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Cyclic Structural Analyses of Anisotropic Turbine Blades for Reusable Space Propulsion Systems

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CYCLIC STRUCTURAL ANALYSES OF ANISOTROPIC TURBINE BLADES

FOR REUSABLE SPACE PROPULSION SYSTEMS (PRELIMINARY)

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SUMMARY

Turbine blades for reusable space propulsion systems are subject to severe thermomechanical loading cycles that result in large inelastic strains and very short lives. These components require the use of anisotropic high-temperature alloys to meet the safety and durability requirements of such systems. To assess the effects on blade life of material anisotrophy, cyclic structural analyses are being performed for the first stage high-pressure fuel turbopump blade (HPFTB) of the space shuttle main engine (SSME). The blade alloy is directionally solidified MAR-M 246 alloy. The analyses are based on a typical test stand engine cycle. Stress-strain histories at the airfoil critical location are computed using the MARC nonlinear finite-element computer code. The MARC solutions are compared to cyclic response predictions from a simplified structural analysis procedure developed at the NASA Lewis Research Center.

INTRODUCTION

Fuel turbopumps for reusable space propulsion systems operate under extreme gas pressure and temperature environments. These operating conditions subject the high-pressure stage turbine nozzles and blades to severe thermal transients that result in large inelastic strains and rapid crack initiation. To attain even the short lives required for these systems necessitates the use of anisotropic turbine blading alloys. Assessing or improving the durability of these components is contingent on accurate knowledge of the stress-strain history at the critical location for crack initiation.

Nonlinear finite-element analysis techniques have become available in recent years for calculating inelastic structural response under cyclic loading. These methods are based on classical incremental plasticity theory with uncoupled creep constitutive models. Many of the nonlinear finite-element computer codes such as MARC (ref. 1) have the capability of handling materials with anisotropic properties. However, these codes are usually too costly and time consuming to use in the early design stages for aerospace applications. Costs are further increased by the geometrical complexity of high-pressure turbine blades which require three-dimensional analyses and sometimes substructuring to obtain accurate solutions. To improve the design of engine hot path components such as turbine blades, simplified procedures for more economically representing structural response under cyclic loading have been under development (refs. 2 to 4).

This paper addresses the problems of calculating the structural response of high-temperature space propulsion components such as fuel turbopump turbine blades. The first high-pressure stage fuel turbine blade (HPFTB) in the liquid hydrogen turbopump of the space shuttle main engine (SSME) was selected for this study. In the past these blades have undergone cracking in the blade shank region and at the airfoil leading edge adjacent to the platform. To achieve the necessary durability, these blades are currently being cast using directional solidification. Single crystal alloys are also under investigation for future SSME applications. The objective of the study was to evaluate the utility of advanced structural analysis methods in assessing the low-cycle fatigue lives of these anisotropic components. MARC elastic-plastic finite-element analyses are being performed for the blade airfoil. Because of the extensive computation time required for the nonlinear finite-element analyses, neither the blade platform nor shank regions were modeled at this time. Analyses of the shank region are also hindered by lack of knowledge as to its thermal environment. A simplified inelastic structural analysis procedure will also be exercised on this problem to assess its applicability to anisotropic turbine blades for space propulsion systems.

PROBLEM DESCRIPTION

The turbine blade airfoil of the high pressure stage of the SSME fuel turbopump was analyzed because of its history of rapid crack initiation. These uncooled airfoils have a span length of 2.2 cm and a span-to-chord width aspect ratio of approximately unity. The blades are cast from directionally solidified MAR-M 246 alloy. Temperature-dependent properties for this alloy were mainly provided by the Rocketdyne Division of Rockwell International Corporation. Material elastic properties are summarized in table I. Mean thermal coefficient of expansion data were converted to instantaneous values for MARC input. Poisson's ratio values of 0.143 and 0.391 were used for the longitudinal and transverse directions, respectively, and were assumed to be constant with temperature. Longitudinal stress-strain properties, summarized in table II, were used for the elastic-plastic region. A single crystal MAR-M 246 alloy is also being considered for turbine blades in future SSME applications.

Cracking has occurred during service at the airfoil base near the leading edge and in the blade root shank area. These cracks apparently initiate during the first few mission cycles due to the severe thermal transients and are propagated by vibratory excitation. Since the primary purpose of this study was to compare nonlinear finite-element and simplified analytical methods, the blade root and platform were excluded from the analysis to reduce the size of the problem and, therefore, the computing time.

The mission used for the analysis is shown in figure 1 in terms of turbine inlet temperature, gas pressure and rpm. This cycle is applicable to a factory test of the engine; it is also reasonably representative of a flight mission except for the foreshortened steady-state operating time. The major factor inducing rapid cracking is the transient thermal stresses and the inelastic strains caused by the sharp acceleration and deceleration transients.

Rudimentary transient and steady-state three-dimensional heat transfer analyses have been conducted using the MARC code. Film coefficients were obtained from preliminary information supplied by Rocketdyne. The gas sink temperature was assumed constant around the airfoil surface for each time step. Colder boundary conditions were assumed at the airfoil base to simulate the effects of the cooling of the blade-to-disk attachment region by the liquid hydrogen fuel. Improved transient heat transfer analyses using more exact boundary conditions will be performed in the near future to obtain more accurate blade temperature input for the nonlinear structural analysis.

ANALYTICAL PROCEDURE

Elastic-plastic analyses are being conducted for the HPFTB airfoil with both the MARC code and a simplified analytical procedure developed at the NASA Lewis Research Center. The MARC analysis used the anisotropic material properties while the simplified analysis used only the Young's modulus and Poisson's ratio for the longitudinal (spanwise) direction.

MARC Finite-Element Analysis

A three-dimensional finite-element model of the airfoil (fig. 2) was constructed of eight-node isoparametric elements. The model consisted of 360 elements with 576 nodes and 1661 unsuppressed degrees of freedom. This model was a shortened version of a finite-element model created by Lockheed for a NASTRAN elastic analysis of the HPFTB blade at steady state condition; this work was done under contract to the NASA Marshall Space Flight Center. The main difference between the NASA Lewis and Lockheed models was that the blade base and most of the platform were omitted for the MARC nonlinear analysis to reduce the computing time and to run the problem in-core on the CRAY computer system at Lewis. Boundary conditions were applied to constrain all nodes at the base of the model to lie on a plane. Additional boundary conditions were imposed to prevent rigid body motion in this plane.

The MARC code has been used extensively at Lewis for inelastic analyses of aircraft turbine blades and combustor liners and of space power components. In conducting a cyclic analysis, the loading history is divided into a series of incremental load steps which are sequentially analyzed. The plasticity algorithm is based on a tangent stiffness approach in which the stiffness matrix is reformulated and reassembled for every plastic load increment. The incremental loads are modified by residual load correction vectors to insure that the solution does not drift from a state of equilibrium. Convergence for the iterative plasticity analysis is indicated when the strain energy used in assembling the stiffness matrix approximately equals the energy change resulting from the incremental solution.

The mission cycle was subdivided into 129 increments. Incremental loading included centrifugal and gas pressure loads and metal temperature distributions as calculated from the heat transfer analysis. Approximately 1000 words of core storage on the CRAY system were needed to run the problem. Each cycle of analysis required about 15 hr of computing time on the Cray system.

The directionality of the elastic material properties causes anisotropic constraints. Lekhnitskii (ref. 6) has derived the generalized elastic strain equations for an anisotropic body with a transverse plane of isotropy. Matrix inversion of these equations to solve for the stresses results in the relationship

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{Bmatrix} = a \begin{Bmatrix} (1 - n\nu'^2) & (\nu + n\nu'^2) & \nu'(1 + \nu) & 0 & 0 & 0 \\ (\nu + n\nu'^2) & (1 - \nu'^2) & \nu'(1 + \nu) & 0 & 0 & 0 \\ \nu'(1 + \nu) & \nu'(1 + \nu) & (1 - \nu^2)/n & 0 & 0 & 0 \\ 0 & 0 & 0 & G'/a & 0 & 0 \\ 0 & 0 & 0 & 0 & G'/a & 0 \\ 0 & 0 & 0 & 0 & 0 & G'/a \end{Bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{yz} \\ \gamma_{yz} \end{Bmatrix}$$

where $n = E'/E$ and $a = nE/((1 + \nu)(1 - \nu - 2n\nu'^2))$. Here E', G', and ν' denote the Young's moduli, shear modulus and Poisson's ratio, respectively, for the longitudinal or span direction while E, G, and ν denote these constants with respect to any direction in the transverse plane of isotropy. This anisotropic stress-strain law was incorporated in the MARC user subroutine, HOOKLW.

Plastic strain calculations were based on incremental plasticity theory using the von Mises yield criterion, the normality flow rule and a kinematic hardening model. The material elastic-plastic behavior was specified by the yield strengths and work hardening properties in the longitudinal direction; transverse properties were not available. Creep analyses are not being performed at the present time because of inadequate knowledge of the creep characteristics for the anisotropic blade material.

Simplified Analysis

The simplified analytical procedure was developed to economically calculate the stress-strain history at the critical fatigue location of a structure subjected to cyclic thermomechanical loading. This procedure has been exercised on a wide variety of problems including multiaxial loading, nonisothermal conditions, different materials and constitutive models, and dwell times at various points in the cycles. Comparisons of the results of the simplified analyses with MARC inelastic solutions for these problems have shown reasonably good agreement.

The basic assumption is that the total strain ranges calculated from linear elastic and nonlinear analyses are approximately equal and, therefore, the material cyclic response can be calculated using as input the total strain history obtained from an elastic analysis. This assumption is essentially true for thermally dominated loading. A corollary of this assumption is that the stress-strain hysteresis loop calculated from an elastic-plastic analysis will be of similar size and shape to that calculated from an elastic analysis, but translated in the stress direction. There is a version (ref. 4) of the procedure that uses Neuber-type corrections (ref. 7) to account for strain redistribution due to mechanical loading; however, this version was not utilized for this study because of the dominance of the thermal loading. Classical incremental plasticity methods are used to characterize the yield surface by a yield condition to describe yielding under multiaxial stress states and by a hardening model to establish the location of the yield surface during cycling. This procedure can accommodate itself to any yield criterion or hardening model. The only requirements are that the elastic input data, whether calculated or measured, be in a form consistent with the yield criterion and that the appropriate material properties be used in conjunction with the hardening model.

As in most nonlinear computer codes, the von Mises yield criterion has been used in applying stress-strain results from elastic finite-element analyses of multiaxial problems as input for the simplified procedure. To compute cyclic hysteresis loops for life prediction purposes, the input von Mises stresses and strains have to be assigned signs, usually on the basis of the signs of the dominant principal stresses and strains.

The elastic input data are subdivided into a sufficient number of increments to define the stress-strain cycle. These increments are analyzed sequentially to obtain the cumulative plastic and creep strains and to track the yield surface. An iterative procedure is used to calculate the yield stresses for increments undergoing plastic straining. First, an estimated plastic strain is assumed for calculating an initial yield stress from the stress-strain properties and the simulated hardening model. Then a new plastic strain is calculated as the difference between the total and elastic and creep strain components. The yield stress is then recalculated using the new plastic strain. This iterative procedure is repeated until the new and previous plastic strains agree within a tolerance of 1 percent. Creep computations are performed for increments involving dwell times using the creep characteristics incorporated in the code. Depending on the nature of the problem, the creep effects are determined on the basis of one of three options to be selected; (1) stress relaxation at constant strain, (2) cumulative creep at constant stress, or (3) a combination of (1) and (2).

A FORTRAN IV computer program (ANSYMP) was created to automatically implement the simplified analytical procedure. A detailed description of the calculational scheme is presented in previous papers on the development of this procedure.

DISCUSSION OF RESULTS

Calculated metal temperatures at the leading edge at midspan and at the crack initiation site at the base of the airfoil (critical location) are presented in figure 3 as a function of elapsed time during the cycle. The assumed gas sink temperature around the airfoil is also plotted. Of particular note is that the leading edge temperature at the airfoil base is cooler than at midspan throughout the cycle. This seems reasonable because of the cooling of the blade-to-disk attachment region by the liquid hydrogen fuel. The colder airfoil base temperatures induce tensile thermal stresses at the critical leading edge location that are additive to the centrifugal stresses.

At the beginning of this study, a steady-state MARC elastic-plastic analysis of the airfoil was conducted for rated power level (RPL). The temperature input was obtained from a NASTRAN steady-state heat transfer analysis performed by Lockheed. In contrast to the large temperature gradients calculated from the NASA heat transfer analysis, Lockheed had a maximum temperature variation in the airfoil of only 35 °C. Effective stress distributions as calculated at the Gaussian integration points closest to the suction and pressure surfaces are presented in figure 4. Since the airfoil was essentially at an isothermal state, the stresses primarily reflect the centrifugal and gas pressure loading and were entirely in the elastic range. The maximum effective stress was only 40 percent of the yield strength. It is apparent that the analysis would not show a low-cycle fatigue problem if transient thermal effects were not considered. A MARC nonlinear finite-element analysis for the complete mission cycle has been initiated but, as of this writing, has not been completed.

CONCLUDING REMARKS

This work is still in a preliminary stage. A transient heat transfer analysis of the HPFTB airfoil has been completed. This analysis is rudimentary because of the inadequate definition of the heat transfer coefficients and omission of the cooled shank region in the finite-element model. However, it is sufficient for the purpose of exercising and evaluating the structural analysis methods. A MARC cyclic stress-strain analysis has been initiated.

The simplified procedure will probably require further development for application to SSME turbopump blade problems. This is not only because of the use of anisotropic materials, but also because of the nonproportionality of the thermal and mechanical loading during the cycle. Experience has indicted that effective stresses and strains are not suitable criteria for relating multiaxial nonproportional stress-strain states to uniaxial material properties.

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TABLE I. - DS MAR-M 246 PHYSICAL PROPERTIES

Temperature, °C	Modulus of elasticity GPa		Means coefficient of thermal expansion, percent/°C
	Longitudinal	Transverse	
21	131	183	-------
93	120	179	0.00113
204	125	175	.00130
316	124	173	.00133
427	119	166	.00141
538	114	162	.00148
649	109	156	.00149
760	103	149	.00156
671	97	142	.00160

TABLE II. - DS MAR-M 246 STRESS-STRAIN PROPERTIES (LONGITUDINAL)

Plastic strain, percent	Stress, MPa		
	21 °C	649 °C	816 °C
0.1	800	808	875
.2	830	855	930
.4	850	895	965
.6	855	930	970
.8	865	945	975
1.0	870	960	980

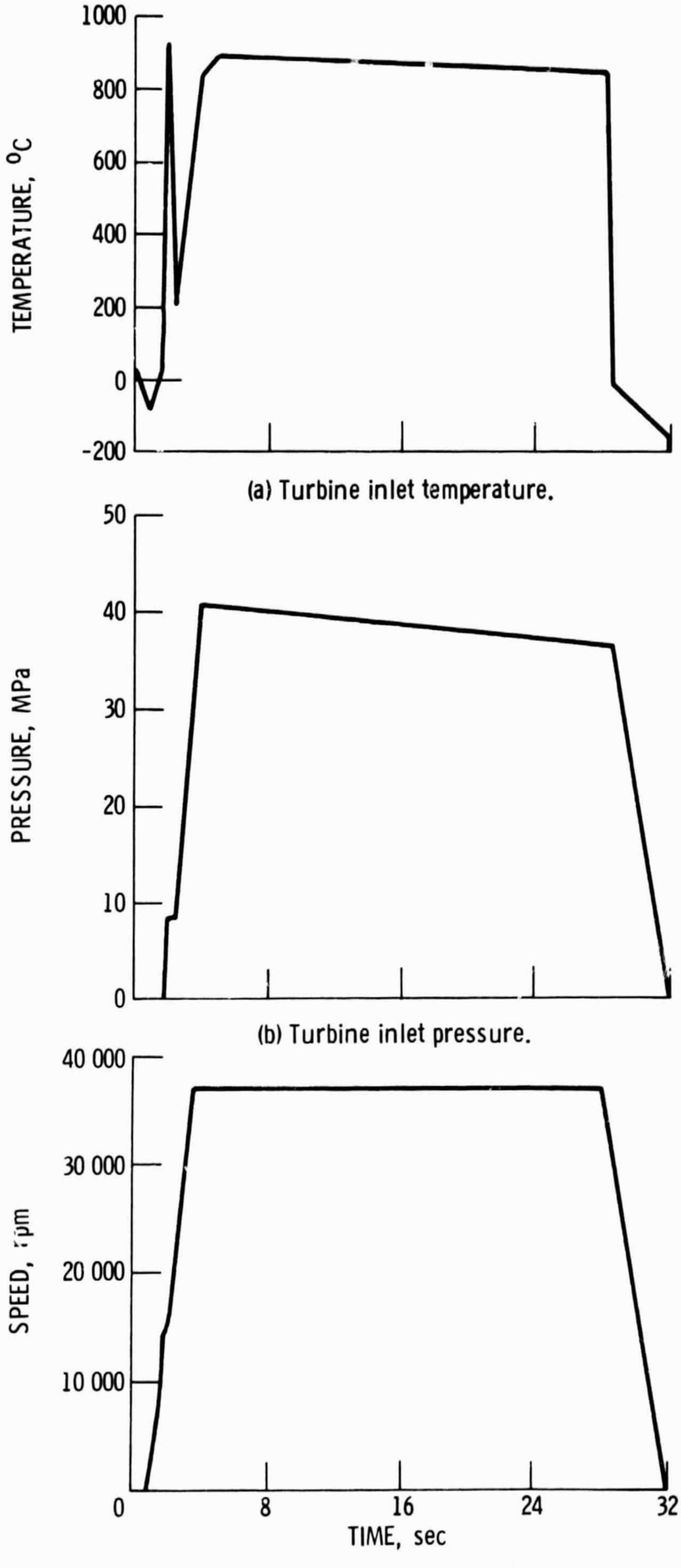


Figure 1. - Mission cycle used for analysis.

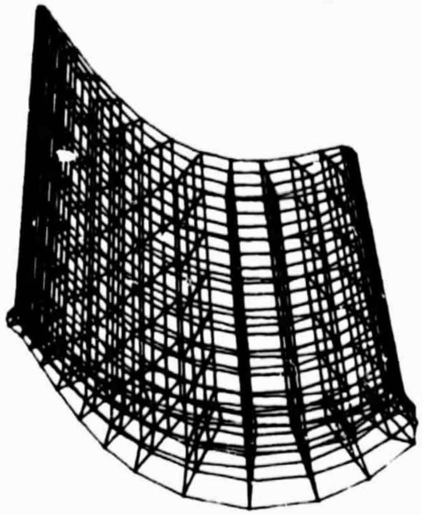


Figure 2. - Airfoil finite element model.

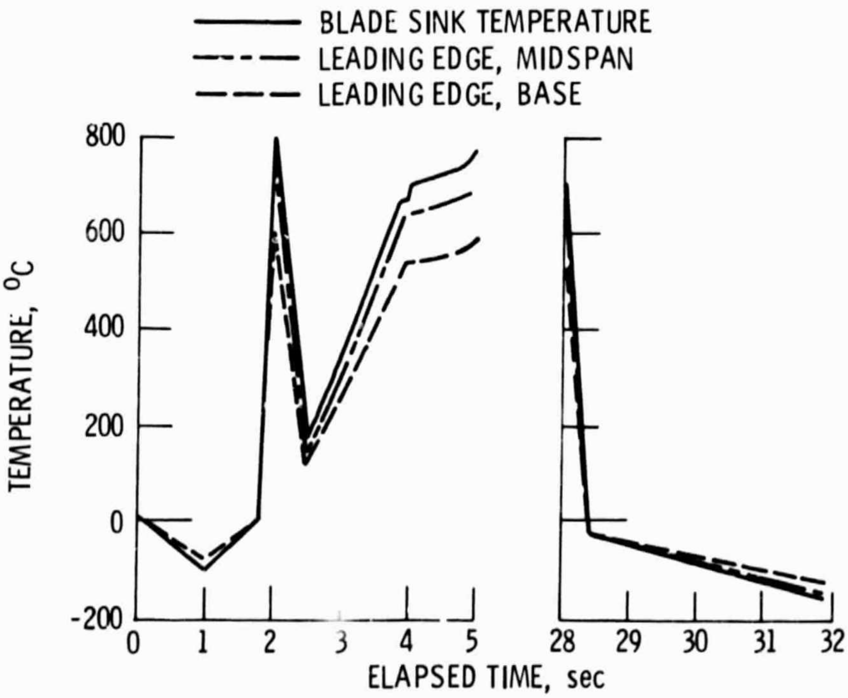
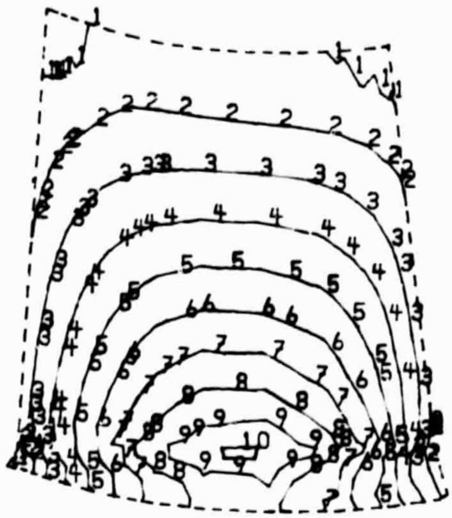
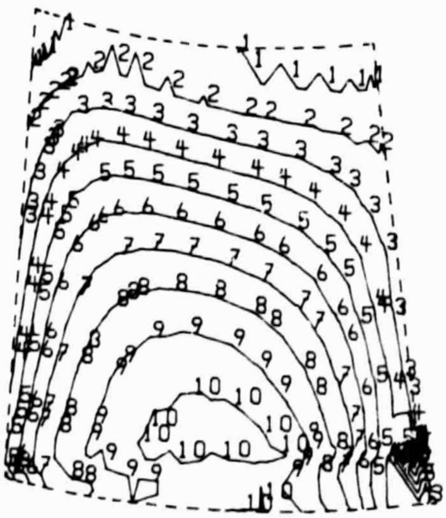


Figure 3. - Airfoil temperature cycle.



	STRESS, MPa
1	39.4
2	77.9
3	115.8
4	154.4
5	193.1
6	231.0
7	269.6
8	307.5
9	346.1
10	384.1

(a) Suction side.



	STRESS, MPa
1	34.0
2	55.4
3	76.5
4	97.9
5	119.3
6	141.3
7	162.7
8	184.1
9	205.4
10	226.8

(b) Pressure side.

Figure 4. - Airfoil effective stress distribution at RPL.