes output
*MNFOD	MODES PROJ ZERO		ANALIZ	Zeros foreign object damage (FOD) values, calls load subroutine and begins FOD calculation
MODINT			MODES	Writes modal integration input, performs integration calculation

*Controlling routine for the module

SECTION 10.0

INPUT AND OUTPUT VARIABLE LISTING

10.1 Input Variables

A listing of input variables used in STAEBL is given below. A description of each variable, its input card and any suggested values, where appropriate, are included. Refer to Appendix A and/or the COPES/CONMIN manual (NASA Report No. NPS69-31-003) for variables used in DATA BLOCK A.

Input Variable	Description	Card
ADLE	Distance from added mass patch to leading edge, inches.	C10
ADTE	Distance from added mass patch to trailing edge, inches.	C10
ADROOT	Distance from added mass patch to blade root, inches.	C10
ADTIP	Distance from added mass patch to blade tip, inches.	C10
ALPHA	Angle between plane of rotation of rotor stage and chord normal (y=0), degrees.	B5
AMPA	Added mass patch option. If >0, AMPA is mass per $inch^2$, $lbsec^2/in^4$.	C9a
ARAD	Aerodynamic radius, inches.	C4
BAA	Fiber angle of outer composite layer, degrees.	C9a
BETA	Modal integration damping factor.	C6
BLADES	Number of blades in initial stage. The number of blades will be varied inversely with chord during optimization in order to preserve solidity.	B10
BRANG	Broach angle, the angle between the center line of the broach slot and an axial plane, degrees.	B9
BRSV	Root chord length for which optimization will begin, inches. All coordinate input will be scaled by BRSV/coordinate input root chord.	C1a
BTA	Inlay fiber angle, degrees.	C9

Input Variables (continued)

Input Variable	Description	Card
CFT	Correction factor for tipmode.	C1b
CF1	Correction factor for first mode.	C1b
CF2	Correction factor for second mode.	C1b
CF3	Correction factor for third mode.	C1b
CF4	Correction factor for fourth mode.	C1b
CF5	Correction factor for fifth mode.	C1b
DLE	Hollow description, distance to leading edge, inches.	C9
DROOT	Hollow description, distance to airfoil root, inches.	C9
DRPM	Delta RPM. This RPM increment is added to the input RPM and another frequency is calculated at the higher speed for the purpose of computing the sensitivity of the natural frequencies to speed. 1000.0 is suggested.	B3
DTE	Hollow description, distance to trailing edge, inches.	C9
DTIP	Hollow description, distance to tip, inches.	C9
E11	Youngs modulus in primary (1-1) direction, psi.	C8
E22	Youngs modulus in secondary (2-2) direction, psi.	C8
GEA	Fiber angle of inner composite layer, degrees.	C9a
G12	Shear modulus, psi.	C8
IORD	Excitation order number.	C5
IST	Station number associated with input thickness.	C2
ITTLE	Descriptive title for airfoil.	B2
NAC	Number of aerodynamic stations.	C3

Input Variables (continued)

Input Variable	Description	Card
NCD	Defines airfoil type: 0 = solid 1 = hollow 2 = superhybrid	Cla
NLAYER	Number of layers for blade. For a solid blade, use 1 or -1. For a hollow blade, use 5 or -5. For a superhybrid blade, use 7 or -7. Note: If positive, program uses preset limits. See Card C11 for the preset TSAI-WU limits. If negative, TSAI-WU limits will be input on Card C11.	Cla
NO	Number of coordinate stations along the chord used to describe the airfoil profile (maximum of 53). Thirty to fifty points are recommended.	B5
NORD	Number of excitation orders input, maximum of 5.	C5
NREF	Leading edge impact node for local foreign object damage. Normally use 16 (see Figure 11).	C7
NRESFF	Resonance margin criteria, determined by: 0 = resonance margins calculated 1 = forcing function calculated. STAEBL-provided forcing functions are applicable to the Energy Efficient Engine fan blade only. User-supplied forcing functions may be incorporated by updating Subroutine FRCFNC. 2 = both of the above. Note: Refer to Card Cla input instructions, Section 4.3, for additional information regarding this parameter.	Cla
NRF	Number of roots calculated by flutter analysis, maximum of 5.	Cla
NRFOD	Number of roots for both local and root foreign object damage (FOD) analysis. Suggested value is 5. If = 0, FOD analysis is not made.	Cla
NRTFOD	Root foreign object damage option: 0 = not calculated 1 = calculated.	Cla

Input Variable	Description	Card
NSTA	Number of spanwise coordinate input stations for blade geometry input description (21 maximum). Suggested value is 11.	B4
NSTEP	For foreign object damage, number of timesteps required. Suggested value is 40.	C7
NTEST	Indicator to start airfoil coordinate read.	B1
NTIPMD	Tipmode search: 0 = no search $\geq$1 = number of modes tested for tip (5 maximum). Note: if NTIPMD $>$ 0 and no tipmodes are found, tipmode defaults to fifth mode.	C1a
NTIS	Number of thickness input stations, maximum of 21, minimum of 2 (5 recommended).	C1a
PCBA	Percent thickness of outer composite material.	C9a
R	Distance from the engine center line to the blade station, inches. The first input station should be the blade attachment, the last the tip station.	B5
R	Foreign object damage bird radius, inches.	C6
RH	Layer mass density, lb sec^2/in^4.	C8
RHO	Foreign object damage bird density, lb sec^2/in^4.	C6
ROOT	Number of frequencies to be calculated, maximum of 5.	B3
RPM	Analysis speed, RPM. This is the speed desired for flutter stability evaluation.	B3
RROOT	Radius of first airfoil station, inches. This radius is the radius at the half-chord point of the airfoil root. RROOT does not have to correspond to an airfoil 1X2Y coordinate input station radius, but must lie between R(1) and R(NSTA).	B9
SPDMC	Minimum cruise speed, RPM.	C5
SPDRL	Redline speed, RPM.	C5

Input Variables (continued)

Input Variable	Description	Card
STPRS	Inlet static pressure, lbf/ft^2.	C4
S6M	Shear term, y-x direction, psi.	C11
S6P	Shear term, x-y direction, psi.	C11
TEMPST	Inlet static temperature, °F.	C3
THER	Blade root angle, degrees. This is the angle between the blade platform and the engine center line. Positive counterclockwise.	B9
THETA	Foreign object damage impact angle relative to ALPHA on Card B5, radians (see Figure 11). THETA can be calculated as: THETA = ALPHA (at impact radius) - ϕ, where $\phi = TAN^{-1}((60 \cdot V_p)/(2\pi \cdot \text{blade impact radius} \cdot RPM))$	C6
TIC	Superhybrid blade center layer thickness, inches.	C9a
TIS	Superhybrid blade skin thickness, inches.	C9a
TLT	Thickness of hollow blade inlay, inches.	C9
TROOT	Thickness of blade neck, inches.	B9
TSTEP	Timestep for foreign object damage, seconds. 1×10^{-5} recommended.	C6
TTI	Thickness of hollow blade skin, inches.	C9
VALT	Thickness at airfoil station, inches.	C2
VOM	Relative inlet Mach Number.	C4
VP	Foreign object damage bird velocity, inches/sec.	C6
V12	Layer poisson ratio.	C8
X	The x coordinates of the blade cross section given in ascending order for NO points, inches.	B6

Input Variables (continued)

Input Variable	Description	Card
X1C	Ultimate compressive strength in fiber direction, psi.	C11
X1T	Ultimate tensile strength in fiber direction, psi.	C11
X2C	Ultimate compressive strength perpendicular to fiber direction, psi.	C11
X2T	Ultimate tensile strength perpendicular to fiber direction, psi.	C11
YL	The lower y coordinates of a blade cross section corresponding to the x coordinates, inches.	B8
YU	The upper y coordinates of the blade cross section corresponding to the x coordinates, inches.	B7

10.2 Output Variables

Output Variable	Is Written From Subroutine	With the Output Message or Header
ADLE	CALCTH	ADLE
ADROOT	CALCTH	ADROOT
ADTE	CALCTH	ADTE
ADTIP	CALCTH	ADTIP
AMPA	CALCTH	MASS PER UNIT AREA
BAA	CALCTH	B/A ANG
BCC	CALCTH	CHORD (IN.)
BLDGPC	ANALIZ	NUMBER OF BLADES
BTA	CALCTH	B/T ANG
DELSAV	ITW751	AERO DAMPING COEF.
DLE	CALCTH	DLE
DROOT	CALCTH	DROOT
DTE	CALCTH	DTE
DTIP	CALCTH	DTIP
FLTSLD	ANALIZ	FLUTTER CONSTRAINT
FMC	FRQTIP,RESMRG	FREQUENCY-CPS
FN1	FRQTIP,RESMRG	
FN2	FRQTIP,RESMRG	
FRL	FRQTIP,RESMRG	FREQUENCY-CPS
GDMAX	GOODMN	MARGIN
GEA	CALCTH	G/E ANG
I	GOODMN	MODE
I	CALCTH	STA.
IFLT	CNSTAV	IFLT

Output Variables (continued)

Output Variable	Is Written From Subroutine	With the Output Message or Header
IFOD	CNSTAV	IFOD
IFREQ	CNSTAV	IFREQ
INFOG	CNSTAV	INFOG
IORD	GOODMN,RESMRG	ORDER
IRTF	CNSTAV	IRTF
ISTR	CNSTAV	ISTR
ITER	CNSTAV	ITERATION NUMBER
J	RESMRG	ROOT NUMBER
NELM	ANALIZ	FOR ELEMENT NUMBER
NELRT	STRCON	FOR ELEMENT NUMBER
NLAY	ANALIZ	AND LAYER
NLYRT	STRCON	AND LAYER
NM	FRQTIP	MODE
NRD	FRQTIP	ON __ E
NSAV	ITW751	CRIT. NODAL DIA
OBJFUN	OBJTV	OBJECT FUNCTION
PC	CALCTH	PCT. SPAN
PCBA	CALCTH	PCBA
PMGDMC	GOODMN	PC MARGIN
PMGDRL	GOODMN	PC MARGIN
R	CALCTH	RADIUS (IN.)
RF	RESMRG	MARGIN (MAX)
RMC	RESMRG	MARGIN (MIN CRUISE)
RRL	RESMRG	MARGIN (REDLINE)

Output Variables (continued)

Output Variable	Is Written From Subroutine	With the Output Message or Header
TPMRG	FRQTIP	TIPMODE FREQUENCY MARGIN
SPD1	FRQTIP,RESMRG	FREQUENCY AT __ RPM
SPD2	FRQTIP,RESMRG	FREQUENCY AT __ RPM
SPMC	GOODMN	SPEED
SPDMC	FRQTIP,RESMRG	MIN CRUISE SPEED-RPM
SPDRL	FRQTIP,RESMRG	REDLINE SPEED-RPM
SPRL	GOODMN	SPEED
SROOT	ANALIZ	ROOT STRESS
STGWT	ANALIZ	STAGE WEIGHT
STRN	ANALIZ	STRAIN
TCC	CALCTH	THICKNESS (IN.)
TIC	CALCTH	TIC
TIS	CALCTH	TIS
TLT	CALCTH	TLT
TMXA	ANALIZ	AT TIME
TOB	CALCTH	THK/CHD
TPMC	FRQTIP	MARGIN
TPRL	FRQTIP	MARGIN
TSRT	STRCON	TSAI-WU STRESS
TSWU	ANALIZ	ROOT FOD
TTI	CALCTH	TTI
WGHT	ANALIZ	BLADE WEIGHT

SECTION 11.0

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SECTION 12.0

APPENDIX A: OPTIMIZATION USING COPES/CONMIN

12.1 Optimization Method

A common engineering design problem is the determination of values for design variables which minimize a design quantity such as weight, drag, or cost, while satisfying a set of auxiliary conditions. In the STAEBL program, the structural design of solid, composite or hollow blades is accomplished by varying airfoil section thicknesses, chord, titanium skin thickness, etc. to minimize a combination of weight and cost subject to constraints on resonance, flutter, stress, and foreign object damage.

12.1.1 General Optimization Theory and Background

The engineering design process can be modeled as a mathematical programming problem in optimization theory. In theoretical terms, this constrained minimization problem can be expressed as follows:

$$\text{minimize } f(\underline{x}), \tag{1}$$

subject to the auxiliary conditions,

$$g_i(\underline{x}) \leqslant 0, \quad i=1, \ldots, m. \tag{2}$$

The quantity $\underline{x} = (x_1, \ldots, x_n)$ is the vector of n design variables. The scalar function to be minimized, $f(\underline{x})$, is the objective function; and $g_i(\underline{x}) \leqslant 0$, i=1, ..., m, are the m inequality constraints. Upper and lower bounds on the design variables, e.g.,

$$L_i \leqslant x_i \leqslant U_i, \quad i=1, \ldots, n, \tag{3}$$

are referred to as side constraints. The n-dimensional space spanned by the design variables is design space. If $f(\underline{x})$ and $g_i(\underline{x})$, i=1, ..., m, are all linear functions of $\underline{x}$, then the optimization problem is a linear programming problem which can be solved by well-known techniques such as Dantzig's simplex method. If $f(\underline{x})$ or any of the $g_i(\underline{x})$'s are nonlinear, then it is a nonlinear programming problem for which a number of solution techniques are also available. If the objective function, $f(\underline{x})$, is to be maximized, then the equivalent problem of minimizing $-f(\underline{x})$ is considered.

Any choice of variables, $\underline{x}$, in design space that satisfies all the constraints, equations (2) and (3), is a feasible point. As shown in Figure 16, the union of all feasible points comprises the feasible region. The locus of points which satisfy $g_i(\underline{x}) = 0$, for some i, forms a constraint surface. On one side of the surface, $g_i(\underline{x}) < 0$ and the constraint is satisfied; on the other side, $g_i(\underline{x}) > 0$ and the constraint is violated. Points in the interior of the feasible region are free points; points on the boundary are bound points. If it is composed of two or more distinct sets, the feasible region is disjoint. A design point in the feasible region that minimizes the objective function is an optimal feasible point and is a solution of the problem posed in equations (1) through (3). As in any nonlinear minimization problem, there can be multiple local minima. In this case, the global minimum is the optimal feasible point. If a design point is on a constraint surface (i.e., $g_i(\underline{x}) = 0$ for some i), then that particular constraint is active. A solution to a structural optimization problem is almost always on the boundary of the feasible region, and is usually at the intersection of two or more constraint surfaces (i.e., there are two or more active constraints).

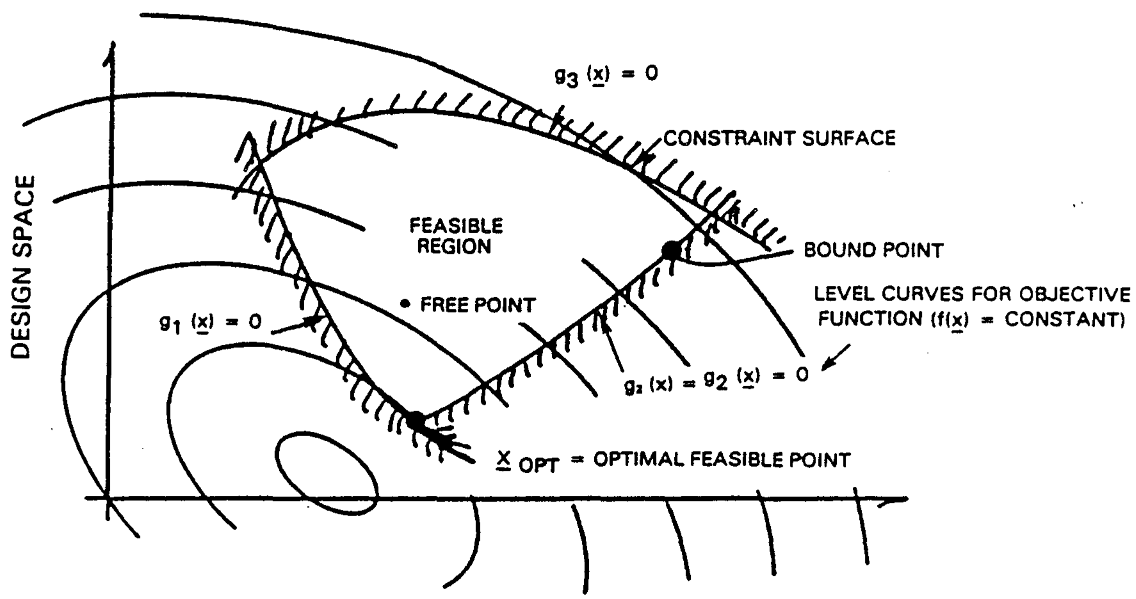

Figure 16 Feasible Region is Union of All Points that Satisfy All Constraints

There are two basic approaches to solving the constrained optimization problem posed in equations (1) through (3): direct methods (e.g., the method of feasible directions as used in STAEBL), and indirect methods (e.g., penalty function methods).

In a direct method, the objective function and constraints are evaluated independently, and the constraints are treated as limiting surfaces. Zoutendijk's method of feasible directions is an example of a direct method and will be discussed further in Sections 12.1.2 and 12.1.3.

Several programs are generally available in software libraries (e.g., International Mathematical and Statistical Libraries, Inc., and HARWELL) that can solve the constrained minimization problem using either direct or indirect techniques. Due to its versatility in solving structural optimization problems at Pratt & Whitney, NASA/Langley, General Motors, and Ford Motor Co., the

COPES/CONMIN (Control Program for Engineering Synthesis/Constrained Minimization) computer program was selected for the STAEBL contract. This program was developed by G. N. Vanderplaats of the Naval Postgraduate School and has the added capability of solving both constrained minimization problems, equations (1) through (3), and unconstrained minimization problems, equation (1). COPES is a user-oriented FORTRAN program that prepares an input data set for the optimization program CONMIN. Two solution techniques are available for the constrained minimization problem.

1. Exact Analysis - utilizes the method of feasible directions applied to the actual objective function and constraints. This approach is discussed in Section 12.1.2.

2. Approximate Analysis - utilizes the method of feasible directions applied to Taylor series approximations and to the objective function and constraints.

12.1.2 COPES/CONMIN Exact Analysis: Method of Feasible Directions

In this method, a sequence of designs ($\underline{x}_0$, $\underline{x}_1$, ...) is produced which converges to a local optimum design, $\underline{x}_{opt}$, provided a feasible region exists. The successive designs are generated iteratively as a sequence of one-dimensional line searches, i.e.,

$$\underline{x}_{i+1} = \underline{x}_i + \alpha \underline{s}_i, \tag{4}$$

for i = 0, 1, 2, ..., where $\underline{s}_i$, the search direction, and α are chosen so that once the feasible region has been entered, all subsequent iterates remain feasible and the magnitude of the objective function is reduced at each step. If the initial design, $\underline{x}_0$, is infeasible, then gradients of the violated constraints are calculated so that search directions can be established which lead to the feasible region, provided one exists.

Once the feasible region has been entered, a particular direction is pursued until either: a) a local minimum of the objective function, $f(\underline{x})$, has been determined, or b) a constraint boundary has been reached. The value of α in equation (4) at the termination point of this one-dimensional line search in the $\underline{s}_i$ direction is determined by interpolating polynomial fits of several trial values of the objective function and constraints. A schematic of a typical case is shown in Figure 17. The initial design, $\underline{x}_0$, is infeasible. The design point, $\underline{x}_i$, is a relative minimum of the objective function. The remaining search directions terminate at constant boundaries until $\underline{x}_{opt}$ is reached.

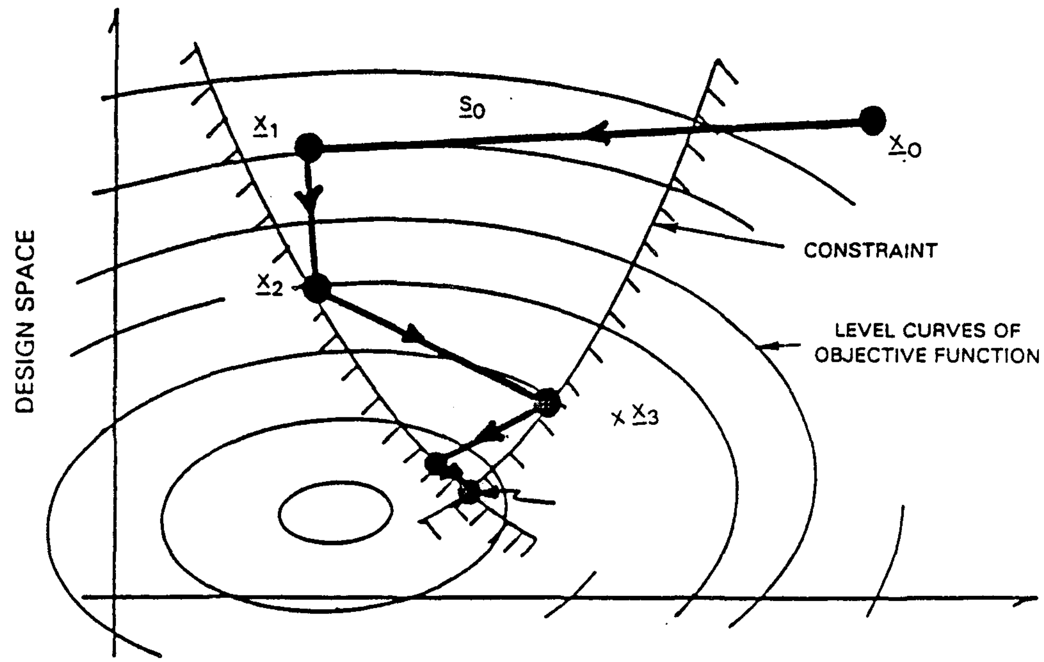

Figure 17 Line Search Terminates Either at Minimum of Objective Function or at a Constant Boundary. Sequence of line searches converge to $\underline{x}_{opt}$.

If a local minimum of the objective function has been reached, then the gradient of the objective function is calculated, and the procedure continues in the direction opposite to this (i.e., the "path of steepest descent"). If a constraint boundary has been reached first, however, then a new search direction can be determined using Zoutendijk's method of feasible directions as follows. A direction, $\underline{s}_i$, is usable if the objective function initially does not increase along this path, i.e.,

$$\underline{s}_i \cdot \bar{\nabla} f(\underline{x}_i) < 0. \tag{5}$$

In addition, $\underline{s}_i$ is feasible if no active constraints are initially violated along this path, i.e.,

$$\underline{s}_i \cdot \bar{\nabla} g_j(\underline{x}_i) \leqslant 0, \; j=1, \ldots, \text{NAC}, \tag{6}$$

where a subscript, j, is chosen for each of the constraints that are active at $\underline{x}_i$. As shown schematically in Figure 18, allowable paths that emanate from $\underline{x}_i$ comprise the usable feasible sector.

12.1.2.1 Choice of Search Parameters for COPES/CONMIN

In Zoutendijk's method, the search direction, $\underline{s}_i$, is determined by solving a sub-optimization problem, i.e.,

$$\text{maximize } \beta,$$

subject to:

$$\underline{s}_i \cdot \bar{\nabla} f(\underline{x}_i) + \beta \leqslant 0,$$

$$\underline{s}_i \cdot \bar{\nabla} g_j(\underline{x}_i) + \theta_j \beta \leqslant 0, \; j=1, \ldots, \text{NAC} \tag{7}$$

$$| \underline{s}_i | \text{ bounded.}$$

The parameter θ_j, the push-off factor, determines the orientation of the new search direction vector, $\underline{s}_i$, in the usable feasible sector by pushing the search away from the constraints into the feasible region. As shown in Figure 18, s_i approaches the constraint surface, $g_j(\underline{x})$, tangentially as $\theta_j \rightarrow 0$, and $\underline{s}_i$ approaches a level curve to the objective function tangentially as $\theta_j \rightarrow \infty$. For a linear constraint, θ_j can be set to zero and the search can proceed along that particular constraint surface. If θ_j is too small, then for nonlinear constraints with convex curvature, the same constraint will be immediately re-encountered. In this case, the search will "skid" along the same constraint boundary with little change in the objective function. If θ_j is too large, then the search will "zigzag" back and forth between two or more constraints, and the objective function will again not be reduced rapidly enough. A compromise value of $\theta_j = 1$ is the default value used by COPES/CONMIN for the initial iteration. Since many of the constraints (e.g., flutter, resonance, etc.) in the STAEBL optimization problems were nearly linear (at least locally), the value $\theta_j = 0.3$ was used for the initial iteration to give more rapid convergence.

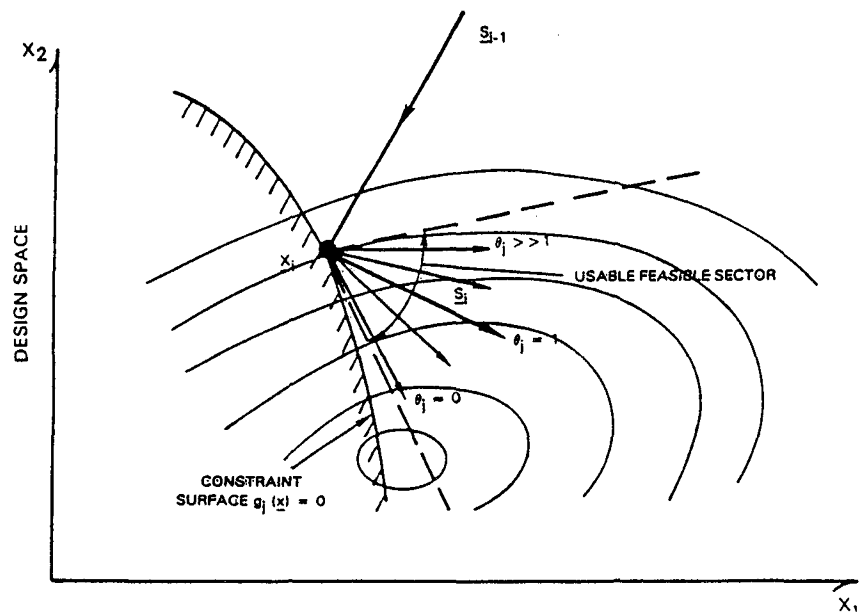

Figure 18 New Search Direction, s_i, Lies in the Usable Feasible Sector. The value of the push-off factor, θ_j, determines the orientation of the new search direction.

The rate of convergence is also affected by the value of CT, the constraint thickness parameter in COPES/CONMIN. For theoretical purposes, the i^{th} constraint is satisfied if $g_i(\underline{x}) \leq 0$ and is active if $g_i(\underline{x}) = 0$. For computational purposes (as shown in Figure 19), COPES/CONMIN considers the i^{th} constraint to be satisfied if $g_i(\underline{x}) \leq CT$ and to be active if $|g_i(\underline{x})| \leq -CT$, where CT is a negative number. If |CT| is too small, then one or more constraints can be active on one iteration and inactive on the next, only to become active again on a subsequent iteration - another instance of "zigzagging". A proper choice of CT ensures that two or more constraints will often be simultaneously active when a new search direction is chosen. In this case, as shown in Figure 20, the search will proceed down the "valley" formed by the constraint surfaces. The default value in COPES/CONMIN is CT = -0.1 (i.e., a constraint is considered active if it is within 10 percent of its specified value). For many STAEBL applications, a value CT = -0.1 was too large since too many constraints were simultaneously active during the early iterations, and new search directions could not be established. Consequently, the value CT = -0.05 was used.

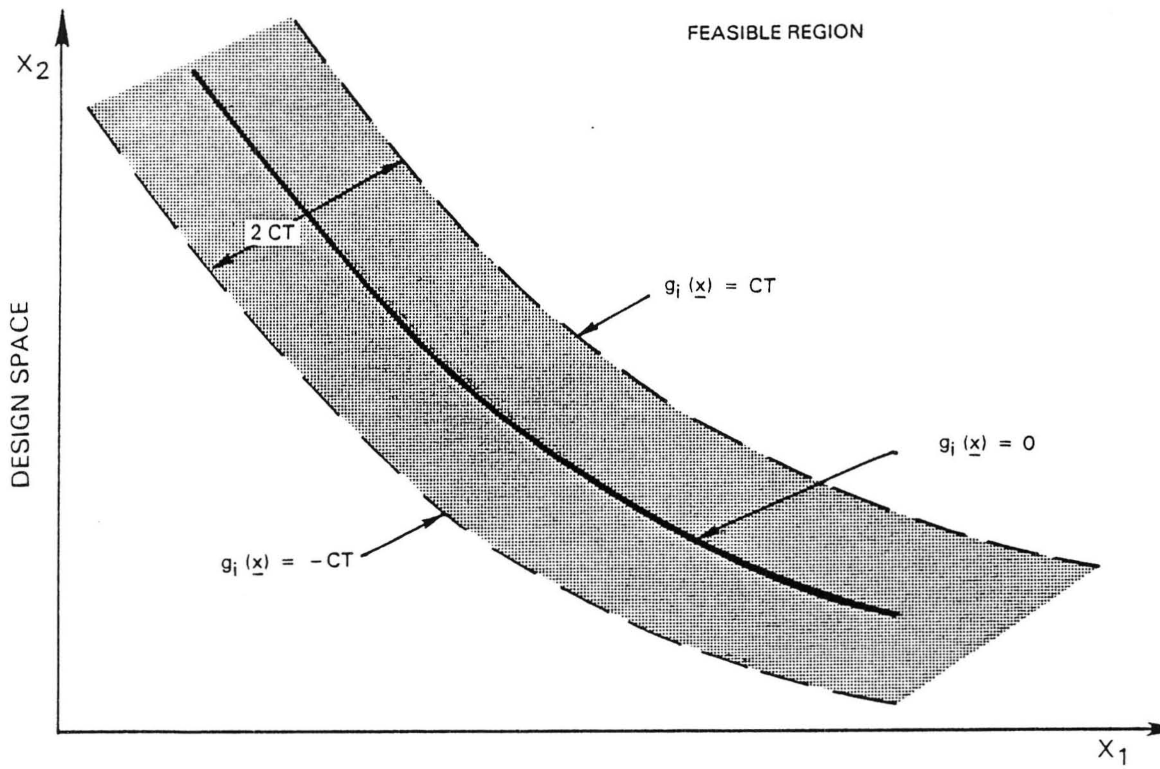

Figure 19 Constraint Thickness Parameter, CT, Determines When a Constraint is Satisfied, Violated, or Active

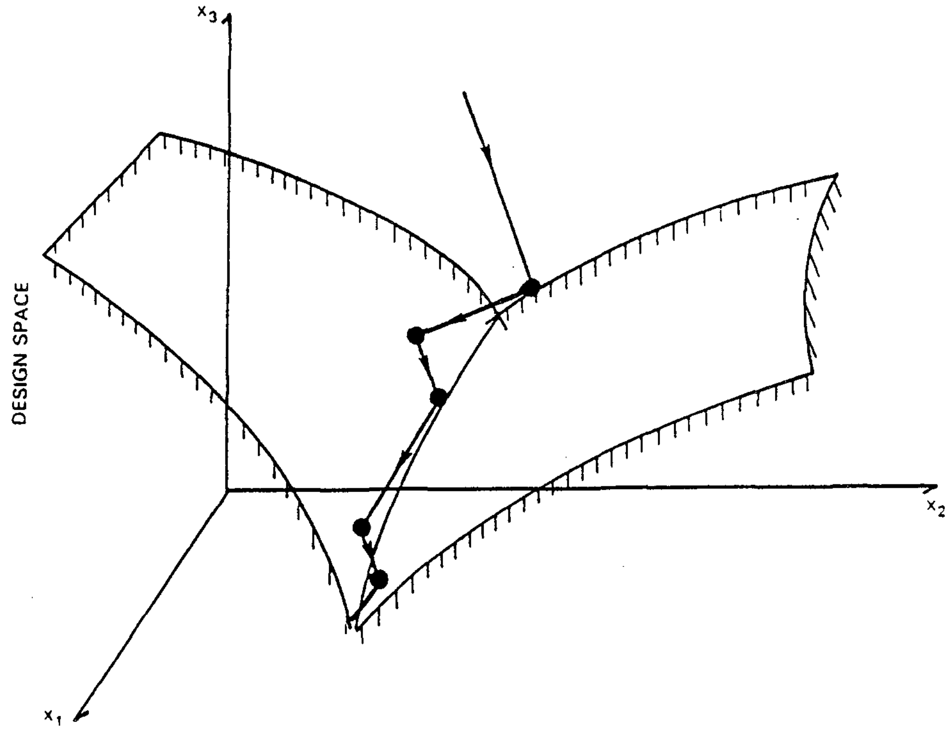

Figure 20 For Proper Choice of CT, Two Constraints Become Simultaneously Active So That Search Proceeds Down the "Valley" Formed by the Constraints

During the COPES/CONMIN optimization procedure, the values of CT and θ_j are updated as follows. After the first few iterations, the value of CT is decreased monotonically so that fewer constraints will be active when new search directions are established. A minimum value of |CT| is given by CTMIN; the default value in COPES/CONMIN is CTMIN = 0.004. In addition, the value of the push-off factor, θ_j, is also readjusted at each iteration according to the value of the active constraint to which it applies and to the current value of CT. Thus, θ_j is a quadratic function of these parameters, i.e.,

$$\theta_j = \theta_o \left(\frac{g_j(\underline{x}_i)}{CT} - 1 \right)^2 , \qquad (8)$$

where θ_o is the initial value of θ_j (for STAEBL we have chosen θ_o=0.3). A maximum value of θ_j = 50 is also imposed.

The iteration is terminated under three conditions in COPES/CONMIN:

1. If the objective functions for three successive iterates are all within a prescribed error tolerance, then the procedure has converged to a local optimum. COPES/CONMIN uses default values of DELFUN = 0.0001 for the relative change in objective function and (DABFUN = 0.0001) x initial objective value for absolute change in the objective function as its convergence criteria. For the STAEBL application, 1 percent differences in the objective function were adequate for convergence so that DELFUN = DABFUN = 0.01. These increased values also reduced the number of function calls required for convergence.

2. If convergence has not been obtained after a certain number of iterations inside the feasible region, the procedure is terminated. Either this design can be accepted or else the optimization procedure can be restarted if progress toward an optimum is obviously being made. COPES/CONMIN uses a default value of 20 for the total number of iterations.

3. If the feasible region cannot be located after a certain number of iterations (the COPES/CONMIN default value is 10), then the process is terminated. At this time, either a new starting guess should be chosen, or else the objective function and constraints should be examined to determine whether or not a feasible region exists.

12.1.2.2 Scaling of Design Variables in COPES/CONMIN

Performance of the method of feasible directions can be greatly affected by the scaling of the design variables. At the beginning of each iteration in COPES/CONMIN, a new search direction is established according to Zoutendijk's method, equation (7). This procedure is based upon the gradient of the objective function and each constraint with respect to each of the design variables. The choice of the search direction is very sensitive to the components of these gradients. For example, in a two design variable problem, suppose that a 1 percent change in x_i leads to a 10 percent change in the objective function, $f(\underline{x})$; whereas a 1 percent change in x_2 leads to only a 0.1 percent change in $f(\underline{x})$. To reduce the objective function most rapidly, the search direction will be primarily in the x_1 direction. The "weak" variable, x_2, will be virtually unchanged, at least for several iterations. To obtain the optimal design, a relatively large change in x_2 must be made to affect the objective function and constraints.

In a well-formulated problem, the components of the gradient of the objective function with respect to the design variables should all be roughly the same order of magnitude. The scaling option in COPES/CONMIN can be used to equilibrate the gradient components as follows. The i^{th} design variable, x_i, is scaled by dividing it by its initial value x_i^o, i.e.;

$$\xi_i = x_i/x_i^o \tag{9}$$

provided x_i^o is nonzero. Using equation (9) in the chain rule, the i^{th} component of the scaled gradient with respect to the nondimensional variable, ξ_i, is given by:

$$\frac{\partial f}{\partial \xi_i} = \frac{\partial x_i}{\partial \xi_i} \frac{\partial f}{x_i} = x_i^o \frac{\partial f}{\partial x_i} \tag{10}$$

Thus, the ratio of the i^{th} components in the scaled gradients is given by:

$$\frac{\partial f}{\partial \xi_i} \Big/ \frac{\partial f}{\partial x_i} = x_i^o \tag{11}$$

The scaling options in COPES/CONMIN are controlled by the input parameter NSCAL and are given as follows:

$$
\text{NACAL} \begin{cases} >0: & \text{Rescale design variables by dividing by current values every NSCAL iteration,} \\ =0: & \text{No scaling (default value),} \\ <0: & \text{Scale design variables by dividing by user-input scaling variables.} \end{cases} \tag{12}
$$

For STAEBL demonstration, scaling was always used. The value NSCAL = n+1 (where n = number of design variables) was recommended by G. Vanderplaats since this strategy worked well for unconstrained minimization problems using the conjugate gradient method.

12.1.2.3 Number of Function Calls for COPES/CONMIN

Engineering design problems are considered small or large according to the number of design variables as follows:

$$
\begin{aligned} &\text{Small:} && n \leq 10, \\ &\text{Moderate:} && 10 < n \leq 50, \\ &\text{Large:} && n > 50. \end{aligned} \tag{13}
$$

The number, N, of function calls required for convergence of the method of feasible directions for COPES/CONMIN can be approximated as follows. As indicated in Figure 17, each iteration consists of a gradient evaluation of the objective function and constraints to determine the search direction, followed by a one-dimensional line search in that direction. When the gradients are not known analytically (as is the case for the STAEBL application), a backward difference gradient approximation is used. For n design variables, n function calls are required for the finite difference gradient calculation. The one-dimensional line search usually requires 3 additional function evaluations to update the objective function and constraints and to determine where the search should terminate. Thus, for m iterations, with n+3 function calls per iteration, we have:

$$
N = m\,(n + 3). \tag{14}
$$

Typically, convergence is attained in approximately 10 iterations so that $N \approx 10n + 30$. Note that N increases roughly linearly as a function of the number, n, of design variables.

The limiting feature in these analyses is the computer time required per function call to evaluate the objective function and constraints.

12.1.3 COPES/CONMIN Interfaces to Vibration, Flutter, and Stress Programs

The COPES/CONMIN program is limited via subroutine ANALIZ to the approximate vibration, flutter, stress, and foreign object damage programs used for the structural analysis of blades.

Once an optimal feasible design has been obtained by COPES/CONMIN, this blade design must be evaluated by the refined analysis (finite element program) for further tailoring and possible re-optimization.

Subroutine ANALIZ is called by COPES/CONMIN in order to evaluate the objective function and constraints. There are three options, designated by different values of the parameter ICALC, utilized by COPES/CONMIN when calling subroutine ANALIZ:

ICALC = 1: Read data, set the parameters that are used throughout the analysis, and analyze the initial design;

ICALC = 2: Analyze the current design;

ICALC = 3: Write output data, parameters and results of analysis on final design.

In order to accomplish these tasks, subroutine ANALIZ calls the vibration, flutter, stress, and foreign object damage programs whenever necessary. The transfer of information between COPES/CONMIN and these approximate analyses is accomplished by accessing the data in common block GLOBCM.

SECTION 13.0

APPENDIX B: STAEBL COMPILED LISTING CONTENTS

Module	Element
COPES/CONMIN	CNMN01
	CNMN02
	CNMN03
	CNMN04
	CNMN05
	CNMN06
	CNMN07
	CNMN08
	CONMIN
	SIMCON
	COPE01
	COPE02
	COPE03
	COPE04
	COPE05
	COPE06
	COPE07
	COPE08
	COPE10
	COPE11
	COPE12
	COPE13
	COPE14
	COPE15
	COPE16
	COPE17
	COPE18
	MAIN
U809SANLIZ	ANALIZ
	LYERAT
	MESAGE
	CNSTAV
	CALCTH
	OBJTV
	RDDATA
	RDW137
U809SANLIZ (continued)	TMAX
	STRCON
	BIRDF
	RTFOD
	RFDSAV
	WTW137
	WT751
	TSWUFL
	MULTZM
	FLTSAV
	BMEVAL
	BMFIT
	ITW751
	NDW751
	RESMRG
	FODSAV
	NASFLT
	NSFLCL
	DREAL
	GOODMN
	FRCFNC
U809PREPRC	MNW137
	DK369
	STAEBL
	PSHEL
	TRIA3
	CORD2R
	MATRL
	BC
	BMFIT2
	CUBIC
	PBMFIT
	LAMINA
	LAMIN8
	HOLLOW
	XPROD
	HOLLW2

Module	Element	Module	Element
U809MNU808	MNU808	U809MNU808	PSTRSS
	APPEND	(continued)	PSTR2D
	BANDER		REBAND
	BMADD		REORDR
	BRMPLY		RESTOR
	CTMASS		RLOAD
	DADOTB		SAVE
	DAXB		SCALE
	DIAG		SDR2WT
	ECHO		SPC
	EMA		SPCARR
	EMGG		STRESS
	EMGPOM		STRES2
	ETRFOD		STRPRT
	ETR3D		STR31D
	FTRNSF		STR32D
	GETVEC		TIPMOD
	GMMATD		TSAIWU
	GOSET		TRANSD
	GP6X6		TRNSFM
	GP6X6B		ZEROFE
	IDENT		ZEROI
	INPUT		
	INTRPD	U809FLUTER	SSCASC
	INTRPI		AKP2
	LEQUSL		AKAPM
	MADD		ALAMDA
	MAT		AKAPPA
	MATCMP		DLKAPM
	MATMPY		ASYCON
	MATMP1		
	MATMP2	U809FOD	MNFOD
	MATPRT		MODES
	MATSTP		FGAB
	MATTMP		MODINT
	MERGE		LOAD
	MODPRT		MTTMPA
	MOOGO		MTMPYA
	MSUB		IMPCT
	PRTRED		

APPENDIX C

PRATT & WHITNEY PROPRIETARY SUPERSONIC FLUTTER ANALYSIS

- For NASA Use Only -

As an option of STAEBL, a Pratt & Whitney proprietary supersonic flutter analysis is available for NASA use only. The optional flutter analysis is automatically referenced by STAEBL when more than one spanwise strip is requested for flutter analysis (NAC on Card C3). With the optional Pratt & Whitney flutter analysis, multiple spanwise strips may be evaluated to determine the overall blade stability. In all other respects, the analysis is similar to the analysis performed by the publicly available NASA flutter code.

<u>Revised Card C3 (Required if NRF > 0 on Card Cla</u>

Contents: Supersonic Flutter Analysis Input Control.

1	2	3	4	
	TEMPST		NAC	
10	20	30	40	

Field	Item	Format	Description
2	TEMPST	F	Inlet static temperature, °F.
4	NAC	I	Number of aerodynamic stations (maximum of 25). NAC = 1 : NASA Flutter Analysis $2 \leq NAC \leq 25$: P&W Proprietary Flutter Analysis (NASA use only)

Subroutine Dictionary, P&W Flutter Analysis

Routine	External Reference	Calling Element	Function
AJO		MAIN2	Evaluate JO Bessel Function
AJ1		MAIN2	Evaluate J1 Bessel Function
LINEAR		MAIN1 MAIN3	Perform Linear Interpolation
MAIN1	LINEAR	MNW751	Read Flutter Input Stream
MAIN2	BMFIT AJO BEVAL AJ1	MNW751	Determine Blade Aerodynamic Loading
MAIN3	LINEAR WORK	MNW751	Determine Unsteady Air Loads, Aerodynamic Damping
*MNW751	MAIN1 MAIN3 MAIN2	ITW751	Driver for P&W Proprietary Flutter Analysis
VALUES			Block Data
WORK		MAIN3	Unsteady Work and Aero. Decrement Calculation

*Controlling routine for the module.

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