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VIBRATION AND FLUTTER ANALYSIS OF THE SR-7L LARGE-SCALE PROPFAN

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ABSTRACT

One of the major research and technology programs at NASA Lewis Research Center is the Advanced Turboprop Program. The goal of this effort is the development of turboprop (also known as propfan) propulsion systems that would have significant gains in fuel economy over turbofans without sacrificing aircraft performance. An important phase of this program is the Large-Scale Advance Propfan Program (LAP). This program involves the development and both ground and flight testing of a complete eight-bladed, 2.7-m- (9-ft-) diameter rotor system.

The SR-7L advanced turboprop blade used in the LAP program is designed for a Mach number of 0.80 at an altitude of 10.7 km (35 000 ft). It uses a number of unique design features, such as thin, highly swept and twisted, composite material blades of low aspect ratio and high disc solidity, to improve propeller performance. Recent research efforts at Lewis have focused on these properties, particularly with respect to improved structural modeling and aeroelastic analysis of the bladed propfan assemblies. Some areas where new analytical techniques have been implemented include composite blade modeling, nonlinear displacement analysis, and three-dimensional, aeroelastic analysis.

This paper presents a structural and aeroelastic analysis of the SR-7L advanced turboprop incorporating the aforementioned techniques. Analyses were conducted for selected cases at different blade pitch angles, blade support conditions, rotational speeds, free-stream Mach numbers, and number of blades. A finite element model of the final blade design was used to determine the blade's vibration behavior and its sensitivity to support stiffness. A computer code recently developed at Lewis, which was based on three-dimensional, subsonic, unsteady lifting surface aerodynamic theory, was used for the aeroelastic analysis to examine the blade's stability at a cruise condition of Mach 0.8 at 1700 rpm. The results showed that the calculated frequencies and mode shapes obtained with this model agreed well with the published experimental data and that the blade is stable for that operating point.

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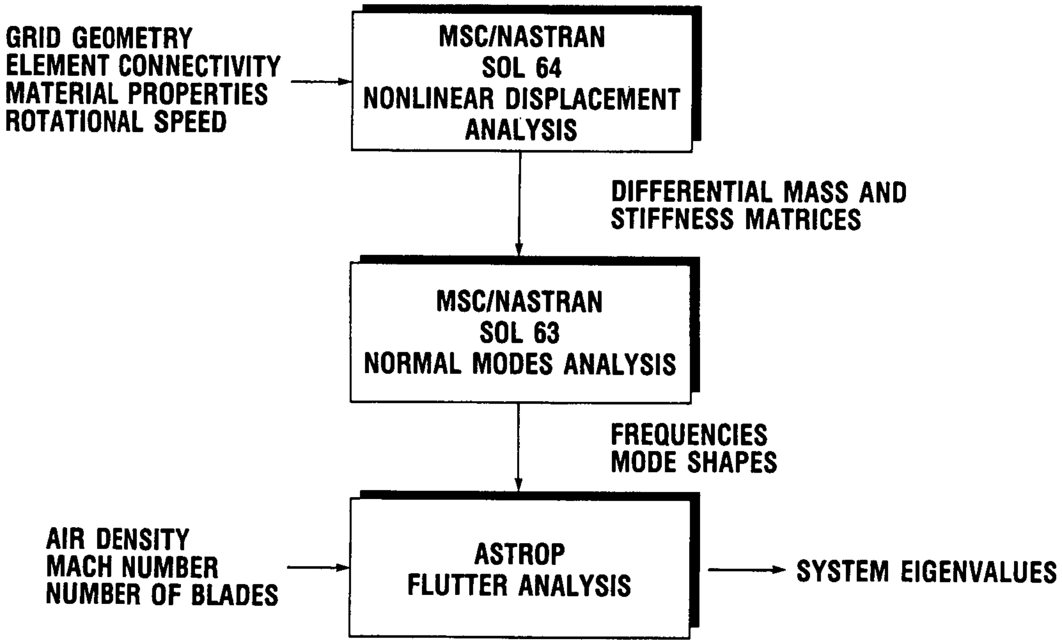
*Work performed on-site at the Lewis Research Center for the Structural Dynamics Branch.

SR-7L FLUTTER ANALYSIS DESCRIPTION

The analysis procedure consisted of using the blade's finite element model to obtain the vibration characteristics at the design rotational speed and then conducting aeroelastic studies to determine unstalled flutter stability at the design condition. The finite element code MSC/NASTRAN was used extensively to calculate the vibration characteristics of the blade using techniques suggested by Lawrence et al. (1984, 1987). The calculated frequencies and mode shapes were then used in conjunction with the computer program ASTROP (Aeroelastic STability and Response Of Propulsion Systems), a recently developed modal flutter code, for the aeroelastic stability studies (Kaza, 1987).



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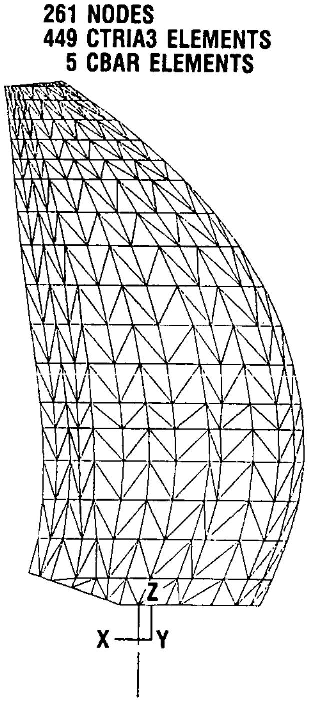
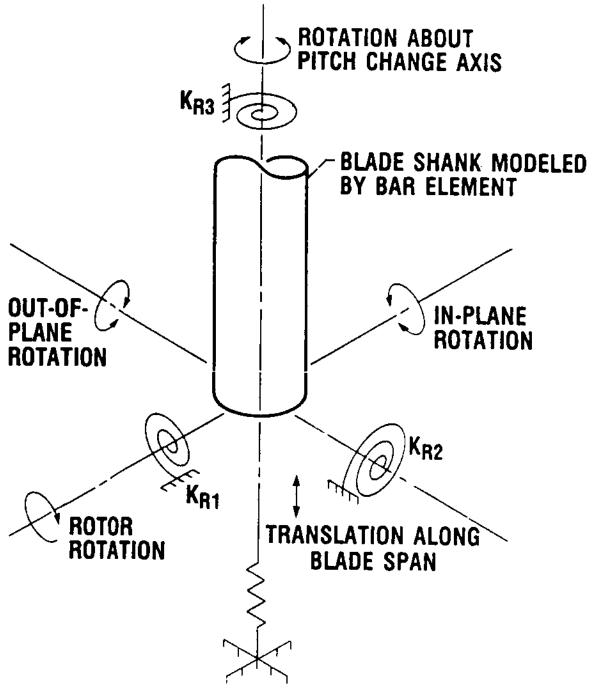
SR-7L FINITE ELEMENT MODEL DESCRIPTION

The NASTRAN finite element model used in this study is based on the final SR-7L design. The blade geometry and airfoil data were obtained from the engineering design drawings. The composite material properties were calculated by a micromechanics approach using available fiber and matrix properties obtained from actual testing of the material. Shell, adhesive, spar, and shell filler material were combined using the composite blade structure analysis (COBSTRAN) program to produce monolithic shell elements (Aiello and Chi, 1987). The finite element model has 261 nodes, 449 triangular shell elements (NASTRAN element CTRIA3), and 5 bar elements (NASTRAN element CBAR). Bar elements were used to model the blade shank. Multipoint constraint cards that couple the displacement of prescribed gird points were used to define the shank-blade interface. The blade constraints were modeled by using spring elements attached to the base of the blade shank. A total of four degrees of freedom for the shank base were allowed: translation along the pitch change axis, bending rotations in and out of the plane of rotation, and rotation about the blade's pitch change axis. The blade shank was completely fixed for translation out of the plane of rotation and normal to the blade's rotation vector and pitch change axis (Chou, S., 1986, "SR-7L Turboprop Blade Finite Element Model," Sverdrup internal communication).





SHANK CONSTRAINT MODEL SHOWING VARIOUS SUPPORT STIFFNESSES, K_R.

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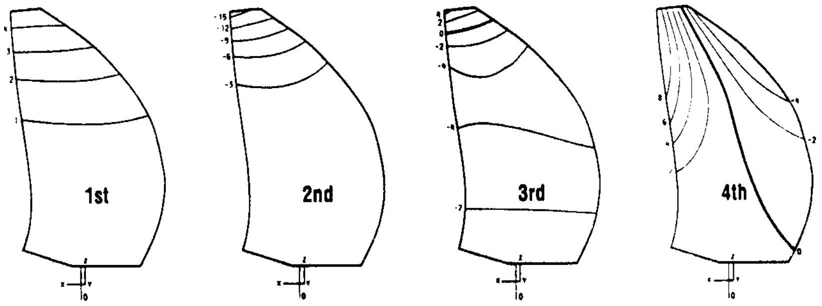
SR-7L CALCULATED MODE SHAPES AND FREQUENCIES

Since aeroelastic analyses are sensitive to blade frequencies and mode shapes, it is important that the blade finite element model and analysis accurately reflect the blade's modal characteristics. To establish the validity of the finite element blade model, it was necessary to show that calculated frequencies agreed well with experimental values. Consequently, frequencies and corresponding mode shapes were calculated at 1200 rpm over a range of blade setting angles from 35° to 60°, and were compared with those given by Turnberg (1986 handout of SR-7L test results distributed at the Advanced Turboprop Workshop, NASA Lewis Research Center). It should be noted that the calculated frequencies do not include the effect of steady airloads.

The blade's first mode is seen to be predominantly a first bending mode with no nodal lines and fairly evenly spaced contours in the upper half of the blade. The second mode is predominantly a first edgewise mode, with most of the motion occurring near the tip in the chordwise direction. The third mode can be classified as the second bending mode since there is a generally chordwise nodal line near the tip. The fourth mode can be classified as the first torsion mode since there is a midchord nodal line.

CONTOUR PLOTS



FIRST BENDING 38.10 Hz

FIRST EDGEWISE 86.89 Hz

SECOND BENDING 101.0 Hz

FIRST TORSION 160.9 Hz

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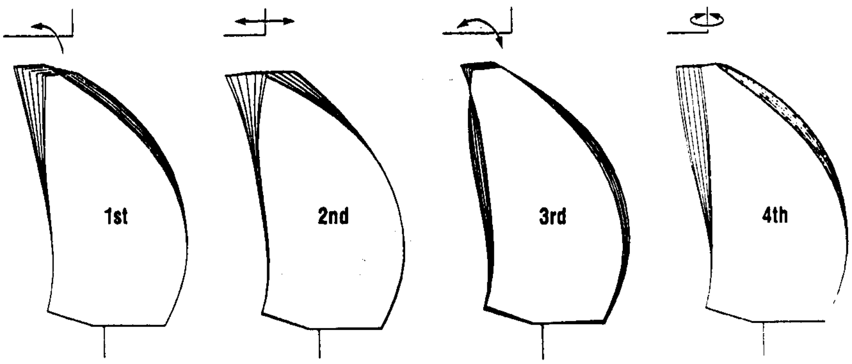
"ANIMATED" MODE SHAPES



FIRST BENDING

FIRST EDGEWISE

SECOND BENDING

FIRST TORSION

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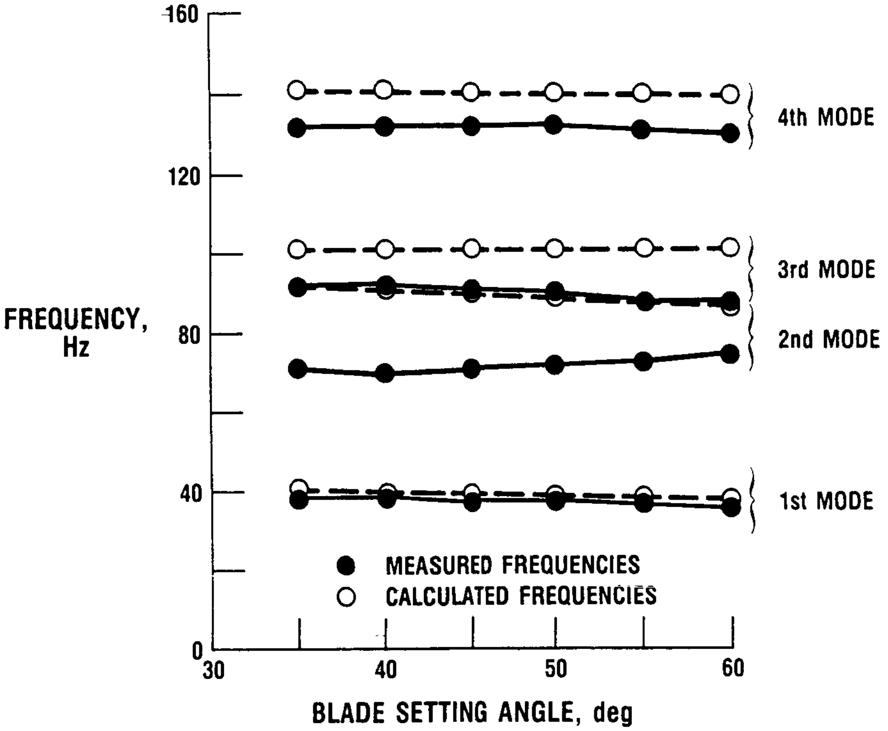
ACCURACY OF CALCULATED SR-7L FREQUENCIES

A comparison of the measured and calculated frequencies shows that there is very good agreement for the first mode (i.e., first bending) over the entire range of blade setting angles. A comparison of the fourth mode frequencies (i.e., first torsion) similarly shows acceptable agreement. However, there is not a good match on the second mode, first edgewise, nor on the third mode, second bending. For both cases, the calculated frequencies were higher than the measured frequencies.



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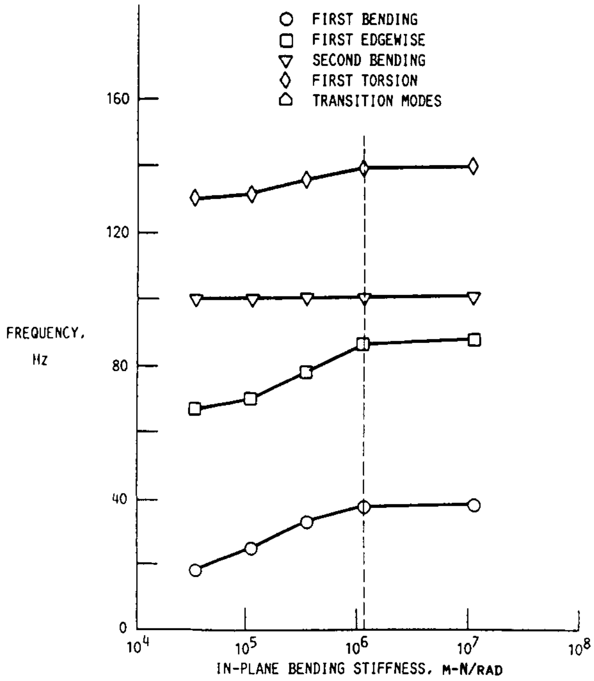
SR-7L CALCULATED FREQUENCIES VERSUS SUPPORT STIFFNESS

The values suggested by Sullivan et al. (1987) for the original model of the blade support stiffnesses were used to make parametric runs to examine the effect of varying these stiffnesses on natural frequencies and mode shapes. Each stiffness value was varied individually while the other values were held constant. Variation of the in-plane bending rotation support stiffness K_{R1} had little effect. The first two modes did have noticeable changes, but only over three orders of magnitude of stiffness changes. The pitching axis support stiffness K_{R3} and spanwise translational support stiffness had virtually no effect on the frequencies. However, the out-of-plane bending rotation support stiffness K_{R2} greatly affected the frequency values for the first edgewise mode. Frequencies for the first and second bending modes and for the first torsional modes were relatively unaffected. The edgewise mode could be selected to be the second, third, or fourth mode, depending on the out-of-plane bending stiffness value.



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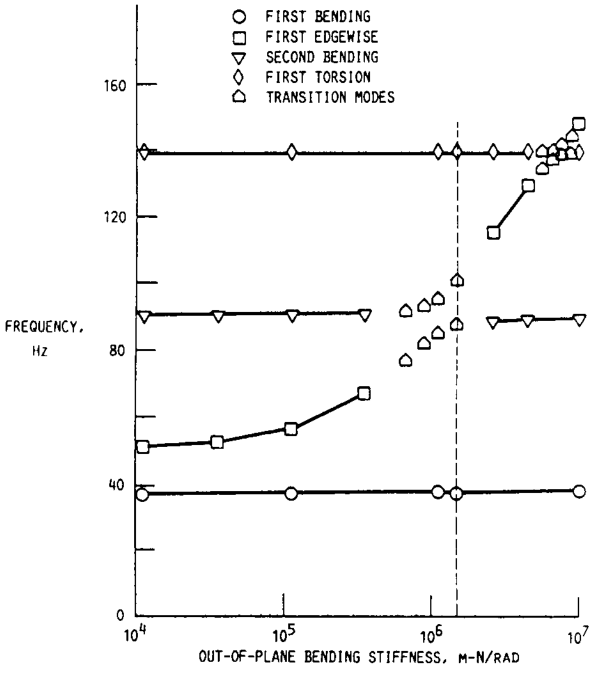

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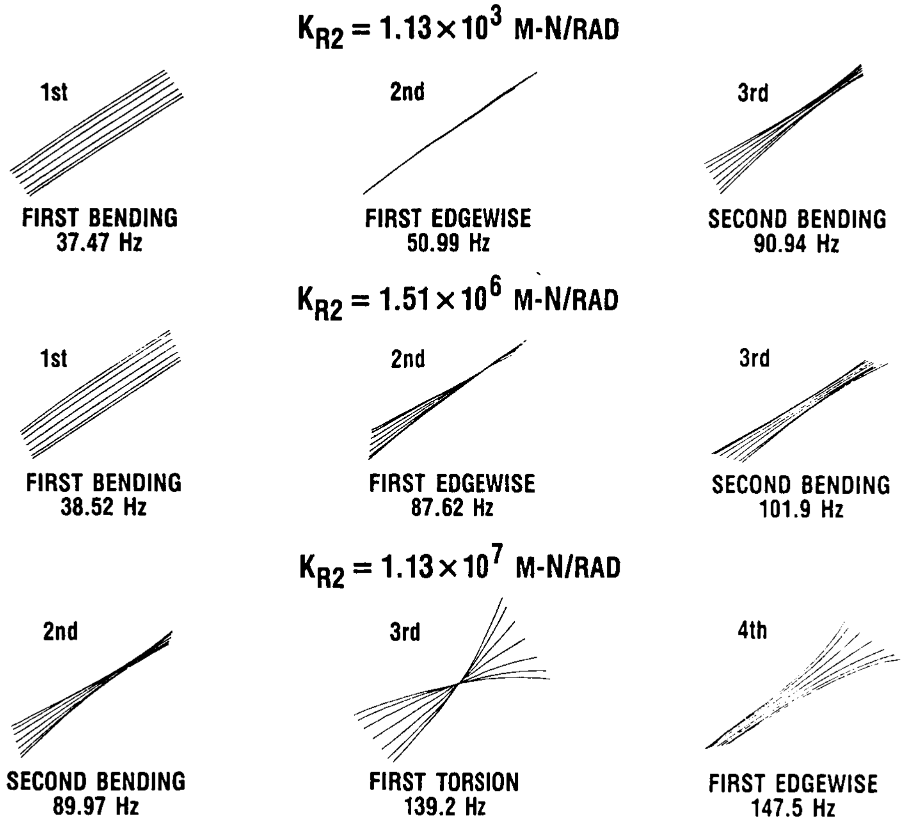
SR-7L BLADE MODAL DISPLACEMENTS VERSUS SUPPORT STIFFNESS

Examining the three-quarters radius chord modal displacement as viewed down the blade span helps characterize the mode shape. For relatively low values of K_{R2}, the second mode is clearly the first edgewise mode since the motion is nearly all in the chordwise direction. The first and third modes can be characterized as the first and second bending modes from the amount of blade normal displacements. The second mode from the first crossover region (K_{R2} = $1.514\text{x}10^6$ m-N/rad) still has a fair degree of chordwise motion, although the leading edge area does have a some blade normal motion. Note that the third mode now also contains a degree of chordwise motion. At the second crossover region (K_{R2} = $1.13\text{x}10^8$ m-N/rad), the second mode can be classified a bending mode because of the predominate blade normal displacements. The third mode is clearly the first torsional mode, whereas the fourth mode appears to be the first edgewise mode because of the chordwise motion at the leading edge.

The originally suggested values for K_{R2} cause the second and third modes to occur in a transition region between the first edgewise and second bending modes. This helps to account for the difference between the experimental and calculated second and third mode frequencies. The experimental edgewise mode is much lower than the calculated one, reflecting that mode's strong sensitivity to the support stiffness. The narrow range of values for the calculated second and third modes, and even for the experimental third mode, also illustrate the effect of the support stiffness within the crossover region.



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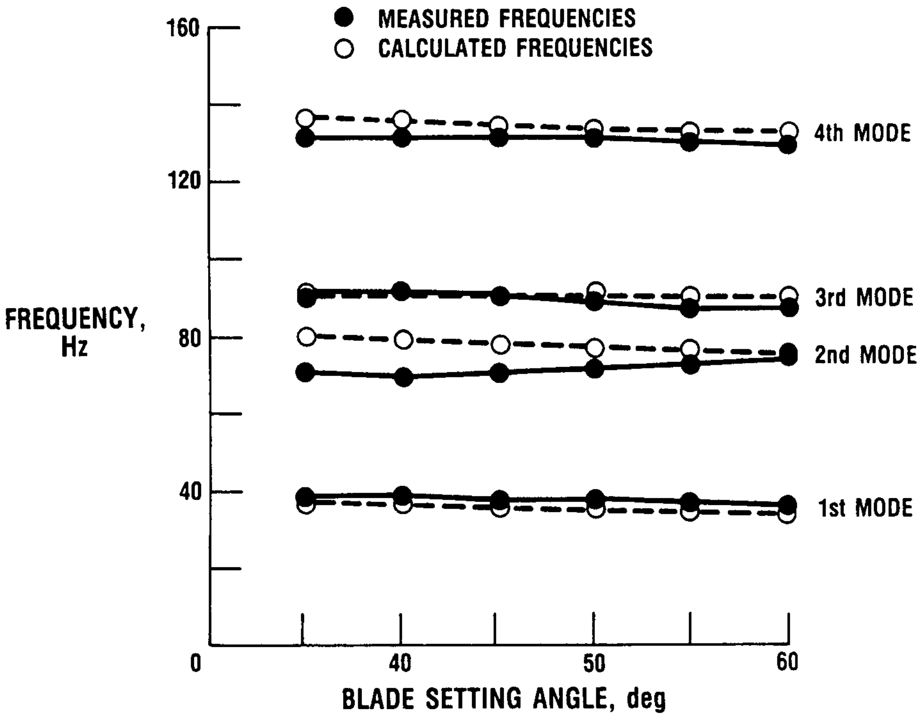
SR-7L CALCULATED FREQUENCIES VERSUS TUNED SUPPORT

From the parametric studies, values for the support stiffnesses were selected so that a "tuned support" model was developed. This was done in an attempt to give the best overall agreement between the calculated and measured frequencies. It was decided to try to soften the support stiffnesses since the edgewise, second bending, and torsional frequencies were too high. The value of K_{R1} was chosen at 4.52×10^5 m-N/rad because this seemed to be the minimum value above which there were very little changes in the blade frequencies. The value of K_{R2} was chosen slightly lower at 9.04×10^5 m-N/rad because this was the value that gave the best agreement with the experimental edgewise mode without greatly affecting the other three modes. Since the K_{R3} value seemed to have very little effect on the frequencies, it was purposely chosen to be very low (1.13×10^2 m-N/rad). The effect of the softer support springs are immediately evident. The first mode frequencies are slightly lower. However, the second, third, and fourth modes show much better agreement than before, especially near the operational blade setting angle of 58°.



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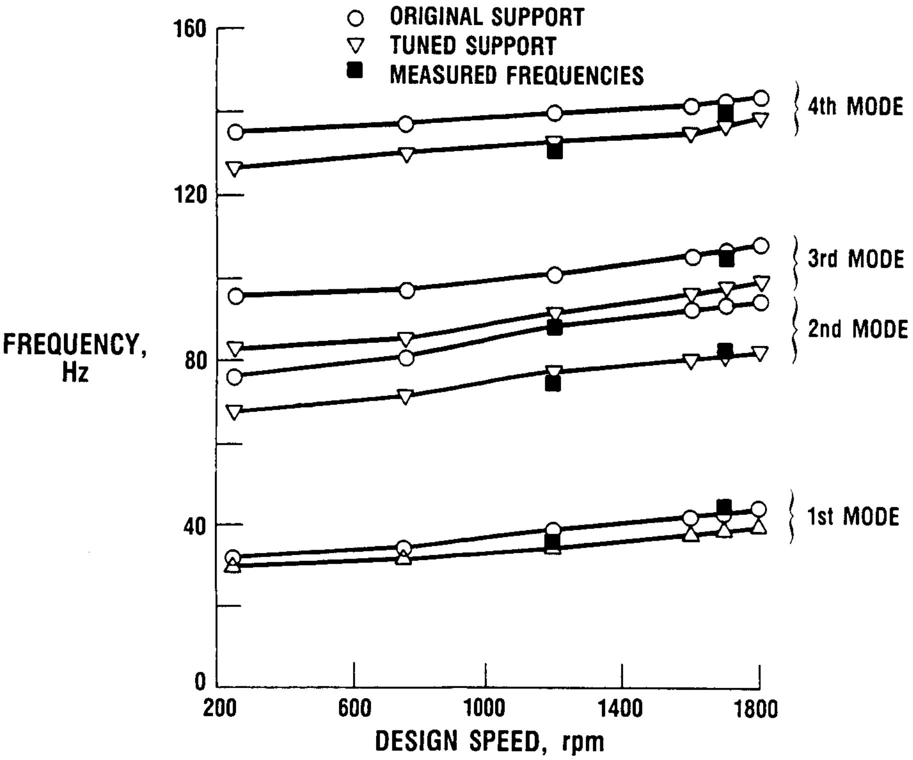
SR-7L CALCULATED FREQUENCIES VERSUS DESIGN SPEED

Parametric studies using the two models were done to examine the effect of rotating speed on natural frequencies for the two models. Because of the softer support, frequencies for the tuned model are generally slightly lower (<10 percent) than for the original model. For the three modes that most affect flutter, first torsion and first and second bending, there is generally better agreement between calculated and measured results at the design speed (1700 rpm) using the original model. Conversely, at 1200 rpm, the tuned, softer support showed better agreement.

A possible explanation for the difference is that at the higher speed the blade shank had seated itself better, resulting in a stiffer support. This is supported by the fact that the measured frequencies showed a greater degree of change between the two test speeds than the frequencies calculated by either of the finite element models. This type of nonlinear support would be impossible to model accurately over a wide range of speeds using linear spring elements.



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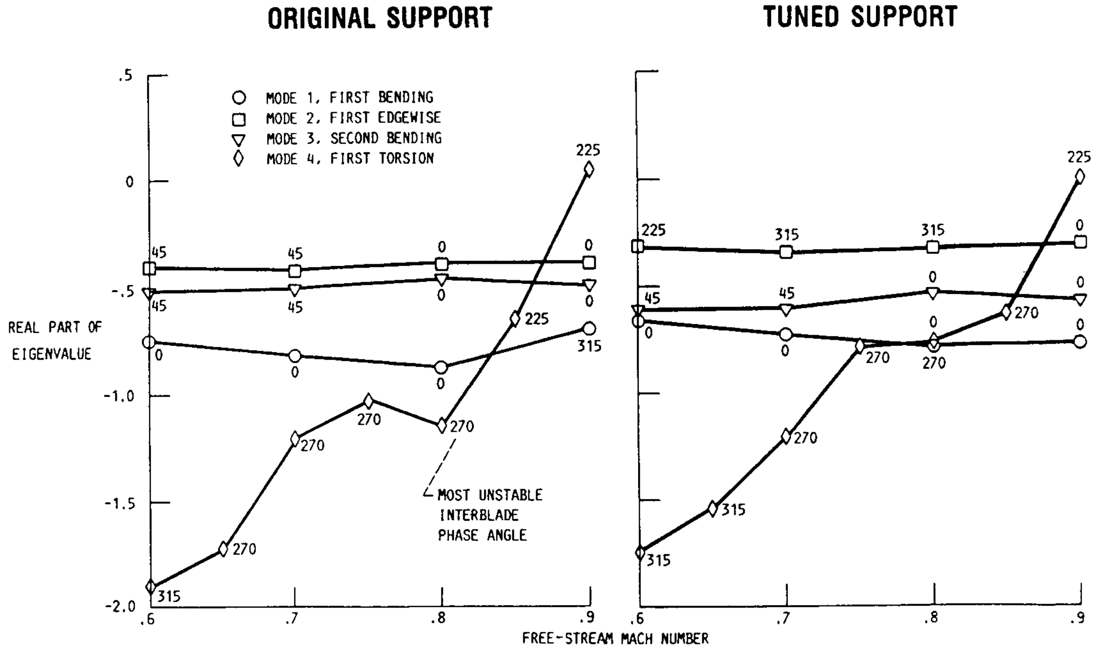
The modal flutter code ASTROP3 was used to calculate the aerodynamic damping. This code is a normal mode analysis method that was developed for the analysis of propulsion blading. It is based on three-dimensional, subsonic (the Mach number of relative flow is less than unity), unsteady aerodynamics as described by Williams and Hwang (1986). However, for the SR-7L configuration at a design free-stream Mach number of 0.80 and a rotational speed of 1700 rpm, the Mach number of relative flow at the tip is greater than one. To calculate the unsteady aerodynamics for supersonic Mach numbers, Kaza et al. (1987) have further extended the aerodynamic model.

The cascade aeroelastic stability is determined by solving the eigenvalue problem for the dynamic system. System damping and damped frequency are represented by the real and imaginary parts of the complex eigenvalue, respectively. Flutter occurs when the real part of the eigenvalue is greater than zero. Aerodynamic damping at the design speed is predicted as a function of free-stream Mach number. Aerodynamic damping values for free-stream Mach numbers greater than 0.8 were also calculated and included so that the available flutter margin for the SR-7L propfan could be estimated. The values shown are for the most unstable SR-7L interblade phase angles for both the original and tuned support condition, respectively. The blade was stable for both cases at the design point of Mach 0.8 and 1700 rpm at an altitude of 10.66 km (35 000 ft). There was also very little difference in the most unstable interblade phase angle identified. The predicted values are considered to be conservative, since neither material nor friction damping due to the hub constraint has been included in the analysis. Additional system damping would only have a stabilizing effect. From these results, it is concluded that the SR-7L propfan is free from flutter at the design point.


ORIGINAL SUPPORT

TUNED SUPPORT

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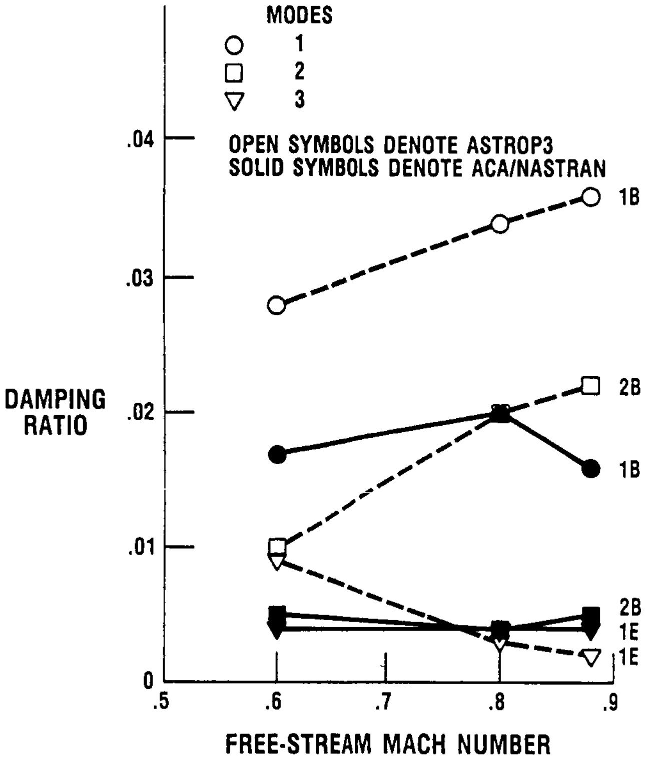
COMPARISON WITH A TWO-DIMENSIONAL AEROELASTIC CODE

The ASTROP3 damping ratio results for the original stiffness model were compared with those given by Hirschbein et'al. (1987). That study used a modal flutter aerocode solver, ACA, available in COSMIC/NASTRAN. The ACA code utilizes the two-dimensional, subsonic cascade aerodynamic theory of Jones and Rao applied in a strip theory manner (Elchuri et al.,1985). The calculated damping values are qualitatively similar: the first mode being much more stable than either the second or third modes, and the third mode showing the least damping. A direct comparison of the values for the critical damping cannot be made because of differences in the aerodynamic theories used, as well as two slightly different blade designs. The finite element blade model used by Hirschbein is based on a preliminary blade design and has higher third and fourth mode (second bending and first torsion) frequencies, 111.6 and 160.7 Hz versus 97.9 and 137.0 Hz, respectively, than the final blade design.



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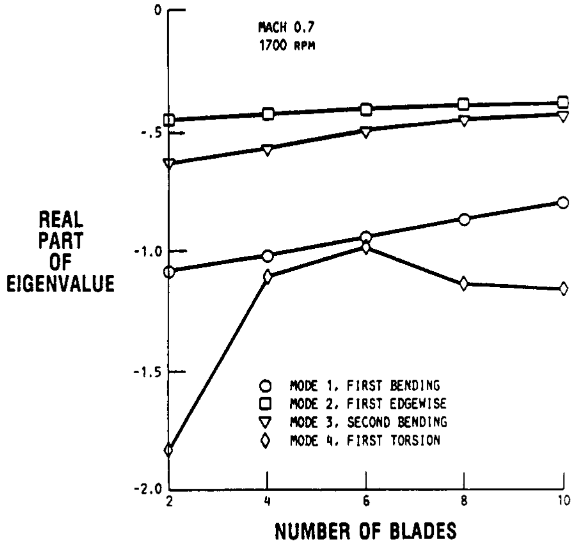
CASCADE EFFECTS ON SR-7L STABILITY

To illustrate the effects of cascade aerodynamics on flutter, parametric studies were made varying the number of blades in the propfan assembly. The effect of the number of blades on modal damping is significant, with the first and third mode aerodynamic damping decreasing by 25 and 16 percent, respectively. The destabilizing influence of the cascade effect is demonstrated as the least stable interblade phase angle shifts to the right with increased blading. The critical frequency is also reduced with increased blading.

AT DESIGN POINT



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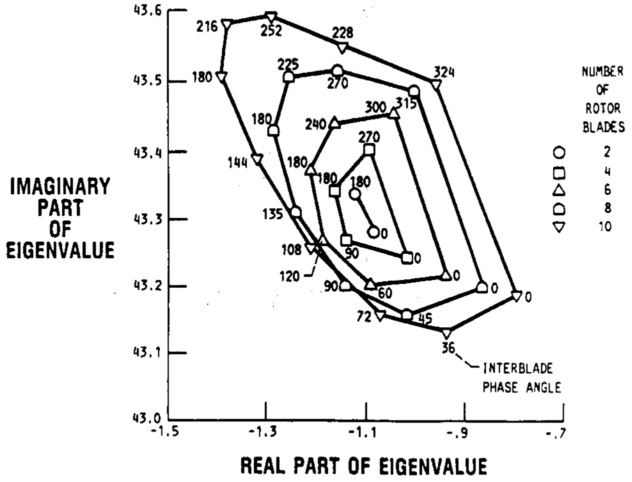
MODE-1 ROOT LOCUS PLOT WITH CASCADE EFFECTS



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SUMMARY OF RESULTS

1. Bending and torsional frequencies were generally insensitive to the support stiffness used. However, the blade edgewise frequencies were particularly sensitive to the out-of-plane support stiffness used.

2. With the exception of the edgewise mode, there was generally good agreement between calculated and experimental frequencies at the design speed. From the available test information, it appeared as if the blade hub constraint stiffness acted in a nonlinear manner with respect to rotational speed. This made it difficult to model the blade constraint condition with linear spring elements over a wide range of speeds.

3. The blade was stable at its design point of Mach 0.8 and 1700 rpm at an altitude of 10.66 km (35 000 ft). The analysis did not consider any structural damping, which would have a beneficial effect on stability.

4. Some components of the blade support stiffness values had little effect on the calculated aerodynamic damping. This would imply that modeling efforts should be concentrated most on matching the in-plane and out-of-plane bending stiffnesses and obtaining reasonably close values (within 10 percent) for the bending and torsional modes.

5. Cascade effects were found to be considerable at the design point for configurations from 2 to 10 blades, although an increase in the number of blades from 8 to 10 did not cause an instability for the configuration analyzed.

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