Experimental Investigation of Propfan Aeroelastic Response in Off-Axis Flow with Mistuning

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Measured vibratory strain amplitudes resulting from off-axis flow are compared for the blades of two eight-bladed, 0.62-m- (2-ft-) diam propfan model rotors with mistuning. One rotor had inherent mistuning. The other was intentionally mistuned by replacing every other blade of the first rotor with a blade of same geometry but different frequencies and mode shapes. The data show that the intentional mistuning had a beneficial effect on the aeroelastic response of the propfan blades for a wide range of off-axis flow angles, blade pitch angles, and rotational speeds. The data also illustrate that large and intuitively unpredictable variations in the aeroelastic response of propfan blades can occur because of inherent mistuning. Statistical trends of blade strain amplitudes are compared for both the rotors in terms of the ratio of the maximum to the mean.

Nomenclature

R = rotor-tip radius
r = radius-to-blade section
t = time
V = velocity of the freestream
W = resultant velocity at a blade section
α = blade section angle of attack
β = blade pitch angle
ϕ = geometric helix angle
Ψ = shaft tilt angle
Ω = angular velocity of rotor

Introduction

PROPFAN, or advanced turboprop propulsion, offers very high fuel efficiency at cruise speeds up to Mach 0.85. However, to be fuel efficient at high flight speeds, propfans have different geometric, structural, and aerodynamic characteristics than conventional propellers. Typically, propfans have eight or more thin, flexible, twisted blades with large sweep and low aspect ratio. Because of these unique characteristics, the aeroelastic design technology used for conventional propellers is inadequate. To develop the required technology and establish a data base for designing propfans, NASA Lewis Research Center has been conducting extensive research that includes both experimental and analytical aeroelasticity. As part of this research, wind-tunnel experiments have been conducted with propfan models.

Because of manufacturing limitations, small property differences between the blades (mistuning) are inherent in all propfan rotors. However, propfan blades have been assumed to be of identical properties (tuned) in aeroelastic analyses performed.[1-4] Analytical and experimental flutter results for a propfan rotor with intentionally mistuned blades were presented in Refs. 5 and 6. The present paper documents experimental results on aeroelastic response, due to off-axis flow, with mistuned propfan blades. Some related analytical work is presented in Ref. 7.

Previous research[8-10] on turbomachinery bladed disks has shown that mistuning can have a significant effect on flutter and forced response. It is known that mistuning generally has a beneficial effect on the flutter characteristics of rotating blades. However, the effect of mistuning on forced response may be beneficial or adverse depending on the system characteristics. These characteristics include the amount and type of mistuning, the degree of structural and aerodynamic coupling between the blades, and the frequency and interblade phase angle of the excitation. As a result of this previous research on turbomachinery, mistuning was also expected to be a factor affecting the aeroelastic forced response of propfan blades.

Mistuning of several different types can exist in a propfan rotor. In the study of aeroelastic forced response, natural frequency, mode shape, and aerodynamic mistuning are of the most interest. All three types of mistuning affect the energy exchange in a structurally coupled blade system during vibration. As a result, the response amplitudes of the blades on the mistuned rotor will differ from those on the tuned rotor. When aerodynamic coupling exists, mistuning causes an additional change in the response amplitudes—effectively changing the aerodynamic damping. Frequency mistuning has generated the greatest attention in the literature, e.g., Refs. 10 and 11, because it is the easiest to analyze. Aerodynamic mistuning, resulting from passage-to-passage differences in the unsteady aerodynamic flow, has also been investigated.[12] The effects of mode shape mistuning have never been reported to the authors' knowledge. The results of this experiment include the effects of all three types of mistuning. However, only natural frequency mistuning is explicitly quantified because mode shape and aerodynamic mistuning were impractical to measure and quantify.

A major consideration in propfan blade design is aeroelastic forced response resulting from off-axis, or angled, flow into the rotor. Propellers have off-axis flow when the propeller thrust axis is inclined to the flow, and this is during most of the flight envelope. Other sources of off-axis flow are airframe-induced flowfield distortions, wing upwash, and gusts. Off-axis flow can cause large blade vibratory stresses and can lead to blade fatigue failure. The vibration occurs because the

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off-axis flow causes the local angle of attack and the resultant velocity, at each blade section, to vary periodically as the blade rotates (this is illustrated in the Appendix). This results in periodically varying lift forces. The major component of the lift forces completes an excitation cycle once per revolution and is referred to as first-order, or 1P, excitation forces. However, as explained in the Appendix, there also are components of the lift forces that complete an excitation cycle twice per revolution. These are referred to as second-order, or 2P, excitation forces.

This experiment was conducted to investigate the effects of mistuning on the aeroelastic forced response of propfan rotors. An additional objective of the experiment was to provide experimental data for the verification of analytical studies and computer codes.

The wind-tunnel experiment was done in two parts. First, an eight-blade inherently mistuned rotor was tested in off-axis flow. Then, every other blade was removed from the rotor and replaced with a blade of different frequencies and mode shapes. This replacement blade was the same as the original, except for the ply orientations of its composite material. Thus, the original rotor was now intentionally mistuned in frequencies and mode shapes. This rotor was also tested in off-axis flow.

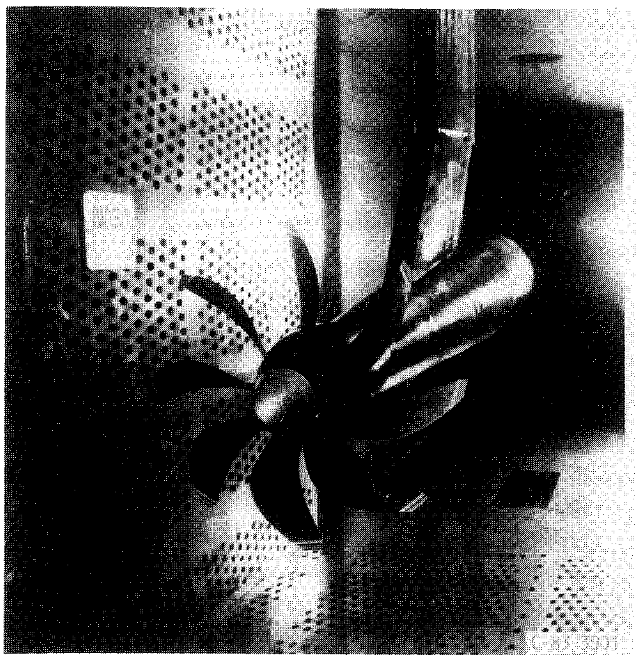


Fig. 1 SR3C-X2 propfan model wind-tunnel installation.

This paper describes the experiment and compares vibratory strain amplitudes of the blades in the two mistuned rotors described above. Also, these strain amplitudes are compared to previously measured strains from a third rotor.[3] The third rotor was inherently mistuned and had eight blades of the type used to intentionally mistune the first rotor of this experiment.

Description of the Experiment

Test Rig Installation

The experiment was conducted in the NASA Lewis 8 × 6 ft (2.44 × 1.83 m) wind tunnel (see Fig. 1). The propfan models were mounted on an air turbine-driven, single-rotation, isolated nacelle test rig. This rig was ceiling-strut mounted. The off-axis, or angled flow, was obtained by remotely tilting the propeller shaft in pitch with respect to the freestream. Eight blades were mounted in a relatively rigid hub.

Models and Procedures

Two existing propfan research models, the SR3C-X2 and SR3C-3,[4-6] each of 0.62-m (2-ft) diam, were used for the experiment. The models had the same geometry and material but differed in natural frequencies and mode shapes. This difference was designed into the blades by varying the ply orientations of the laminated graphite/epoxy unidirectional blade material. Both models had 80% of the plies in the blade pitch axis (0-deg) direction, as shown in Fig. 2. The remaining plies were distributed at the ± 22.5-deg directions for the -X2 blades, and at the ± 45.0-deg directions for -3 blades. The aeroelastic characteristics of the blades differed because of frequency and mode shape differences between them. The -X2 blades were designed for classical flutter experiments, and the

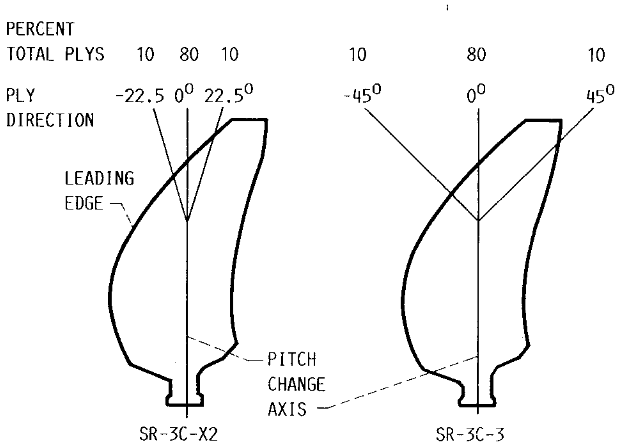


Fig. 2 Blade ply directions.

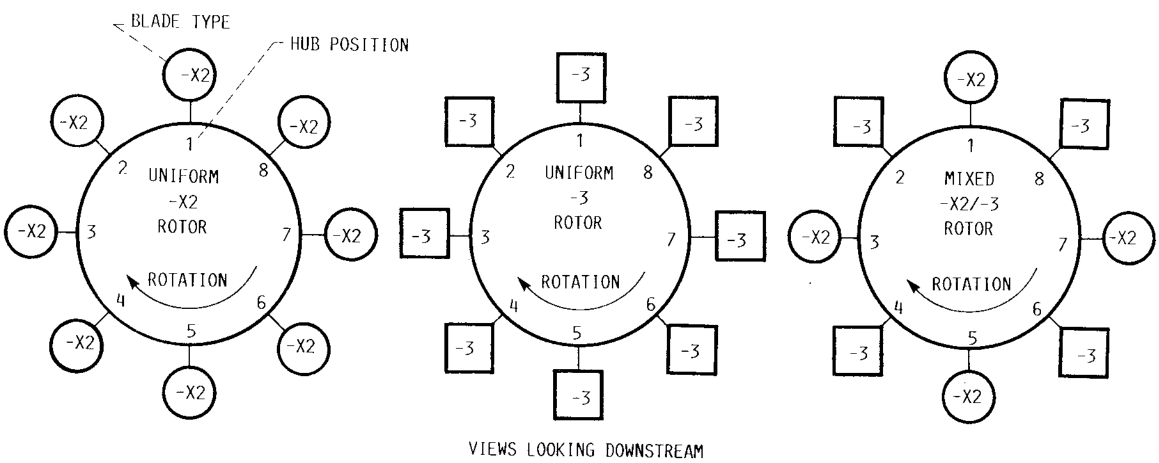


Fig. 3 Schematic diagrams of uniform and mixed-rotor configurations.

BLADE STRAIN GAUGES

HUB POSITION	ROTOR		
	-X2	-3	-X2/-3
1	-1,-2	-1	-1,-2
2	-1	-----	-1
3	-1	-1	-1
4	-1	-----	-1
5	-1,-2	-1,-2	-1,-2
6	-1	-----	-1
7	-1	-----	-1
8	-1,-2	-----	-1,-2

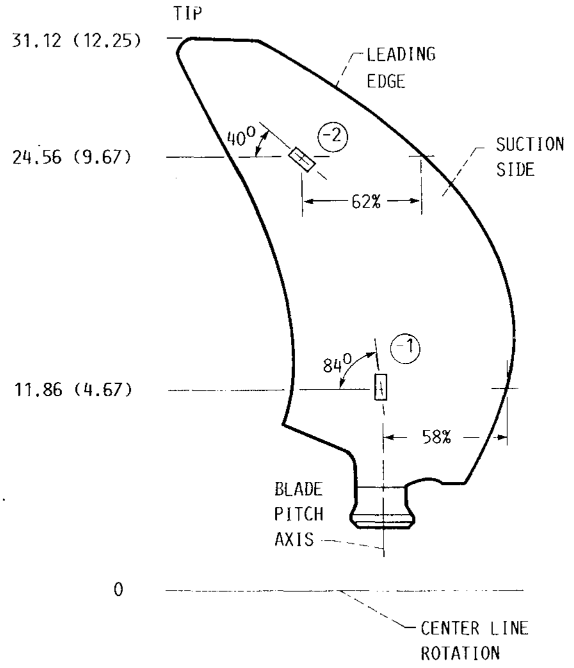


Fig. 4 Blade strain gauge instrumentation.

-3 blades for aeroelastic response experiments. The -X2 and -3 models were wind-tunnel tested prior to the present experiment and performed as designed. Experimental and analytical results were reported in Refs. 4–6 for the previous flutter experiments and in Refs. 2 and 3 for the previous aeroelastic response experiments.

The present experiment was done in two parts. First, an eight-bladed -X2 rotor was tested in off-axis flow. This rotor had inherent mistuning from manufacturing differences of the blades. Then, every other -X2 blade was removed from the rotor and replaced with a -3 blade. The rotor was now intentionally mistuned, based on the different frequencies and mode shapes of the blades (to be discussed later). The intentionally mistuned rotor also was tested in off-axis flow.

Three eight-blade rotor configurations will be referred to in this paper (see Fig. 3). One rotor has all -X2 blades, and another has all -3 blades. These are the uniform rotors and will be called the -X2 and -3 rotors, respectively. A third rotor has both -X2 and -3 blades in alternate rotor positions. This rotor will be called the mixed rotor. Blades are identified by the hub positions they occupy in the rotor, as shown in Fig. 3.

The test variables were shaft tilt angle, rotor speed, and blade pitch angle (the acute angle that the blade chord makes with the plane of rotation at the 0.75 blade radius). Blade vibratory strain data were recorded at combinations of the following conditions: at blade pitch angles of 48.1, 56.1, 61.2, and 68.0 deg; at shaft tilt angles of 4, 8, and 12 deg; and during dwells at constant rotor speeds from windmilling to 9000 rpm. All testing was done at a tunnel Mach number of 0.36. The test procedure was to lock the blade pitch angle manually and then start the tunnel. When the tunnel speed was set, the rotor shaft was tilted and power was applied to the rotor.

Blade-mounted foil strain gauges provided the vibration data. Each blade had at least one gauge at a common location since the effect of mistuning on all the blades was being studied. Only dynamic strain signals were recorded and monitored during the testing. Figure 4 shows the instrumentation installed on the blades of the -X2 and the mixed rotors of this experiment. Also shown are the locations of strain gauges installed on the blades of the -3 rotor of the previous experiment. Gauge 1 is located inboard and gauge 2 near to the tip. Both gauges have uniaxial grids. The gauges were located to

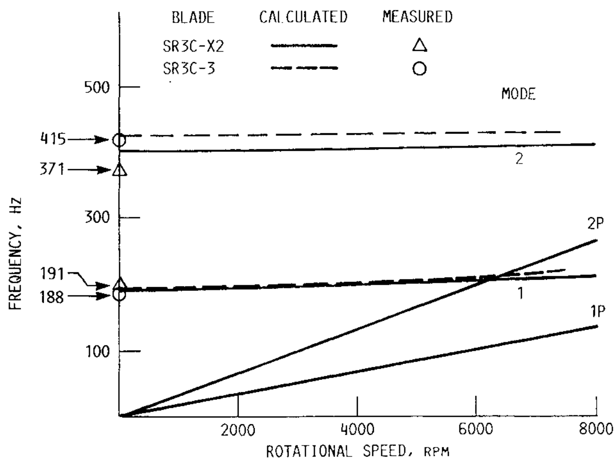


Fig. 5 Campbell diagrams of -X2 and -3 blades, blade angle = 61.2 deg.

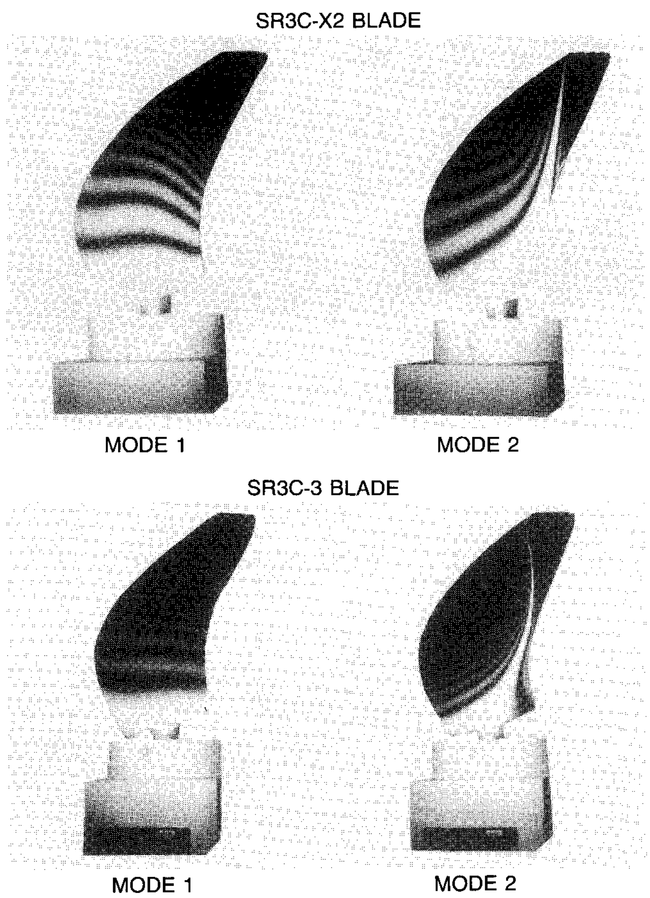
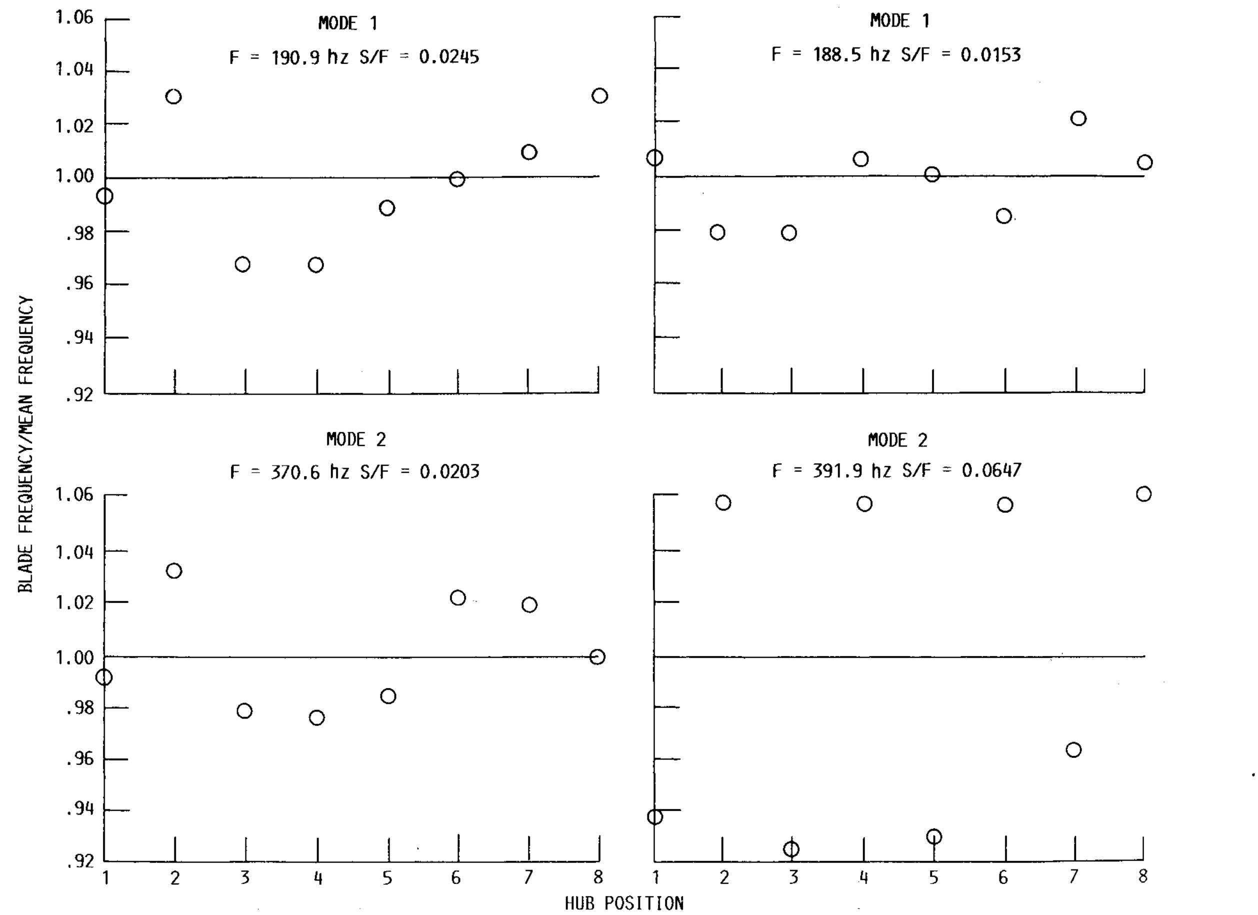


Fig. 6 Bench-measured blade natural mode shape contours.



a) -X2 rotor b) Mixed rotor

Fig. 7 Blade natural frequencies for uniform -X2 and mixed rotors.

provide good strain sensitivity to the first four blade natural modes as determined by finite element analyses.

Propfan Blade Campbell Diagrams and Mode Shapes

Campbell diagrams (see Fig. 5) will help explain the blade responses that were experienced during the experiment and natural frequency differences between the blades. These were obtained by finite element analyses. Only the first two natural frequencies are shown since the higher modes contribute little to the response of the blades for the conditions of this experiment. The solid and dashed lines in Fig. 5 show the variation of calculated natural frequencies with rotational speed. The average measured bench natural frequencies of the blades are also shown for comparison (the average value for the SR3C-3 blades is for the four blades in the mixed rotor). The difference between the average measured (371 Hz) and the calculated frequency (399 Hz) for the second mode of the SR3C-X2 blade is attributed to unknowns in blade properties due to manufacture and/or blade shank modeling errors. Also shown are the 1-per-rev (1P) and 2-per-rev (2P) excitation order lines since these were the dominant excitations present during the experiment.

The curves for both blades show similar variation of the first and second modes with rotational speed. The first mode frequencies of both blades are very close, but the second mode frequency of the -3 blade is higher than that of the -X2 blade (i.e., the -3 blade is stiffer in the second mode). As explained in the Appendix, the major blade excitation with the rotor tilted in the freestream occurs at a frequency of 1P. Since the first blade mode is nearest to the 1P excitation order line, it should be the mode with the dominant response to a 1P excitation. Also, since the first mode frequency approaches the 1P line as rotational speed increases, the 1P blade response should increase with increasing rotational speed because of dynamic amplification. The data to be presented follow this expected trend. It should also be noted that dynamic pressure increases with rotational speed and also contributes to the increase in blade response. Figure 5 shows that there is a crossing of the first mode and the 2P excitation order line. The data will show that the blades in the -X2 rotor responded with larger amplitudes than the blades in the mixed rotor near this crossing.

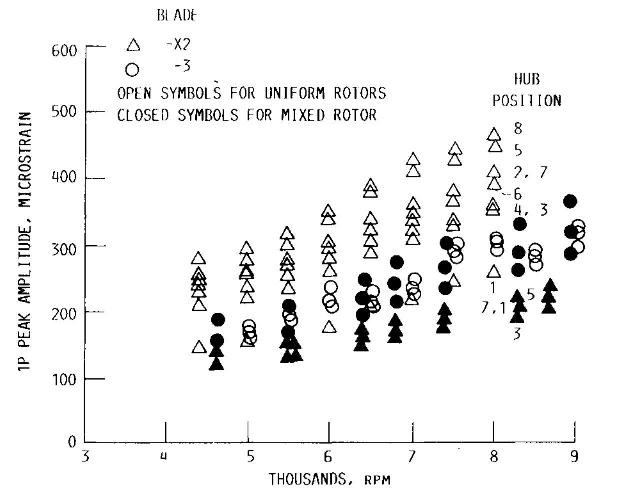
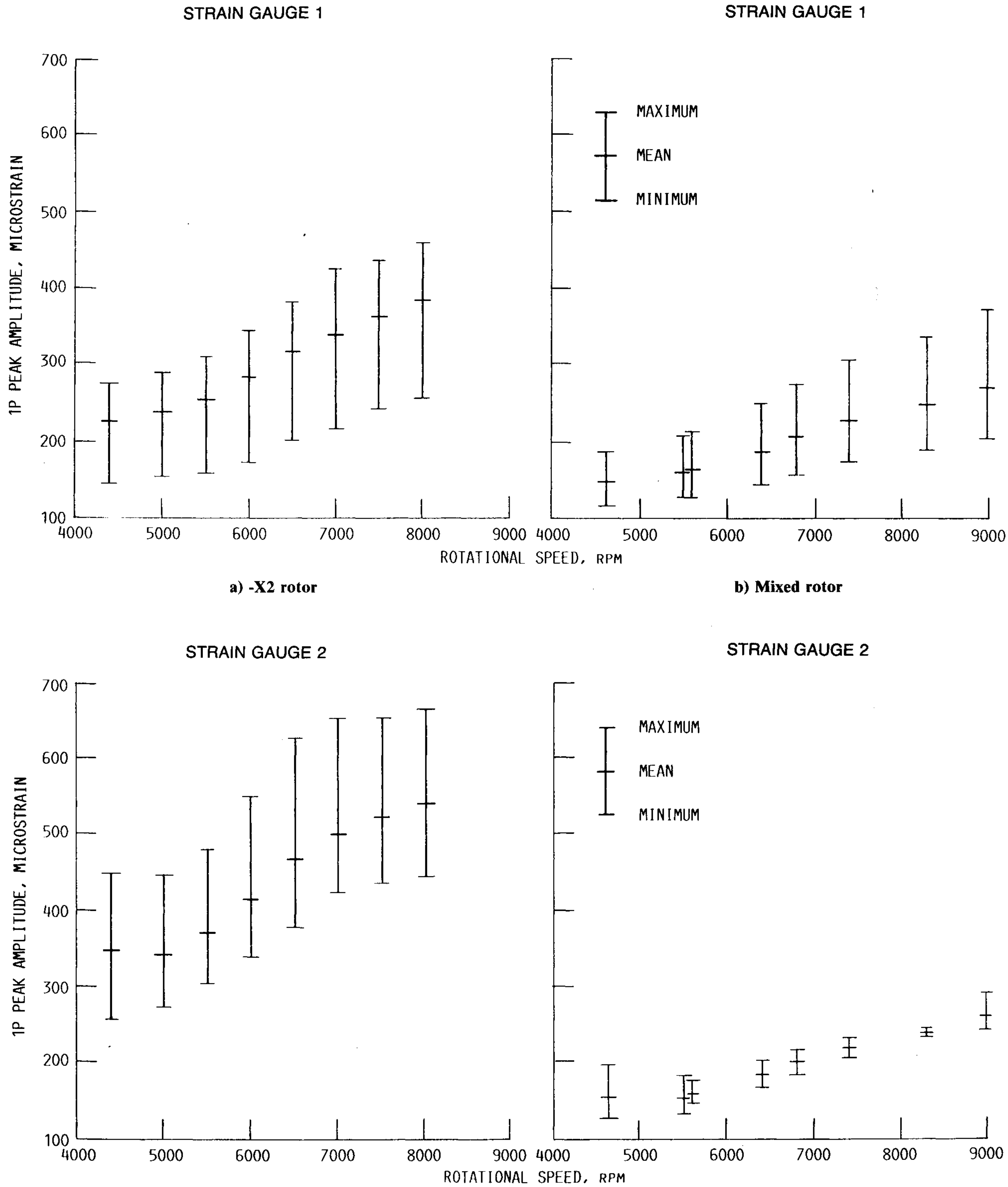


Fig. 8 1P amplitude for blades in the uniform and mixed rotors, tilt angle = 8 deg, blade angle = 48.1 deg, freestream Mach number = 0.36, gauge 1.

The first two natural mode shapes of the -X2 and -3 blades differ, and the differences are part of the mistuning present in the mixed rotor. The differences can be seen from photos of hologram mode shape contours of the -X2 and -3 blades (see Fig. 6) from bench vibration tests. The black fringes represent contours of constant displacement, and the whitest fringes are node lines. The blade modes consist of coupled motions, primarily because of blade sweep. The first mode of the -X2 blade has greater torsion/bending coupling than the -3 blade. This is indicated by the greater slope of the displacement contours. The second modes of the blades have node lines of different shape. There were also small mode shape differences between the blades of the uniform rotors, but these are not shown.

Levels of Frequency Mistuning in the Rotors

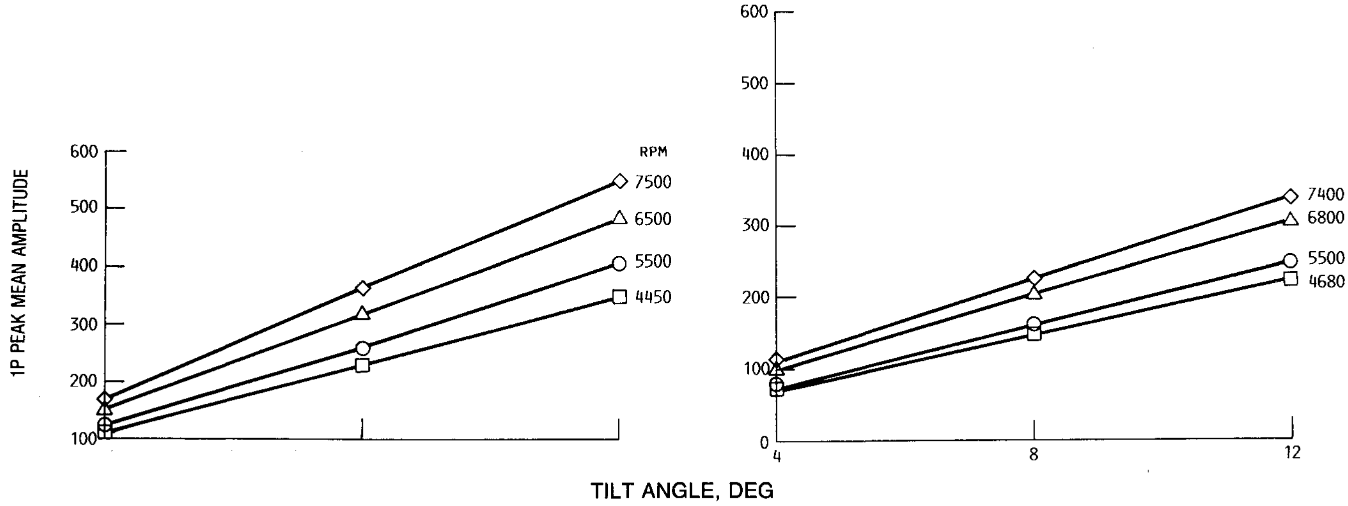
The variation of the bench-measured individual blade frequencies about the mean blade frequency was used as the measure of the frequency mistuning in each rotor. The variation of the natural frequencies for the first two modes of the blades in the uniform -X2 rotor and the mixed rotor is shown in Fig. 7 (this information was not available for the uniform -3



a) -X2 rotor b) Mixed rotor

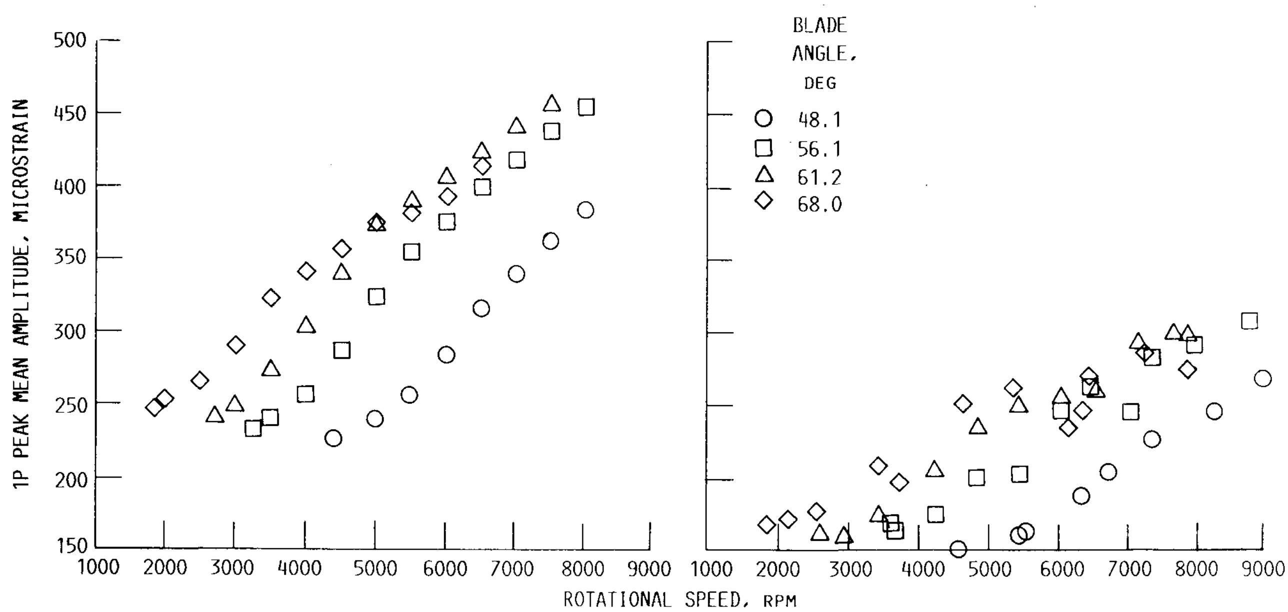
c) -X2 rotor d) Mixed rotor

Fig. 9 Comparison of mean, maximum, and minimum amplitudes, tilt angle = 8 deg, blade angle = 48.1 deg.



a) Uniform rotor b) Mixed rotor

Fig. 10 Effect of tilt angle on 1P amplitude, blade angle = 48.1 deg, strain gauge 1.



a) -X2 rotor b) Mixed rotor

Fig. 11 Effect of blade angle on the 1P amplitude, tilt angle = 8 deg, strain gauge 1.

rotor). Also, listed for each mode are the mean frequency F and the coefficient of variation (standard deviation divided by the mean frequency, S/F). The two modes of the -X2 rotor have a maximum frequency that is 1.03 times the mean and a coefficient of variation of 0.0245 and 0.0203, respectively. The first mode frequencies of the blades in the mixed rotor have slightly less variation about the mean than those of the -X2 rotor (the measured first mode frequencies of the -X2 and -3 blades were very close), whereas the second mode frequencies have significantly greater variation of an alternate pattern about the mean. Therefore, the mixed rotor has greater frequency mistuning of an alternate nature in the second mode and less frequency mistuning in the first mode compared to the -X2 rotor.

Discussion and Results

The results will be presented in three parts. First, an overview of the 1P vibratory blade amplitudes will be given at typical test conditions to show 1) how the 1P vibratory amplitudes of the individual blades in the rotors compare and 2) how the shaft tilt angle and blade angle affect the mean 1P amplitude of the blades in the rotors. The mean amplitudes reported for each rotor were calculated for all eight blades in the rotor. Second, statistical data plots of the 1P vibratory amplitudes will be given in terms of the ratio of the maximum amplitude to the mean at one set of test conditions. Third, the 2P vibratory strain amplitudes will be compared for a blade common to both the -X2 and mixed rotors.

Individual Blade 1P Strain Amplitudes

A typical variation of 1P strain amplitude of individual blades in the uniform -X2, -3, and the mixed rotors is shown in Fig. 8. Data are shown for the eight blades in the -X2 rotor, three blades in the -3 rotor (only three blades were strain gauged, Ref. 3), and the eight blades in the mixed rotor. The hub position of the blade associated with each strain amplitude is identified for the -X2 and the mixed rotors at 8000 and 8300 rpm, respectively. The relation between hub position and the relative amplitude of blade response was about the same at the other rotational speeds. The 1P strain amplitude increases with rotational speed as expected (discussed earlier).

In off-axis flow, the uniform -X2, -3, and the mixed rotor all experience identical aerodynamic excitation at the same flow conditions and rotational speed. However, the responses are different, as shown in Fig. 8, because of the differences in the modal properties of the blades mounted on the three rotors.

Comparing the response of the two uniform rotors, we note that the amplitudes of the blades in the -X2 rotor are generally higher than those in the -3 rotor. Thus, the differences in the mode shapes and the second mode natural frequencies make the -3 blade act stiffer than the -X2 blade in 1P response. The wide variation in the amplitudes of the blades in the -X2 rotor at constant rotational speed is due to the presence of inherent mistuning in the modal properties of the blades on the -X2 rotor. It would be of great benefit if the blade with the highest response (critical blade) could be identified a priori knowing the inherent mistuning in bench natural frequencies of the blades (see Fig. 7a). However, there is general disagreement[13] in the analytical studies of forced response as to the identification of the critical blade, which has been reported to be the blade with the largest mistuning,[14] the blade with the least mistuning,[15] and the blade with the lowest natural frequency.[11] The results (see Fig. 8) of this experiment do not substantiate any of the above observations. Thus, if only a few blades in the -X2 rotor had been monitored, the blade of highest response may have been missed.

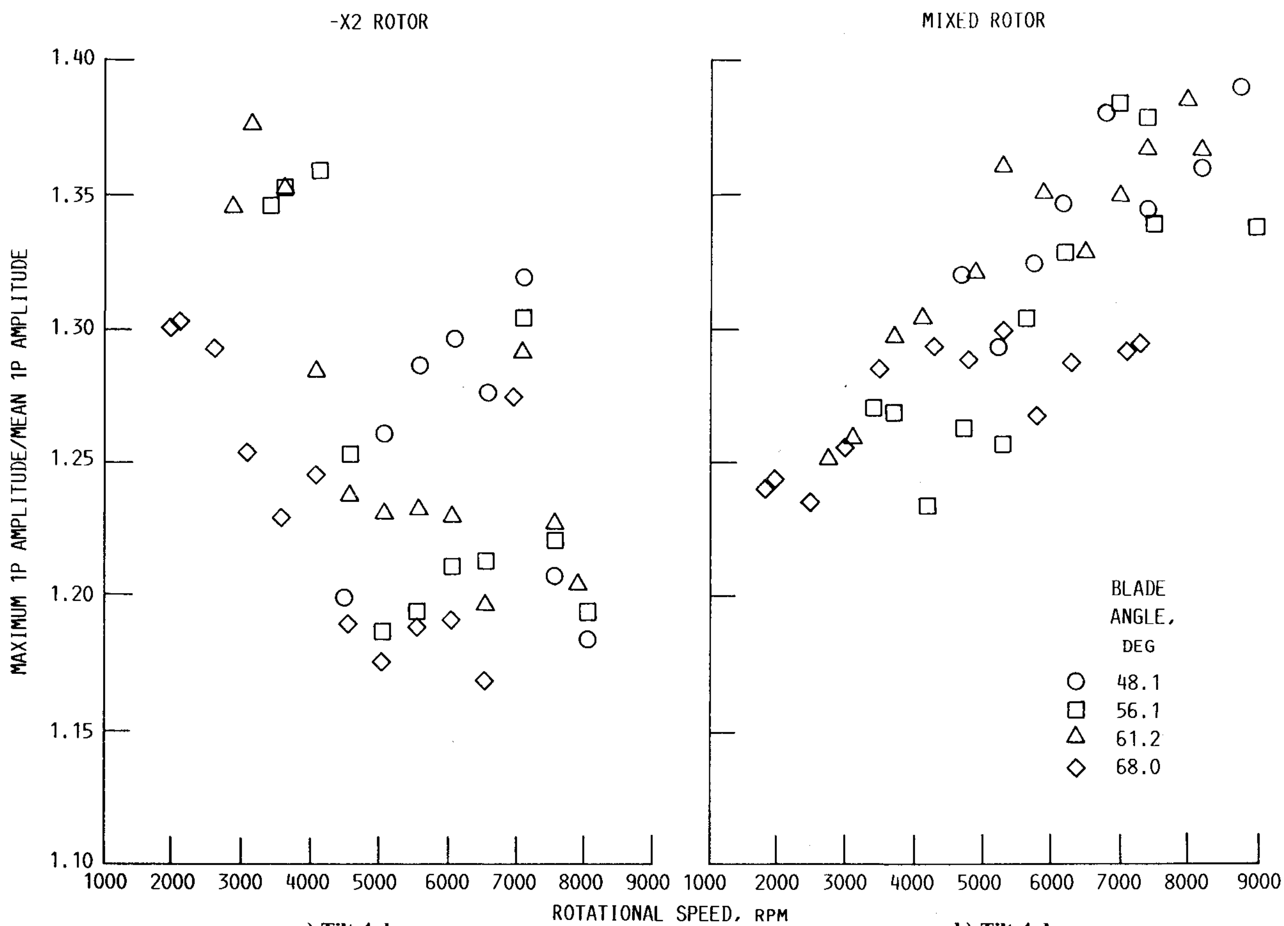
A comparison of the response of the uniform rotors with that of the mixed rotor shows that in the mixed rotor the amplitudes of the -X2 blades drop significantly and are below those of the -3 blades; the amplitudes of the -3 blades have relatively small changes. The surprisingly large reduction in the -X2 blade amplitudes, from the uniform -X2 to the mixed rotor, suggests that the intentional mistuning introduced in the mixed rotor added significant aerodynamic damping to the rotor 1P response. Note that this large reduction occurred although the response is dominated by the first mode, which is closely frequency tuned for both the rotors. This implies that the mistuning in the mode shapes and second mode frequencies of the blades in the mixed rotor contributed to this effect. Another contributing factor may be aerodynamic mistuning from differences among blade passages caused by small variations in blade-setting angles and steady-state deflections.

Comparison of Mean, Maximum, and Minimum 1P Amplitudes

A comparison of the mean and range of the 1P amplitudes for all the blades in each of the -X2 and the mixed rotors can be made from Fig. 9. Figures 9a and 9b are for strain gauge 1 and represent part of the data in Fig. 8. The effect of the intentional mistuning on reducing the response of the blades is again demonstrated here. Also, the rate of increase of the mean 1P amplitude with rotational speed is smaller for the mixed than the -X2 rotor. This may be related to an effective increase in the aerodynamic damping due to mistuning. The same plots as above but for strain gauge 2 are shown in Figs. 9c and 9d. Similar trends as discussed above for strain gauge 1 also exist here. Note that Figs. 9a and 9c show that the mean and maximum strain amplitudes of the -X2 rotor are significantly higher for strain gauge 2 than strain gauge 1. Therefore, monitoring a root gauge only in the -X2 rotor would not have provided the total picture of what was occurring. Also note that Figs. 9b and 9d show that the mean strain amplitude of the mixed rotor is about the same for strain gauges 1 and 2, but the maximum and range of the amplitudes are less for strain gauge 2 than strain gauge 1. So, the intentional mistuning had a greater effect on the amplitude of strain gauge 2 than strain gauge 1.

Effect of Tilt Angle on the Mean 1P Amplitude

The variation of the 1P mean strain amplitude of the blades in the -X2 and mixed rotors with tilt angle at four rotational



a) Tilt 4 deg

b) Tilt 4 deg

Fig. 12 Effect of blade angle on the maximum to mean 1P amplitude ratio, strain gauge 1.

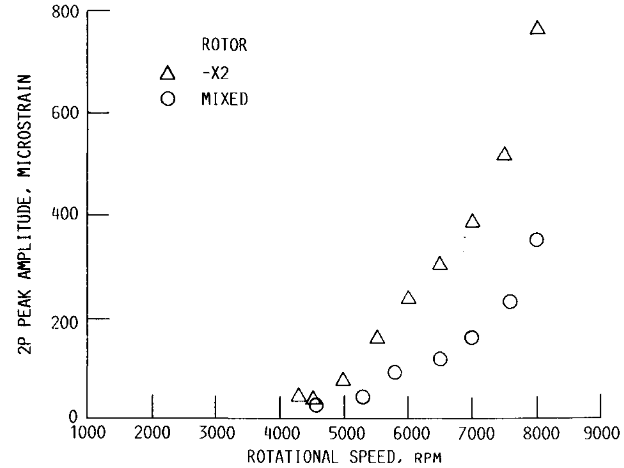


Fig. 13 Comparison of 2P peak response for uniform -X2 and mixed rotors, tilt angle = 8 deg, blade angle = 48.1 deg, blade 1, strain gauge 2.

speeds is shown in Figs. 10a and 10b, respectively. (At some rotational speeds, the mean amplitudes shown are interpolated from data at nearby rotational speeds.) Theoretically, for a tuned rotor, the 1P strain amplitude increases linearly with tilt angle. The data for both rotors follow the expected linear trend.

Effect of Blade Angle on the Mean 1P Amplitude

The 1P peak mean strain amplitude of the blades in the -X2 and mixed rotors at four blade angles is shown in Figs. 11a and 11b. The lowest amplitudes occur at the lowest blade angle for both rotors, at 48.1 deg. For the -X2 rotor there is an increase in blade stress with increasing blade angle at a constant rotational speed, but the amplitudes tend to converge at the three highest blade angles with increasing rotational speed. The mixed rotor amplitudes have more scatter at the three highest blade angles but have the same trends as the -X2 rotor data.

Statistical Data Plots

Statistical data regarding the effects of blade mistuning on propfan aeroelastic forced response are not currently available. Propfans are relatively new and the data have not been generated. In general, propfan blades will be manufactured to be within geometric tolerance limits, and the nature and degree of mistuning will probably not be a consideration of the rotor assembly. However, it has been shown in both analytical studies and the present experiment that mistuning can have significant and intuitively unpredictable effects on the amplitude of blade vibratory stresses. Statistical data for the -X2 rotor will be presented to provide some measured values for a propfan rotor with random mistuning. Random mistuning is typically present for turbomachinery rotors. Statistical data will also be given for the mixed rotor, with intentional frequency and mode shape mistuning for comparison.

Effect of Blade Angle on the Maximum to Mean 1P Amplitude Ratio

The variation of the maximum to the mean 1P amplitude ratio with rotational speed is given in Fig. 12 for the -X2 and mixed rotors. The plots are for a tilt angle of 4 deg and four blade angles. For the -X2 rotor, at a constant blade angle, the amplitude ratio generally decreases with increasing rotational speed, and decreases with increasing blade angle at a fixed rotational speed. Although not shown, the amplitude ratio becomes more constant with rotational speed as the tilt angle increases. For the mixed rotor, at a constant blade angle, the amplitude ratio shows an increase with rotational speed and a more random relationship with blade angle at a fixed rotational speed.

Comparison of 2P Amplitudes

There was a large difference in the 2P response of the -X2 blades in the -X2 and mixed rotors. This is illustrated in Fig. 13. The 2P amplitude variation with rotational speed for blade 1 in the -X2 and mixed rotors is shown. As rotor speed increases, the 2P amplitude of the blade in the -X2 rotor increases at a faster rate than in the mixed rotor. At 8000 rpm, the amplitude of the blade in the mixed rotor is about half that in the -X2 rotor. So, the mistuning in the mixed rotor resulted in a significant reduction in the 2P response of blade 1. A similar reduction occurred in the 2P response of the other -X2 blades. The measured critical speed appears to be slightly above 8000 rpm. However, Fig. 5 shows the calculated critical speed at about 6000 rpm. This difference is believed to be due to inaccuracies in the finite element analyses at high rotational speed.

Concluding Remarks

The measured aeroelastic response of the blades for two mistuned propfan rotors have been compared over a wide range of inflow angles, rotor speeds, and blade angles. The -X2 rotor had inherent random mistuning and the mixed rotor had intentional alternate mistuning. If the blades of the -X2 rotor were identical, then, theoretically, the aeroelastic response of all the blades would have been the same. However, because of inherent mistuning, the blades of the -X2 rotor had a large variation in aeroelastic response that could not be intuitively predicted. Since similar variations may exist for other propfans with inherent mistuning, it is recommended that mistuning be considered in designing propfans for aeroelastic forced response. The following was observed from the data:

1) There is considerable blade-to-blade variation in the 1P aeroelastic response of the inherently mistuned rotor. Thus, for actual rotors, all of the blades should be monitored during engine tests to determine the maximum blade response.

2) Intentional alternate mistuning caused a large reduction in the 1P and 2P amplitude of the higher responding blades, a relatively small change in the 1P amplitudes of the lower responding blades, and a reduction in the rate of increase of the mean 1P amplitude with rotational speed.

3) Mean 1P amplitude increased with increasing blade angle, at a constant rotor speed, for the inherently mistuned (-X2) rotor and had a more random, although similar, trend for the alternately mistuned rotor. Also, both the inherently mistuned (-X2) rotor and the alternately mistuned rotor had a linear increase in the 1P strain amplitude with shaft tilt angle.

4) In general, as rotor speed was increased, the blade response became more uniform for the inherently mistuned (-X2) rotor but less uniform for the alternately mistuned rotor.

Appendix: Explanation of Dynamic Blade Excitation for a Propeller Rotor in Off-Axis Flow

The source of dynamic blade excitation from off-axis flow is illustrated in the schematic diagrams of Fig. A1. Figure A1a shows a side view of a propfan rotor in a uniform, steady freestream of velocity V and at an angle Ψ from the axis of rotation. The angle Ψ is referred to as the shaft tilt angle. The components of V along the axis of rotation and in the plane of rotation are $V \cos\Psi$ and $V \sin\Psi$, respectively. Only velocity components of airflow in the plane of rotation and normal to blade sections will be considered for blade lift. Blade sweep will be neglected for this explanation for simplicity. The magnitude of the in-plane velocity component normal to sections of the blade varies with the position of the blade during rotation. This variation is illustrated in the front view of Fig. A1a. At the 0- and 180-deg positions, the in-plane component of velocity is radial and does not contribute to blade lift. As the blade rotates to the angular position Ωt, the circumferential component of the freestream airflow normal to the blade

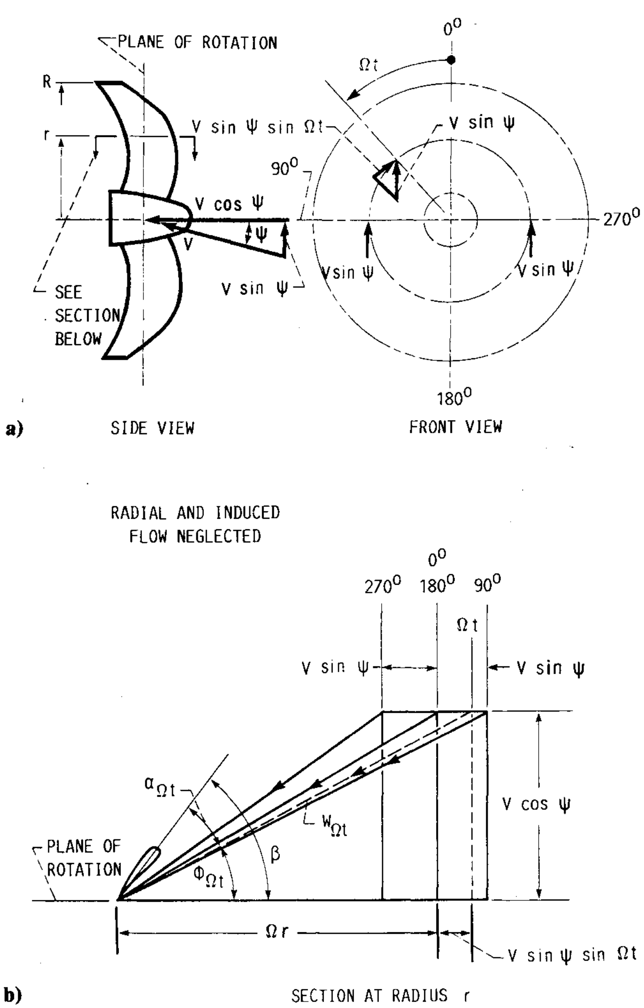


Fig. A1 Velocity diagram for a propfan operating in off-axis flow.

section is given by $V \sin\Psi \sin\Omega t$ and is in the same direction as the relative velocity due to rotation. As shown in Fig. A1a, when the blade reaches the angular position of 90 and 270 deg, all of the in-plane freestream component is normal to the blade section, and is in the same sense as the relative velocity due to rotation at 90 deg but in the opposite sense at 270 deg.

Figure A1b illustrates the velocity diagram for a typical blade section at a blade angle β. The velocity of the airflow and the angle of attack as seen by the blade at an angular position Ωt are denoted by $W_{\Omega t}$ and $\alpha_{\Omega t}$, respectively. As shown in the figure, both the relative velocity and the angle of attack are periodic functions of the angular position and complete an excitation cycle once per revolution of the rotor. In unstalled conditions, the lift forces are proportional to the angle of attack and to the square of the relative velocity. Hence, the rotating blade experiences periodic lift forces due to the off-axis flow. The variation of angle of attack and the relative velocity with angular position results primarily in forces at a 1P excitation frequency, but there are also smaller force components at a 2P excitation frequency. Excitations at frequencies above 2P are negligible when the tilt angle is small. The 2P frequency lift components arise from the periodic but not purely sinusoidal variation of the angle of attack and from the dependence of the lift on the square of the relative velocity. Thus, off-axis flow conditions result in both 1P and 2P excitations acting on the blades. Note that the varying lift forces from the off-axis flow cause the blades to experience a dynamic excitation even though the rotor is in a steady, uniform flowfield.

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