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PROPFAN MODEL WIND TUNNEL AEROELASTIC RESEARCH RESULTS

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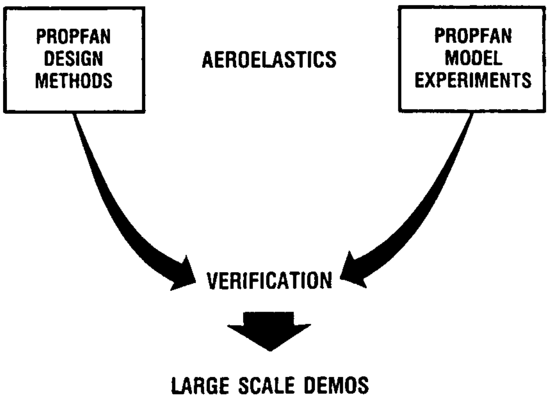
ABSTRACT

The propfan offers the excellent propulsive efficiency of the conventional turboprop, but extended out to flight speeds from Mach 0.7 to 0.8. It is the thinness and sweep of propfan blades which provide the aeroacoustic gains of the propfan over lower sweep conventional turboprops. The aeroacoustic requirements of propfans also have resulted in twisted blades of low aspect ratio and high solidity, operating in high subsonic and transonic flow conditions. Then, the structural requirements of propfans have resulted in blades made of composite materials. All these characteristics make the structural design of propfans more complex than that of conventional propellers. To develop reliable technology for the structural design of these advanced propellers NASA has been conducting both experimental and analytical research in aeroelastics. This research is addressing the unconventional structural and aerodynamic characteristics of advanced propellers and is being used to improve existing and develop new aeroelastic analyses.

This short article will describe some of the single rotation propfan model wind tunnel aeroelastic findings from the experimental part of this research program. These findings include results for unstalled or classical flutter, blade response from separated flow excitations, and blade response from aerodynamic excitations at angled inflow conditions. A more comprehensive and detailed explanation of the experimental results that are given in this article can be found in the references.

PROPFAN AEROELASTIC TECHNOLOGY DEVELOPMENT

The development of propfan aeroelastic technology is being accomplished by developing theoretically based design methods and conducting propfan model experiments. As shown schematically on top, this combination is being used successfully to verify that reliable propfan design methods are developed. The research areas being investigated include flutter and aerodynamic forced excitation. The bottom figure illustrates the flight conditions where these phenomena usually are of concern. For separated flow excitations, it is at zero and low flight speeds, at operating conditions of high forward and reverse thrust. For unstalled or classical flutter, it is at high flight speeds. Whereas, for forced excitations due to angled inflow and the other sources shown, it is at both low and high flight speeds.



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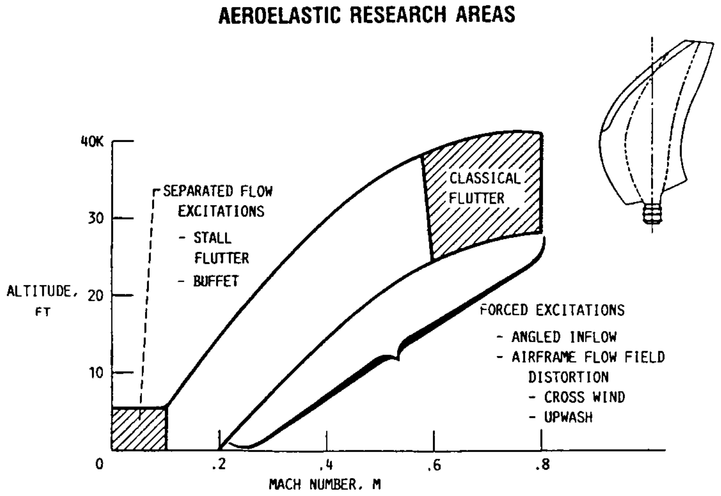

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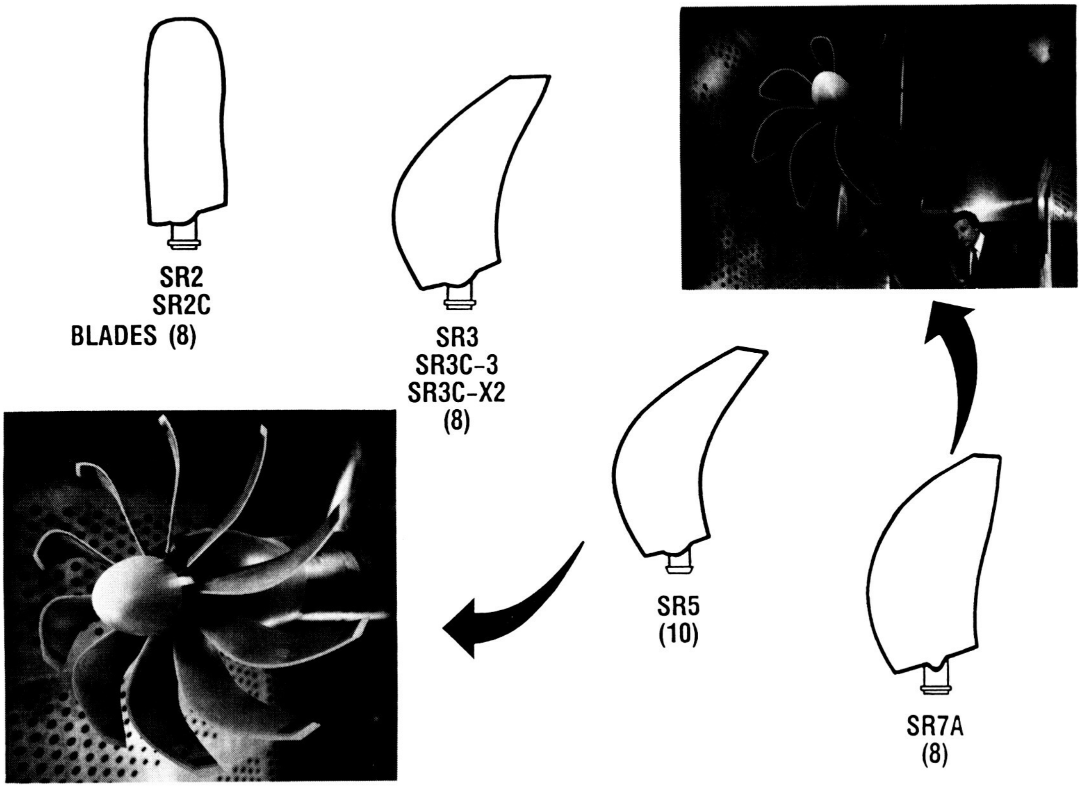
PROPFAN MODELS USED FOR AEROELASTIC EXPERIMENTS

Aeroelastic research experiments were started in 1981 with single rotation (SR) propfan models. Shown below are some of the blade shapes that have been used and wind tunnel installation photos of two of the models. All the models are of two foot rotor diameter. The SR2, SR3, and SR5 blades are made of metal, and have 0, 45, and 60 degrees of geometric tip sweep, respectively. The SR2C and the SR3C blades have the same geometry as the corresponding metal blades but are made of graphite/epoxy material. More will be said about the SR3C blades on the next page. The SR7A blade is the first aeroelastic propfan model to be designed and tested. It has the same structural dynamics and aerodynamics as a nine foot diameter propfan demo blade that was flight tested in April, 1987. The SR7A blade consists of a metal spar, for the blade shank and core, and a composite shell over the spar. This construction is similar to that of the nine foot demo blade. All together we have competed about 1000 hours of wind tunnel aeroelastic SR model tests.



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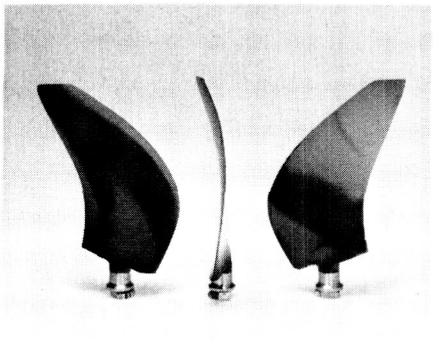
TAILORED AEROELASTIC DESIGN WITH COMPOSITE MATERIAL

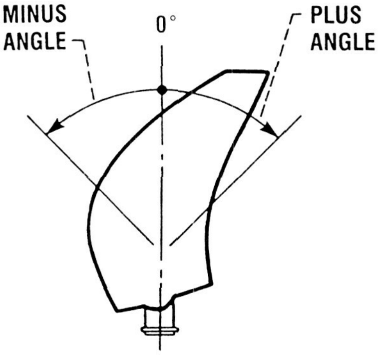
The SR3C-X2 blade was designed to flutter and the SR3C-3 blade was designed to be stable. The use of composite material for the blade construction made these tailored aeroelastic designs possible. Both blades are made from a layered buildup of graphite/epoxy unidirectional tape or ply material. The two models are identical except for the orientation of some of the plys. The figure illustrates how the blades differed in construction. The ply fiber direction variation provided a difference in stiffness and mode shapes between the blades. Both models were wind tunnel tested and performed as designed. Some of these test results are given on the following pages.

SR3C BLADE SHAPE



PLY DIRECTIONS

MODEL	PLY DIRECTION	PERCENT TOTAL PLYS
SR3C-3	0° ±45°	80 20
SR3C-X2	0° ±22½°	80 20



PLY DIRECTION VARIATION

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STIFFNESS, MODE SHAPE VARIATION

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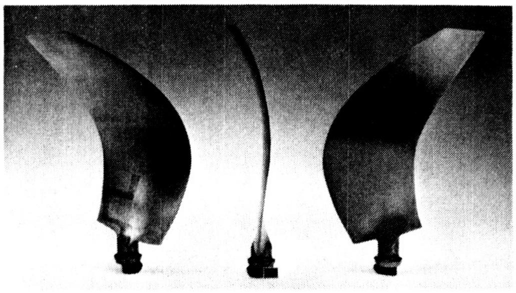
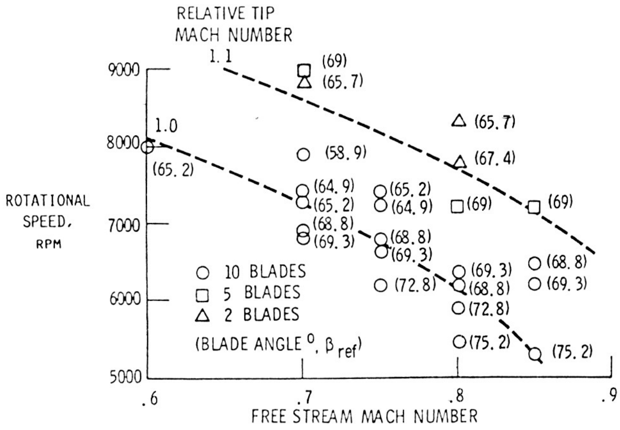
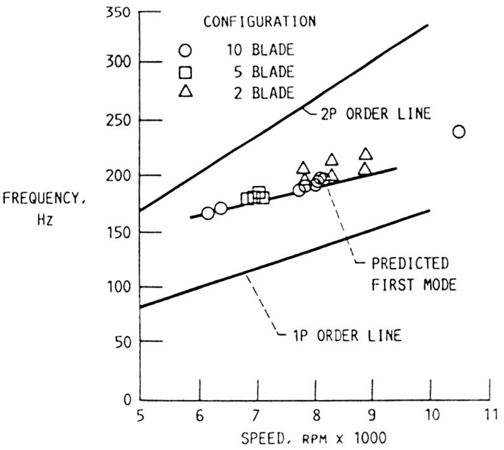
SR5 MODEL FLUTTER CHARACTERISTICS

The first experience with propfan unstalled (classical) flutter occurred unexpectedly at the Lewis 8 x 6 - Foot Wind Tunnel with the highly swept SR5 model. No flutter was experienced with the less swept SR2 and SR3 models during similar aerodynamic tests previously completed. When the flutter was discovered it was not understood. So the SR5 test was then redirected to investigate what type of flutter was occurring and what factors were causing the blade to flutter. Strobed video pictures taken during flutter showed a coupled bending and torsion motion occurring. At flutter the blade strain gage signals indicated the blades locked into a system mode, vibrating at a common frequency and with a common phase angle between blades. From the measured flutter conditions, shown in the figure on the left, the following is observed. A decrease in stability occurred both with an increase in blade number and an increase in blade pitch angle. The flutter occurred at relative tip Mach numbers of about one, and at conditions of both high and low blade loading, including windmilling. The test data and analytical studies led to the conclusion that it was classical flutter, and that the aerodynamic coupling between blades, known as cascade effects, and blade sweep had to be included in propfan flutter analysis. The figure on the right shows the measured flutter frequency variation with rotational speed. The measured flutter frequencies fell very close to the predicted first natural blade mode frequencies.





MEASURED FLUTTER CONDITIONS



MEASURED FLUTTER FREQUENCY

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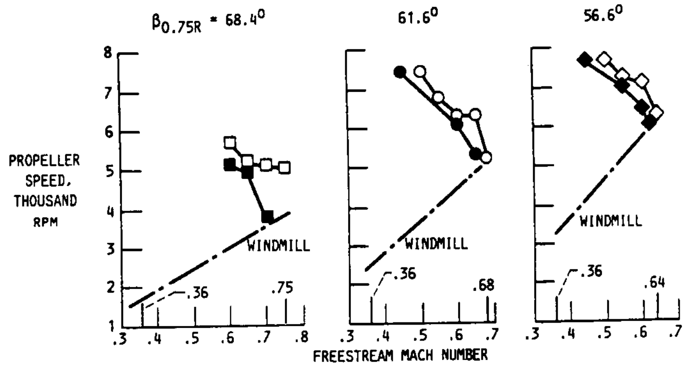
SR3C-X2 MODEL FLUTTER CHARACTERISTICS

After the SR5 flutter experiment another flutter experiment was planned and conducted to validate new flutter analyses that had been developed (Mehmed, 1982; Elchuri, 1983; Turnburg, 1983) at NASA and industry. The SR3C-X2 model, described earlier, was intentionally designed to flutter at subsonic relative velocities for this experiment. The figures below give some of the measured flutter results. The trends shown in the top and lower left figures agree with those found with SR5. That is, a decrease in stability occurs with an increase in blade number and with increasing blade angle. Note, as with SR5, the flutter here also occurred at the windmilling condition. Not shown, but reported by Mehmed and Kaza (1986), the flutter occurred at relative tip Mach numbers between 0.77 and 0.86 with eight blades, and between 0.80 and 0.90 with four blades. The lower right figure shows the flutter frequency for SR3C-X2 was between the predicted first two blade natural modes. It was seen on the previous page that the SR5 flutter frequency was much closer to the first natural blade mode. This difference is due to the larger blade-to-air mass ratio of SR5 than SR3C-X2, 115 and 33, respectively. The flutter data from the SR3C-X2 model provided validation of and confidence in the classical flutter analyses developed for propfans after the SR5 flutter experiment.

MEASURED FLUTTER CONDITIONS

OPEN SYMBOLS DENOTE 4 BLADES IN ROTOR
CLOSED SYMBOLS DENOTE 8 BLADES IN ROTOR



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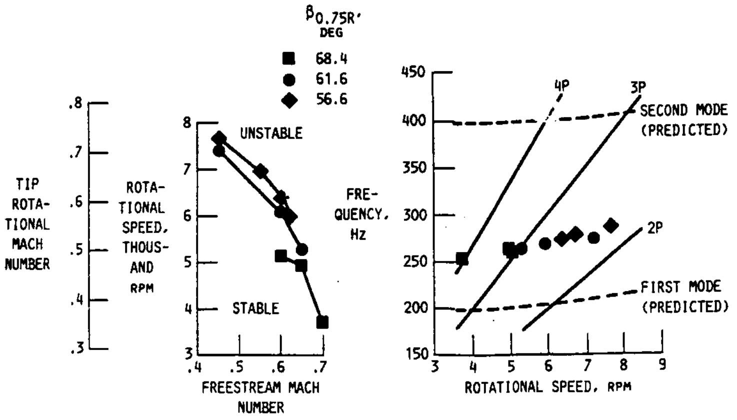
MEASURED FLUTTER CONDITIONS
8 BLADES IN ROTOR

MEASURED FLUTTER FREQUENCIES
8 BLADES IN ROTOR



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CLASSICAL FLUTTER - PERSPECTIVE

The classical flutter phenomenon discovered with a very highly swept propfan model, SR5, was fortuitous. It led to the development of reliable classical flutter analyses for propfans. Both the SR7 aeroelastic model and the large scale demo propfan have been operated without flutter, as indicated in the chart. Another flutter experiment with a counter rotation (CR) model has recently been completed at Lewis, and will help the development of flutter analyses for CR propfans.

CLASSICAL FLUTTER-PERSPECTIVE

- DISCOVERED WITH SR5
- NEWLY DEVELOPED FLUTTER ANALYSES VERIFIED WITH SR3C-X2 AND SR3C-3
- SR7 AEROELASTIC MODEL (2-FT DIAMETER) CLEARED TO 0.9 MACH AT LEWIS
- SR7 DEMO BLADE (9-FT DIAMETER) CLEARED TO 0.83 MACH AT MODANE AND TO 0.89 MACH AT 28,000 FT IN FLIGHT
- FLUTTER EXPERIMENT WITH A CR MODEL COMPLETED AT LEWIS (DEC. 1987)
  - TO INVESTIGATE THE IMPORTANCE OF ROTOR INTERACTIONS ON CLASSICAL FLUTTER

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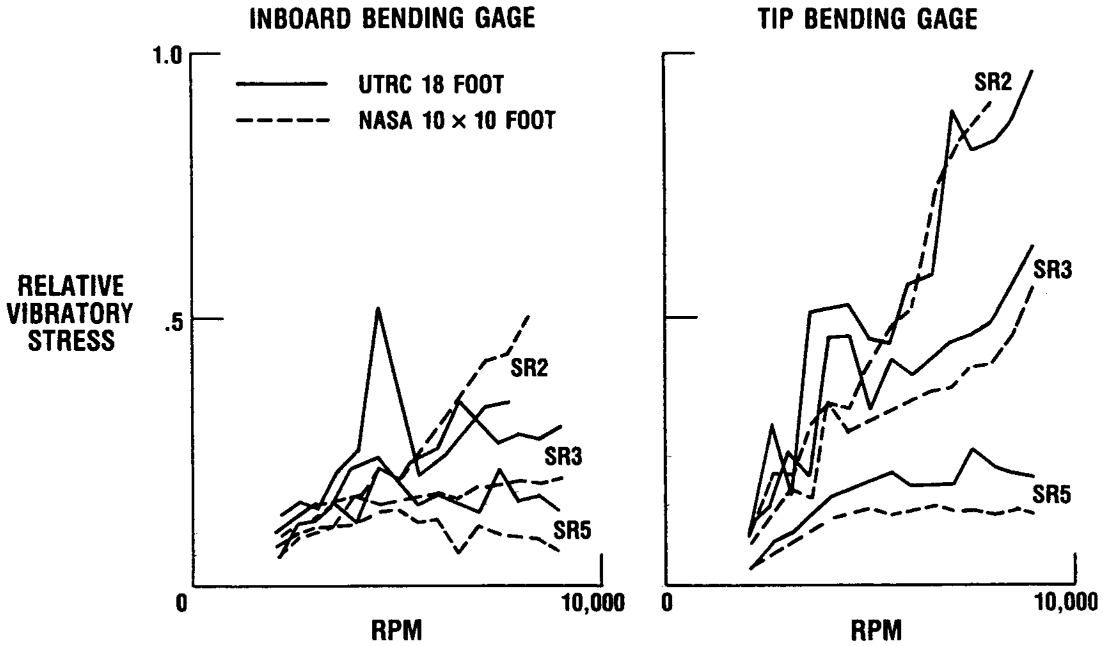
PROPFAN BLADE VIBRATIONS IN RESPONSE TO SEPARATED FLOW AT ZERO FORWARD VELOCITY

The figures below display vibratory response strain gage data for three propfan models of different sweep. The excitations are from separated flow excitations and critical speeds. The test conditions are zero forward velocity, zero thrust axis tilt, and a blade setting angle of 32 degrees. The left and right figures show bending stress data measured at blade locations inboard and near the tip, respectively. Also, data from two different facilities are compared in each figure. It is seen that the straight blade model (SR2) has the largest response, the next higher sweep model (SR3) has a lower response, and the most highly swept model (SR5) has the lowest response. This trend agrees at both blade measurement locations. The data from the two facilities shows good consistency.

PROPFAN BLADE VIBRATIONS IN RESPONSE TO SEPARATED FLOW AT ZERO FORWARD VELOCITY

Mach no. = 0, no tilt, $\beta_{ref} \sim 32°$



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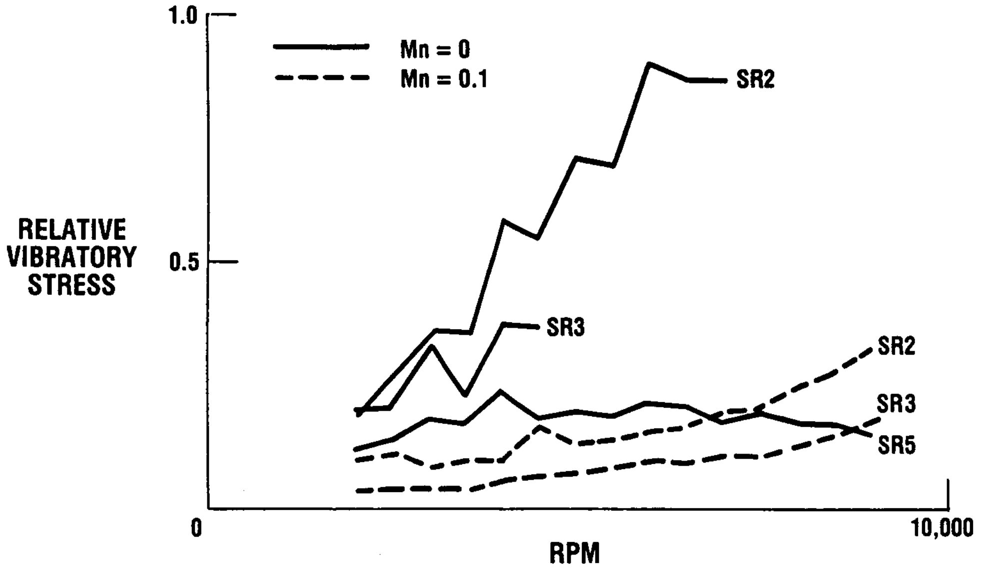
PROPFAN BLADE VIBRATIONS IN RESPONSE TO SEPARATED FLOW WITH FORWARD VELOCITY

This figure is similar to the one on the previous page, except it shows the effect of forward velocity on blade vibratory response. The figure compares the blade response at forward velocities of 0 and 0.1 Mach, for a blade setting angle of 36 degrees. It is seen at both velocity conditions that the swept blades have a lower vibratory response than the straight blades, and that a significant decrease in blade stress occurs with forward velocity. This is expected, since forward velocity causes a decrease in the blade angle of attack and a corresponding decrease in separated flow.

PROPFAN BLADE VIBRATIONS IN RESPONSE TO SEPARATED FLOW WITH FORWARD VELOCITY

NO TILT, $\beta_{ref} \sim 36°$, NASA 10 × 10 FOOT, INBOARD BENDING GAGE



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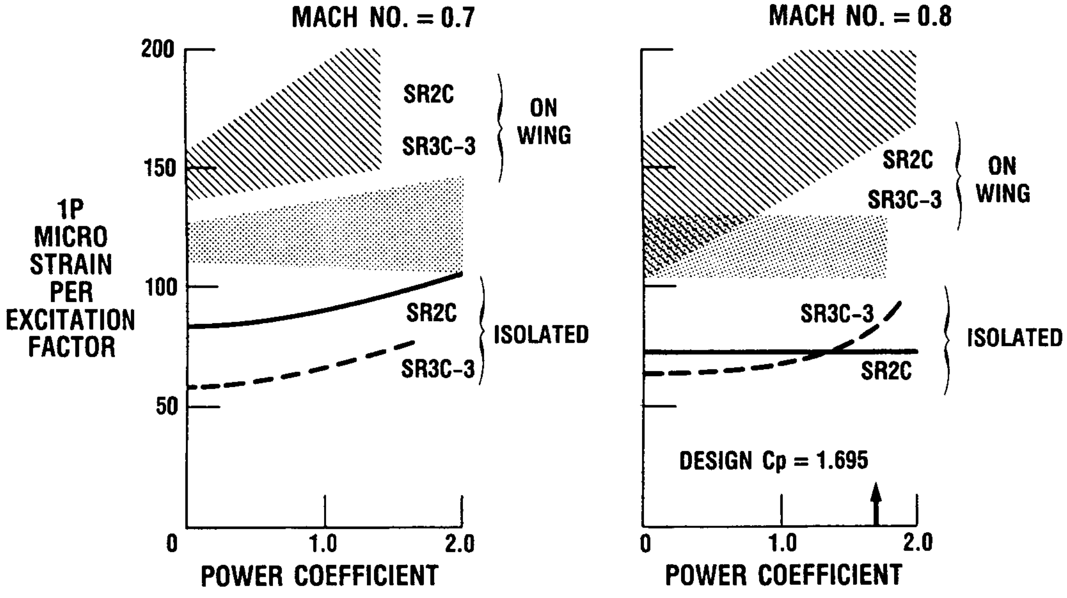
SR2C AND SR3C PROPFAN FORCED RESPONSE IN ANGLED FLOW

The figures show the measured 1P strain sensitivity variation with power coefficient for the straight SR2C and the swept SR3C-3 composite propfan models. The measurements were made with the propeller thrust axis inclined to the freestream, both in an isolated nacelle and on a wing in a tractor configuration. Strain sensitivity is defined as the amplitude of the 1P strain component per unit excitation factor. Excitation factor (E.F.) is proportional to the product of the thrust axis tilt and the freestream dynamic pressure, and the 1P strain component varies linearly with both of these parameters. The figures show that the installation on the wing causes a greater blade response than the isolated configuration. This is due to the increased angular inflow into the propeller rotor from the wing flowfield. The figures also show that the swept blade has less strain sensitivity than the straight blade at most of the operation conditions.

SR2C AND SR3C-3 PROPFAN FORCED RESPONSE IN ANGLED FLOW

ISOLATED AT NASA—LEWIS 8 × 6 FOOT
ON WING AT NASA—AMES 14 FOOT



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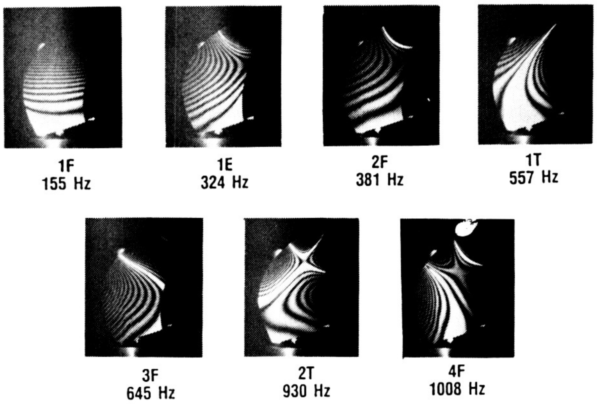
SR7A MEASURED NATURAL FREQUENCIES AND MODE SHAPES

The bench measured natural frequencies and corresponding hologram photos of the natural mode shapes of a SR7A aeroelastic model blade are shown in the figure on top. The whitest fringes represent nodes and the black fringes represent constant displacement contours. All the modes involves a coupling of the flatwise, edgewise, and torsion motion, but the mode is identified by its predominant component of motion. The measured natural frequency variation with rotational speed is shown in the bottom figure for a blade angle at 3/4R of 32 degrees. Calculated natural frequencies using MSC NASTRAN for a blade angle of 57.6 degrees are also shown. The analytical model is slightly stiffer than the actual blade for the 1E and the 2F modes, and stiffer yet for the 1T mode, but less stiff for the 1F mode at the high rpm point.

BENCH MEASURED

BLADE SERIAL NUMBER 15



1F 155 Hz; 1E 324 Hz; 2F 381 Hz; 1T 557 Hz

3F 645 Hz; 2T 930 Hz; 4F 1008 Hz

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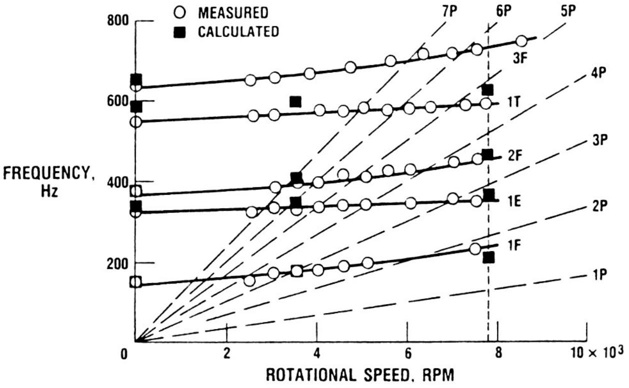
SR7A MEASURED NATURAL FREQUENCIES

LEWIS 9 × 15 WIND TUNNEL AND BENCH



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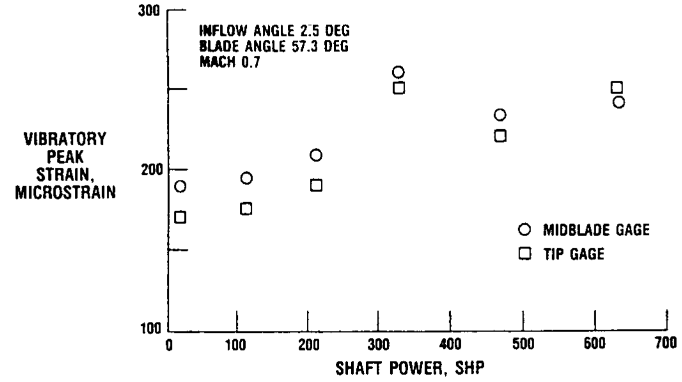
SR7A PROPFAN MODEL FORCED RESPONSE IN ANGLED INFLOW

The SR7A aeroelastic model had no classical flutter and the blade vibratory response followed expected trends. The top figure shows the total vibratory peak strain amplitude variation with shaft power for an isolated nacelle configuration. The strains show a linear increase with power for both the mid-blade and tip bending gages, except at 325 shp. These points at 325 shp are near the 1E/3P critical speed crossing and have a significant 1E amplitude component. The 1P strain is the major component of the total vibratory strain at the other conditions. The bottom figure shows the 1P vibratory strain sensitivity (defined on the previous page) with shaft power. The greatest strain sensitivity occurs at the lowest Mach number (0.6). The strain sensitivity increases with shaft power but at Mach 0.6 it falls after an initial rise.

TOTAL VIBRATORY PEAK STRAIN AMPLITUDE VARIATION WITH SHAFT POWER

SR7A PROPFAN 8 × 6 WIND TUNNEL



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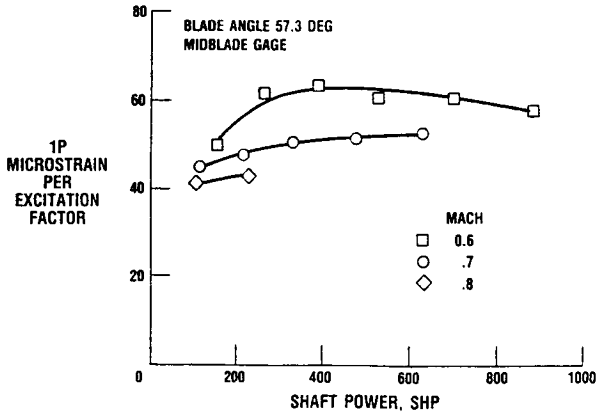
1P VIBRATORY STRAIN SENSITIVITY VARIATION WITH SHAFT POWER

SR7A PROPFAN 8 × 6 WIND TUNNEL



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SUMMARY

The complex characteristics of propfans required the development of new aeroelastic technology for their design. To help develop this technology experiments were conducted with propfan sub-scale models. The objectives were to understand the aeroelastic phenomena of propfans, to provide a data base, and to develop and verify aeroelastic analyses. Full scale flight testing has demonstrated the successful propfan designs developed from this experimental and analytical research program.

- CLASSICAL FLUTTER
  - IS UNDERSTOOD AND CAN BE AVOIDED THROUGH DESIGN
- SEPARATED FLOW EXCITATION
  - NO STALL FLUTTER OCCURRED WITH THE SWEPT MODELS
  - HIGHER SWEEP REDUCES RESPONSE
  - FORWARD VELOCITY REDUCES RESPONSE
- FORCED EXCITATION AT ANGLED INFLOW
  - HIGHER SWEEP REDUCES RESPONSE
  - WING INSTALLATION INCREASED 1P STRAIN SENSITIVITY OVER THAT OF ISOLATED BY ABOUT TWO TIMES
  - THE 1P STRAIN SENSITIVITY INCREASED WITH SHAFT POWER IN THE BLADE DESIGN RANGE

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- GENERAL
  - SWEPT BLADES EXHIBIT LESS FORCED RESPONSE THAN STRAIGHT BLADES
  - THE AEROELASTIC MODEL PERFORMED AS PREDICTED BY ANALYSES
  - COMPOSITE MATERIAL CAN BE USED TO TAILOR THE AEROELASTIC DESIGN OF PROPFANS

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