https://ntrs.nasa.gov/search.jsp?R=19880013873 2020-03-20T06:21:55+00:00Z

N88-23257

SSME SINGLE-CRYSTAL TURBINE BLADE DYNAMICS

Larry A. Moss*
Sverdrup Technology, Inc.
(Lewis Research Center Group)
NASA Lewis Research Center

ABSTRACT

There are many concerns surrounding the current directionally solidified (DS) blades for the first-stage rotor of the space shuttle main engine (SSME) high-pressure fuel turbopump (HPFTP). The blades' design life goal of 55 launches is not being met. The blade life has been shortened primarily by fatigue cracking. One method of lengthening blade life is by substituting single-crystal (SC) material. Past experience and current applications in commercial and military aviation have shown the feasibility of using SC material.

Research was conducted at Lewis to predict the SC blade natural frequencies and to find possible critical engine-order excitations. The effort was both experimental and analytical. Experiments were used to validate the analytical procedures. Bench experiments for SC blades at different crystal orientations were conducted to determine their nonrotating natural frequencies and mode shapes. These results were compared with the analytical results to confirm the validity of the MSC/NASTRAN model.

The analytical effort examined the blades' dynamic characteristics with respect to crystal orientations under typical operating conditions. Additional investigations attempted to determine the crystal orientation that would most effectively avoid critical engine-order excitations.

The conclusions developed from the analyses and tests were as follows:

1. The MSC/NASTRAN blade model successfully predicts the nonrotating natural frequencies and mode shapes of the SC blades.

2. From a dynamics viewpoint the SC blade is an improvement over the DS blade. No new engine-order interferences were introduced with the material substitution.

3. The engine-order interferences of the SC blades can be minimized by changing the crystal orientation.

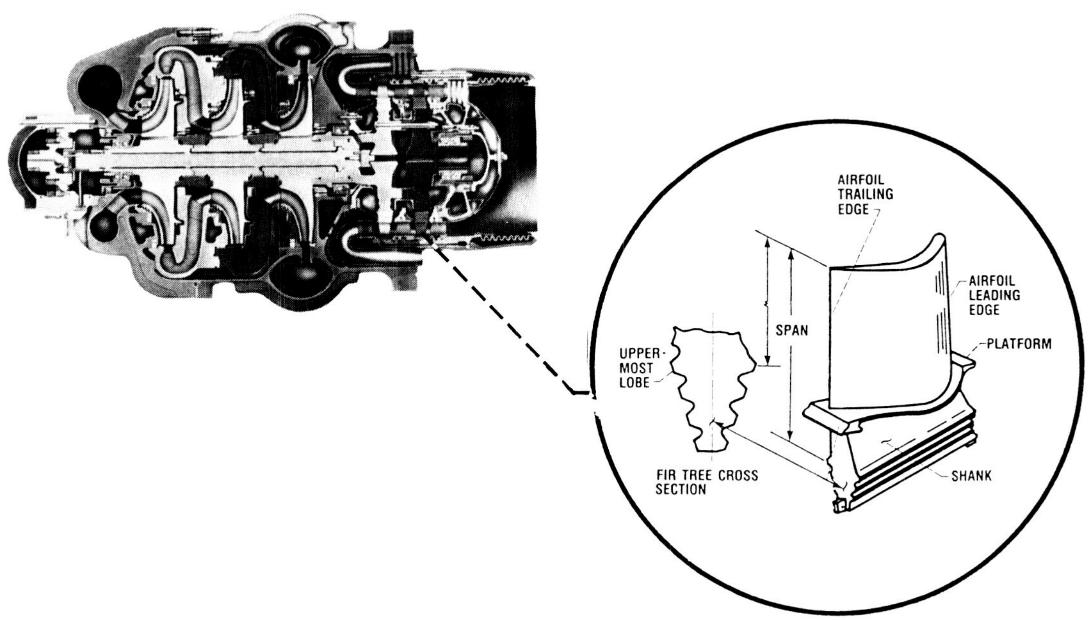
---

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

PRECEDING PAGE BLANK NOT FILMED

SSME HIGH-PRESSURE FUEL TURBOPUMP AND FIRST-STAGE TURBINE BLADE

Sixty-three blades are mounted within the first-stage rotor of the SSME high-pressure fuel turbopump (HPFTP), as shown below. The mounted blades have a tip diameter of approximately 11 in. The blade consists of four sections; airfoil, platform, shank, and fir tree. The airfoil is highly cambered and the cross section is nearly constant along the slightly twisted blade span. The four-lobed fir tree section mates with the rotor.

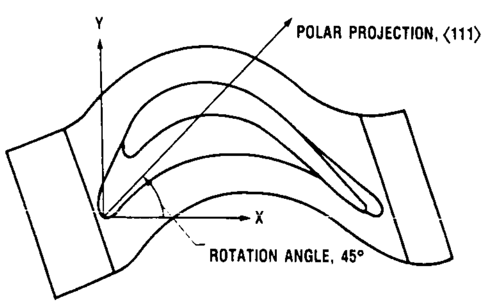


CD-88-31885

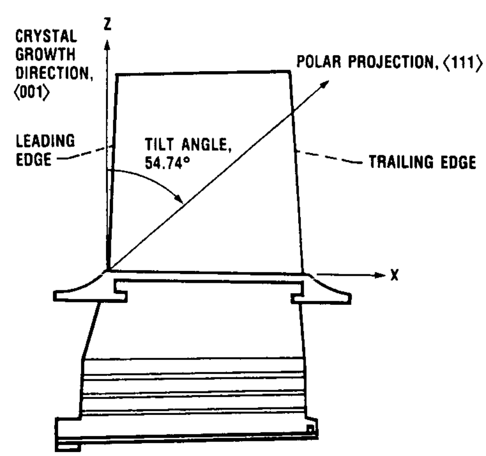
MATERIAL ORIENTATION OF SINGLE-CRYSTAL BLADE

The SC material orientation is determined from Laue x-ray diffraction techniques. Polar projections of the material's <111> axis are developed. The <111> axis is referenced within the HPFTP blade according to its projected rotation and tilt angles. The tilt angle is referenced according to the <111> axis projection on the X-Y plane of the blade. Positive rotation is measured counterclockwise from the blade chord (leading edge to trailing edge) with respect to the trailing edge, as shown below.

A cylindrical coordinate system was defined to specify the crystal orientation in the blade analyses. The variation in the single-crystal orientation was accommodated by supplying the appropriate direction cosines for the material coordinate system.



TOP VIEW

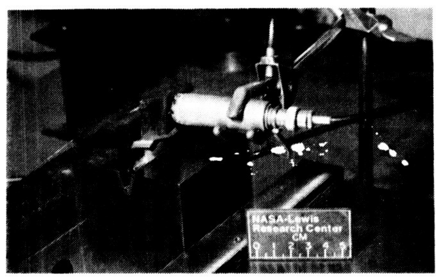


CD-88-31886

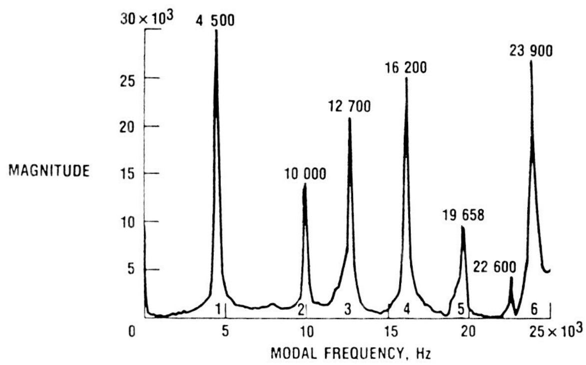
EXPERIMENTAL FREQUENCIES AND MODE SHAPES

The blade attachment to the actual rotor was simulated by brazing the SC blades in a stainless steel mounting block as shown in the photograph. Each blade tested had a different crystal orientation. The tests were conducted at nonrotating, room-temperature conditions. Two experimental methods were used to identify the modal frequencies and to approximate the mode shapes of the SC blades. These methods involved a modal analyzer and interferometry. Experimental modal frequencies between 0 and 25 000 Hz determined from the modal analyzer are shown in the graph. Mode shapes determined by interferometry are shown in a later figure.

MODAL ANALYZER



EXPERIMENTAL MODAL FREQUENCIES

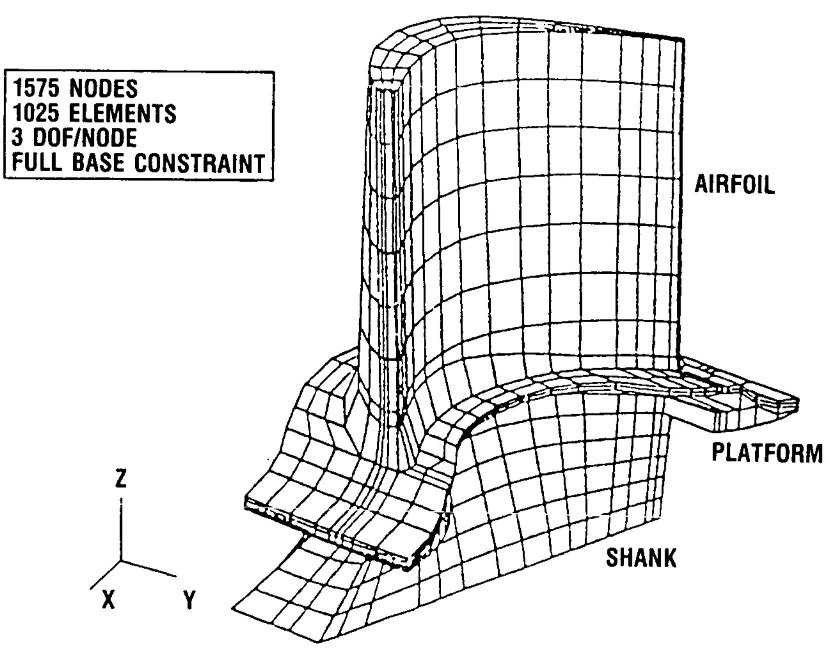


CD-88-31887

MSC/NASTRAN FINITE ELEMENT MODEL

MSC/NASTRAN was used to perform the analysis (Joseph, 1981). The finite element model shown below consists of 1025 solid eight-node hexahedron elements with three degrees of freedom per node. The base of the blade was fully constrained at the center of its uppermost fir tree attachment lobe. The in-disk span length was defined from this attachment point to the blade tip. The in-disk span length was assumed to simulate the blade's span length under actual rotor conditions.

A geometric nonlinear, large-displacement, static analysis was used to determine the steady-state displacements of the blade under centrifugal and thermal loading. Then a normal modes analysis was performed on the geometry to estimate the blade's natural frequencies and mode shapes.

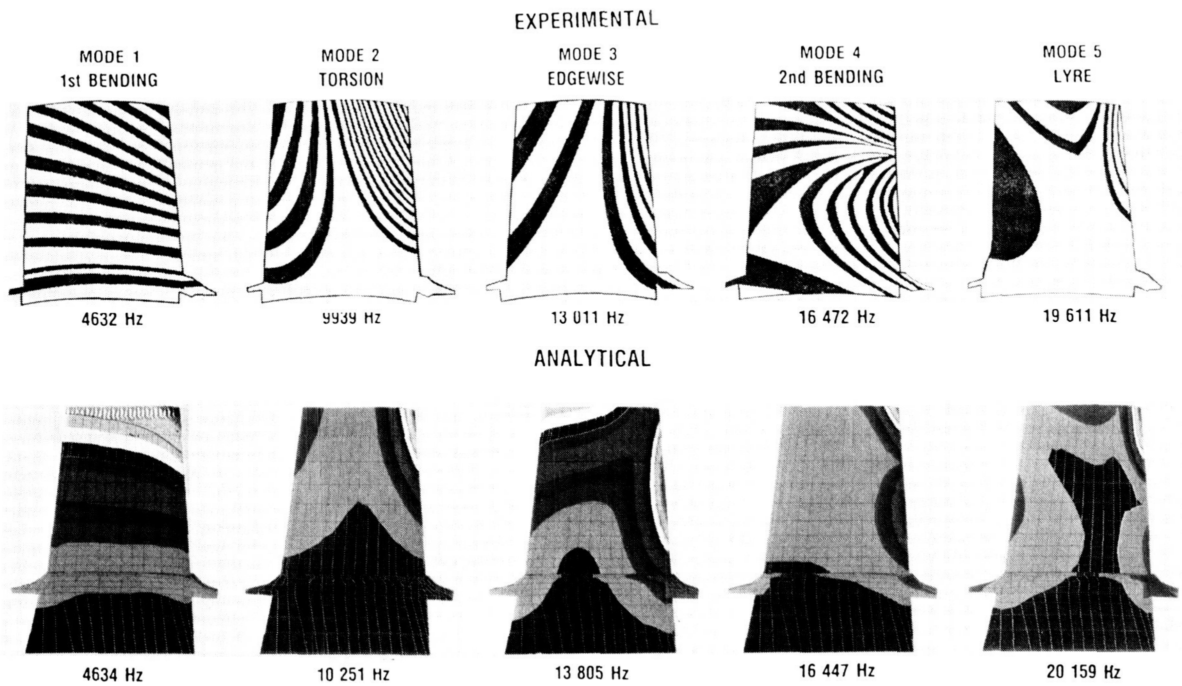


CD-88-31888

EXPERIMENTAL AND ANALYTICAL FREQUENCIES AND MODE SHAPES

The experimental mode shapes and frequencies for one SC orientation blade are shown below. Even though these modes are not pure beam modes, they can be classified by using beam terminology. Mode 1 proved to be first bending in the flatwise direction. Modes 2 and 3 were difficult to distinguish. The two modes appear similar because of the blade's high camber. Data from the modal analyzer indicated mode 2 to be first torsion and mode 3 to be bending in the edgewise direction. Mode 4 was second bending. Mode 5 appeared to be the lyre mode, and mode 6 (not shown) was a tip mode.

The analytical results from the same blade had excellent agreement with the interferometry results, shown below. The first five mode shapes duplicated the holograms. The modal frequencies were within 6 percent of the experimental results.

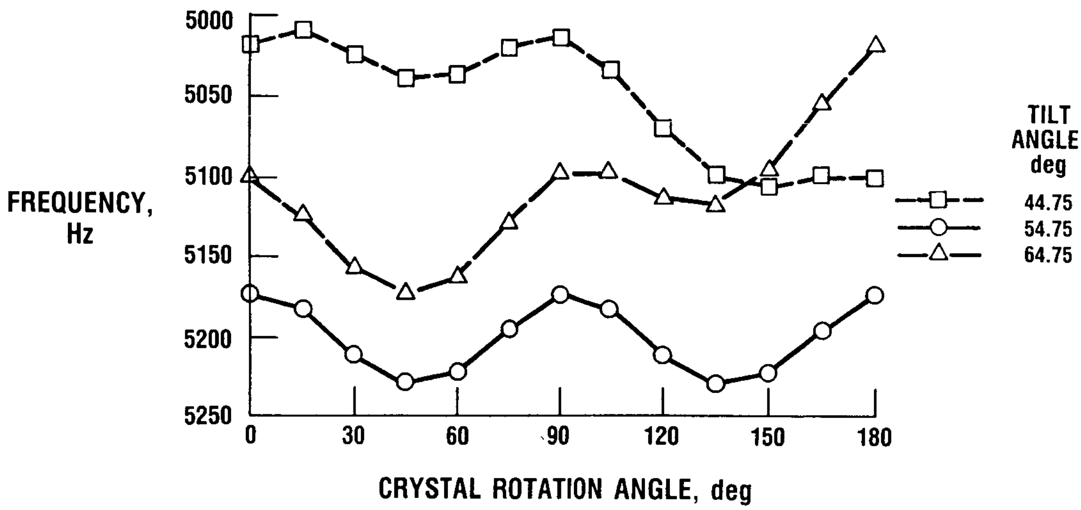


CD-88-31889

ORIGINAL PAGE IS
OF POOR QUALITY

PARAMETRIC STUDY OF CRYSTAL ORIENTATION

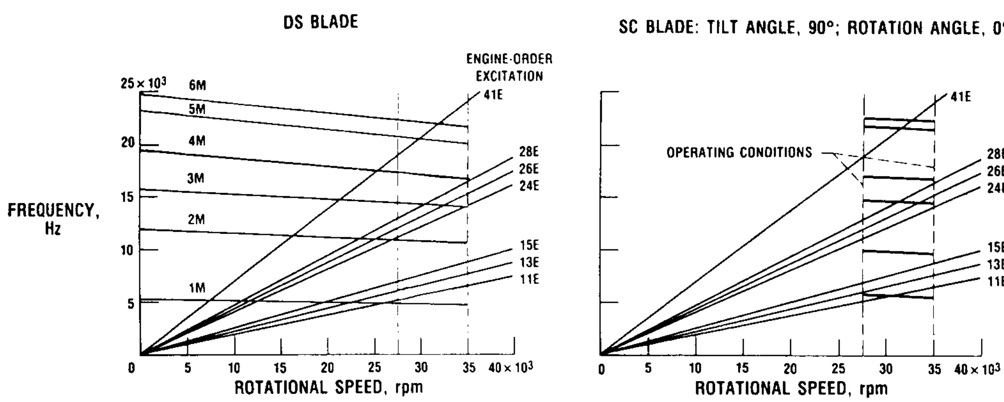
A parametric study was performed on the SC blades to investigate the effect of crystal orientation on the blades' natural frequencies. The figure graphically represents frequency as a function of rotation angle for three distinct tilt angles. The effects of crystal orientations on the nonrotating first blade mode are shown. The analyses of SC material were conducted at both nonrotating room-temperature conditions and operating conditions.



CD-88-31890

CAMPBELL DIAGRAM

Attempts were made to find an orientation that would eliminate or minimize the critical engine-order excitations. The Campbell diagram below shows that orienting the <111> axis in the chordwise direction (90° tilt angle) reduced the number of critical excitations when compared with the DS blade. This is a beneficial effect of SC blading.



CD-88-31891

SUMMARY

An MSC/NASTRAN finite element blade model successfully determined the natural blade modes of single-crystal SSME turbopump blades. The SC blade dynamic characteristics were further analyzed with respect to crystal orientation under typical operating conditions. From a dynamics viewpoint the SC blade was an improvement over the DS blade. No new engine-order interferences were introduced with the material substitution. Additional studies proved that the engine-order interferences can be minimized by changing the blades' crystal orientation.

- **SC BLADES' NATURAL MODES WERE PREDICTED BY MSC/NASTRAN.**
- **NO NEW ENGINE-ORDER INTERFERENCES WERE INTRODUCED WITH THE SC MATERIAL SUBSTITUTION.**
- **BLADE INTERFERENCES WERE MINIMIZED BY OPTIMUM SC ORIENTATIONS.**

CD-88-31892

BIBLIOGRAPHY

Bowen, K., Nagy, P., and Parr, R.A., 1986, "The Evaluation of Single Crystal Superalloys for Turbopump Blades in the SSME," AIAA Paper 86-1477.

Dreshfield, R.L., and Parr, R.A., 1987, "Application of Single Crystal Superalloys for Earth-to-Orbit Propulsion Systems," AIAA Paper 87-1976, (NASA TM-89877).

Joseph, J.A., ed., 1981, "MSC/NASTRAN Application Manual," NacNeal-Schwendler.

Moss, L.A., and Smith, T.E., 1987, "SSME Single Crystal Turbine Blade Dynamics," NASA CR-179644.