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Flutter of Swept Fan Blades

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ABSTRACT

The purpose of the research presented in this paper is to study the effect of sweep on fan blade flutter by applying the analytical methods developed for aeroelastic analysis of advanced turboprops. Two methods are used. The first method utilizes an approximate structural model in which the blade is represented by a swept, nonuniform beam. The second method utilizes a finite element technique to conduct modal flutter analysis. For both methods the unsteady aerodynamic loads are calculated using two-dimensional cascade theories which are modified to account for sweep. An advanced fan stage is analyzed with 0, 15 and 30 degrees of sweep. It is shown that sweep has a beneficial effect on predominantly torsional flutter and a detrimental effect on predominantly bending flutter. This detrimental effect is shown to be significantly destablilizing for 30 degrees of sweep.

INTRODUCTION

A research program to develop advanced turboprops (or propfans) is currently being conducted at the NASA Lewis Research Center. As shown in Fig. 1, the blades being considered are of complex shape including substantial, nonuniform sweep. The primary reasons for using thin, swept airfoils are to reduce acoustic noise and to increase efficiency during high subsonic (M=.8) flight conditions. A possibly detrimental effect of sweep is on flutter. The research program at NASA has included aeroelastic experiments and development of analytical methods for predicting flutter of swept, rotating blades. For a description of some of these experiments and the analytical methods see Refs. 1 to 4.

It is expected that the use of advanced, swept fan blades in turbofan engines would also result in similar improvements in efficiency and noise as in advanced turboprops. However, it is not known whether it is possible to design practical, swept fan blades which have adequate flutter margin. Since the analytical methods developed for the advanced turboprop blades include unsteady cascade aerodynamic effects, they are also applicable to fan blades of turbofan engines. The purpose of the research presented in this paper is to conduct an initial study of the effect of sweep on fan blade flutter by applying the analytical methods developed for aeroelastic analysis of advanced turboprops.

Whereas a practical swept fan blade is likely to have a curved elastic axis (the locus of section shear centers), similar to the shape shown in Fig. 1, the initial parametric studies reported herein are of swept blades with straight elastic axes. This assumption simplifies the structural analysis by removing the effect of curvature. However, future research must consider additional parameteric studies of the actual configurations which are likely to be used. Some effects to be studied are elastis axis-c. g. placement, transonic and three-dimensional aerodynamics, and cascade-sweep interaction.

THEORY

Two analytical methods are used in this study. The first one (Refs. 1 and 5) utilizes an approximate structural model in which the blade is represented by a swept, nonuniform beam (the beam must have a straight elastic axis). As mentioned above, practical swept fan blades are likely to have curved elastic axes. Therefore, this method can only be used to study parametric trends (which is the purpose of this paper).

The second method (Refs. 2, 3, and 6) is an extension to the well known finite element program NASTRAN to include cascade effects in the flutter analysis of swept blades. This method is capable of modelling blades of complex configuration including sweep, curved elastic axis, and can also consider structural coupling between blades.

For both methods the unsteady aerodynamic loads are calculated using two-dimensional cascade theories which are modified to account for sweep. The techniques used to account for sweep differ between the two methods and are described below. It must be mentioned that the actual flow field is complicated by three-dimensional and transonic effects, especially at the tip region. Cascade unsteady aerodynamic models including these effects are currently under development and are not presently available. The authors are currently conducting research in this area which will be reported in future publications. The three-dimensional effects are expected to be less significant for swept turbofans than for advanced turboprops because of the presence of the duct.

Beam Method

The details of the derivation of the beam method for unswept blades are given in Ref. 5. This method was developed for pretwisted, nonuniform blades by using Hamilton's principle. The derivation of the equations has its basis in the geometric nonlinear theory of elasticity in which elongations and shears are negligible compared to unity. A general expression for foreshortening (axial shortening of the tension axis due to bending, torsion, and noncoincidence of the elastic and tension axes) is explicitly used in the formulation. This method for unswept blades was modified in an approximate manner to account for blade sweep. For simplicity it was assumed that, although the blades are swept, the elastic axis is straight (see Fig. 2). Only the component of centrifugal load along the blade axis is considered. Also, for the flutter problem the blade is assumed to be vibrating about its undeformed position. The use of these assumptions can result in significant errors in the prediction of higher mode flutter characteristics. For example, it is known that proper consideration of the steady state displacements can cause the pure torsion mode (nonrotating) to change into a lower frequency, highly coupled bending-torsion mode. This modified version of the Ref. 5 method also has the capability to consider blade mistuning, but this is not considered herein.

Both subsonic (Ref. 7) and supersonic (Ref. 8) two-dimensional unsteady cascade aerodynamic theories are used. The assumed relative flow is the component normal to the elastic axes. The chord and stagger angle are also defined for sections normal to the elastic axis. The lift and moment are integrated in a stripwise manner to give a quasi-three-dimensional effect. These aerodynamic loads are corrected for sweep effects by using similarity laws. This method, used in (Refs. 9 and 10) for an isolated, nonrotating, swept wing, involves modification of the two-dimensional lift and moment expressions for an unswept wing. The spanwise component of flow is neglected and similarities in the vertical velocity boundary conditions for swept and unswept wings are utilized.

The space variable in the resulting coupled integro-partial differential equations of motion is eliminated by using a modified Galerkin's method. The trial functions are the uniform beam mode shapes. For all results presented in this paper two modes were used for each of three types of motion; bending in the plane of rotation, bending perpendicular to the plane of rotation, and torsion. The assumption of simple harmonic motion results in a generalized eigenvalue problem which is iteratively solved to determine the flutter boundary. Further descriptions of this analytical method can be found in Refs. 1 and 5.

Finite Element Method

The detailed description of this method is given in Refs. 2, 3, and 6. For the reader's convenience a brief description follows. The method consists of three steps: 1) a "differential stiffness" matrix is determined from the steady state solution (by considering both centrifugal and steady aerodynamic loads and by using a Newton-Raphson iteration to determine the equilibrium position), 2) by using the additional stiffness from step 1, a free vibration analysis is performed to determine the modal characteristics, and 3) a modal flutter analysis is performed.

The two-dimensional, subsonic, cascade theory described in Ref. 11 is used to calculate the unsteady aerodynamic loads. The theories of Ref. 7 and 11 are closely related and give similar results. A supersonic aerodynamic theory including sweep effects has yet to be incorporated into this method. The subsonic unsteady aerodynamic loads are modified to account for sweep effects by considering only the component of flow normal to the local leading edge. Although this method can include steady aerodynamic loads, they are not considered herein.

In general, a blade is a surface with multiple curvature. The method to form the aerodynamic forces for such a surface is as follows. For each station a "mean surface" is constructed between chord lines (which are normal to the leading edge and not parallel to each other) for this station and the adjacent spanwise locations (inboard and outboard). The modal translations normal to this surface are then used to construct the generalized aerodynamic force matrix.

As in the beam method, a complex generalized eigenvalue problem results. The flutter boundary is determined by repeated use of the "KE-Method" (Ref. 12) for different axial Mach numbers and rotational speeds. Since this computer code presently lacks supersonic unsteady aerodynamics, the relative flow Mach number (perpendicular to the local leading edge) at all stations must be less than one. This restricts the operating conditions at which this method can be used.

RESULTS AND DISCUSSION

The baseline fan stage used for these studies is the same unswept, unshrouded advanced fan stage that was considered in Ref. 5. This stage has 28 blades, a .38 hub-to-tip ratio, and an aspect ratio (length/hub chord) of 3.3 (unswept). The physical and material properties for the blade are listed in Table I. In the studies to follow, the blade is modified to include a constant sweep angle while keeping the inner and outer radii constant (i.e., a constant annular flow area). Thus, the swept blade is longer. In addition, the chord (defined in a direction normal to the elastic axis direction) and stagger angle have the same radial distribution as the baseline blade.

The parametric studies described in this paper are for the cases of 0, 15, and 30 degrees sweep. Figure 3 shows the planform of the blade for 0 and 30 degree sweep. Because the inner and outer radii are constant, the elastic axis of the blade lengthens with increased sweep. This causes the blade natural frequencies to decrease with sweep. In Ref. 5 the unswept version of this baseline blade was studied and was found to encounter flutter in a predominantly torsion mode. In the following discussion the modes are classified as either bending or torsion. The aeroelastic modes are actually coupled bending-torsion modes. However, for the blade considered herein, there is only weak aerodynamic coupling between the bending and torsion modes. To aid in understanding the flutter behavior, flutter boundaries will be shown for each mode even though only the most critical is of practical interest.

Beam Analysis

The section properties of the unswept blade were given in Ref. 5. As mentioned above, the swept blade is similar to the unswept one except in length. Therefore the section properties in planes normal to the elastic axis are the same as those listed in Ref. 5. The blade lengths (measured along the elastic axis) are .63, .66, and .73 meters for the 0, 15, and 30 degree sweep cases, respectively.

The blades were first analyzed without aerodynamic loads to find the natural frequencies of the various swept configurations. Figure 4 shows the dependence of frequency on rotational speed for 0 and 30 degrees sweep. As expected, the frequency of the bending modes increases with rotational speed more than the torsional modes, and the longer, 30 degree, swept blades have lower frequencies.

The unsteady aerodynamic loads were added to investigate the flutter characteristics. In Ref. 5 it was predicted that the unswept blade would encounter torsional flutter at an axial Mach number of .43 and a rotational speed of 3330 rpm. With M=.43, the rotor speed was varied and the aerodynamic damping (percent of critical) of the both the torsional and bending modes was calculated. The results for the torsional mode are shown in Fig. 5. As can be seen, sweep tends to stabilize the torsional mode. The use of 15 degrees of sweep is equivalent to adding approximately .3 percent critical damping and increases the flutter rotational speed by approximately 10 percent. The use of 30 degrees of sweep has a stronger effect. At 3330 rpm (the unswept blade flutter point) the added equivalent damping is approximately 1 percent. The flutter rotational speed is increased over that of the unswept blade by more than 30 percent. The stability calculations were repeated for other axial Mach numbers and the flutter boundaries are summarized in Fig. 6. It is seen that increasing sweep always has a beneficial effect on the torsion mode. As previously mentioned, this method is questionable for this mode because of the possible errors in frequency and mode shape. Finally, it should be mentioned that the critical interblade phase angle for the torsion mode was always 77.14 degrees (a 6 nodal diameter forward travelling wave).

Since the blade is pretwisted, the first bending mode of this blade is "coupled bending-bending" involving motion both in and out of the plane of rotation. It was shown in Ref. 5 that the unswept blade would not flutter in this first bending mode. The axial Mach number was fixed at .43 and the damping was predicted for a range of rotational speeds. The results, given in Fig. 7, show that, in contrast to the previous results for the torsion mode, sweep has a detrimental effect on bending mode flutter. For 15 degrees of sweep the blade is predicted to flutter at 3630 rpm. At this rpm the effect of sweep is equivalent to reducing the damping by .35 percent. For 30 degrees of sweep the detrimental effect is greater. The flutter rotational speed is further reduced to 2500 rpm. The stability calculations were repeated for other axial Mach numbers and the flutter boundaries, along with the torsion flutter boundaries, are shown in Fig. 6. Comparing flutter boundaries for 15 and 30 degrees sweep shows the severely detrimental effect of sweep on bending flutter.

Unlike for torsion, the critical interblade phase angle for the bending modes varied with sweep, Mach number, and rotational speed. Also in contrast to the torsion mode, the critical interblade phase angle always represented a backward traveling wave. The critical interblade phase angles for the bending modes are always in the range -25.7 to -90.0 degrees (2 and 7 nodal diameter backward travelling waves).

A comparison of the bending and torsion modes in Fig. 6 shows that for 15 degrees of sweep, the two flutter boundaries are close together and in the stabilized direction (higher rotational speed and/or Mach number) compared to the boundary for the unswept blade. This is an overall improvement in the flutter boundary. This is not the case for 30 degees of sweep, where the torsion mode is greatly stabilized, but the bending mode is destabilized to such an extent that it lies well to the left of the unswept blade boundary. This represent an overall degradation of the blade's flutter behavior. In summary, for the three sweep angles considered, the 15 degree blade is a slight improvement over the unswept blade and the 30 degree blade is significantly less stable.

The results described above for the bending modes are qualitatively in agreement with those of Ref. 13 in which the effects of sweep on fixed wing flutter are presented. In Ref. 13 it is shown that the additional coupling terms between the aerodynamic loads and displacements (Ref. 8 and 9) provide the mechanism to permit pure bending flutter. It appears likely that this same mechanism is the primary cause of the significant destabilizing effect on the bending modes shown herein.

Finite Element Analysis

The model, shown in Fig. 8, consisted of 40 nodes, 56 elements, and 193 active degrees-of-freedom. This mesh density is known to be inadequate for detailed stress information, but adequate for natural frequency and the associated modal flutter analyses. The well-known CTRIA2 elements, which also have been shown to be adequate for predicting the first few natural frequencies and mode shapes of plates with moderate twist, were used (Ref. 14).

The natural frequencies and mode shapes were calculated and compared with the beam analysis. The predicted frequencies at 2750 rpm are compared with the beam method results in Fig. 4. There is good agreement with the first mode and poor agreement with the higher. This was expected since the beam analysis is questionable for low aspect ratio, plate-like blades and can include the effects of steady state displacements only approximately.

As mentioned above, this method is currently limited to relative Mach numbers (normal to the local leading edge) less than one. Therefore, high axial Mach numbers or rotational speeds cannot be currently considered. Because of the relatively low Mach number and rotational speed predicted above for the onset of flutter in the bending mode, attention is focused on bending flutter of the blade with 30 degrees sweep. The axial Mach number was fixed at .35 and the rotational speed was varied. Figure 9 shows the damping versus rotational speed predicted by using the finite element method. For comparison the results are also shown for the beam method. There is fair agreement between the two methods for the first mode damping. The finite element method results are approximately .1 percent lower than those of the beam method. However, because of the relative insensitivity of damping to rotational speed, the difference in speed at which flutter will occur is more than 300 rpm. The higher modes were stable at these operating conditions and are not shown, however, it should be noted that the aerodynamic damping predictions of the two methods for the higher modes show poor agreement.

The finite element stability calculations were repeated at other operating conditions and the resulting flutter boundary is shown together with the beam results in Fig. 6. As can be seen, the first mode flutter boundary for the blade with 30 degrees of sweep is similar to that of the beam method but is somewhat more unstable. Thus, two independent methods predict that sweep has a significantly destablizing effect on bending mode flutter. The finite element method can not be presently used to predict torsion mode flutter for the 30 degree blade or for either mode of the 0 and 15 degree blade because of the restriction to subsonic relative flow.

SUMMARY AND CONCLUSIONS

The effect of sweep on fan blade flutter was studied by applying two analytical methods. An advanced fan stage was analyzed with 0, 15, and 30 degrees of sweep. The major conclusions from this investigation are summarized as follows:

1. Sweep has a predominantly aerodynamic effect on fan blade flutter which is beneficial for torsional modes and detrimental for bending modes.

2. The critical flutter mode is predominantly torsional for low sweep angles (less than 15 degrees) and predominantly bending for high sweep angles.

3. With significant sweep (30 degrees or more) the blades are significantly less stable than similar unswept blades.

4. The flutter modes are always found to be forward travelling waves for the torsional modes and backward travelling waves for the bending modes.

5. For the blade with 30 degrees of sweep there is fair agreement between the finite element and beam method damping predictions for the first mode and poor agreement for the higher modes.

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TABLE I. - BLADE PHYSICAL AND MATERIAL PROPERTIES

Number of blades	28
Hub radius, m	0.03876
Tip radius, m	1.021
Material Density, kg/m^3	4374.
Air density, kg/m^3	1.
Speed of sound, m/sec	340.3
Modulus of elasticity, N/m^2	1.23×10^{11}
Shear modulus, N/m^2	4.744×10^{10}

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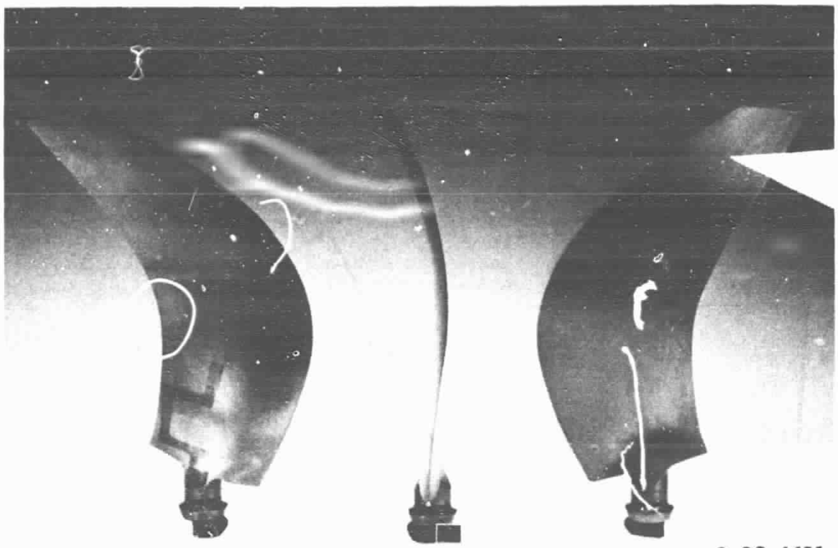
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Figure 1. - Advanced turboprop shape.

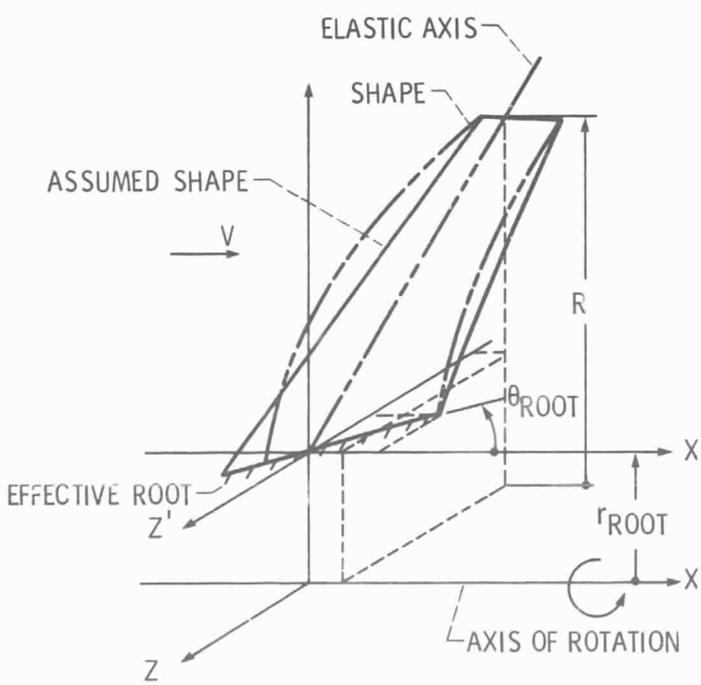

Figure 2. - Structural model-beam method.

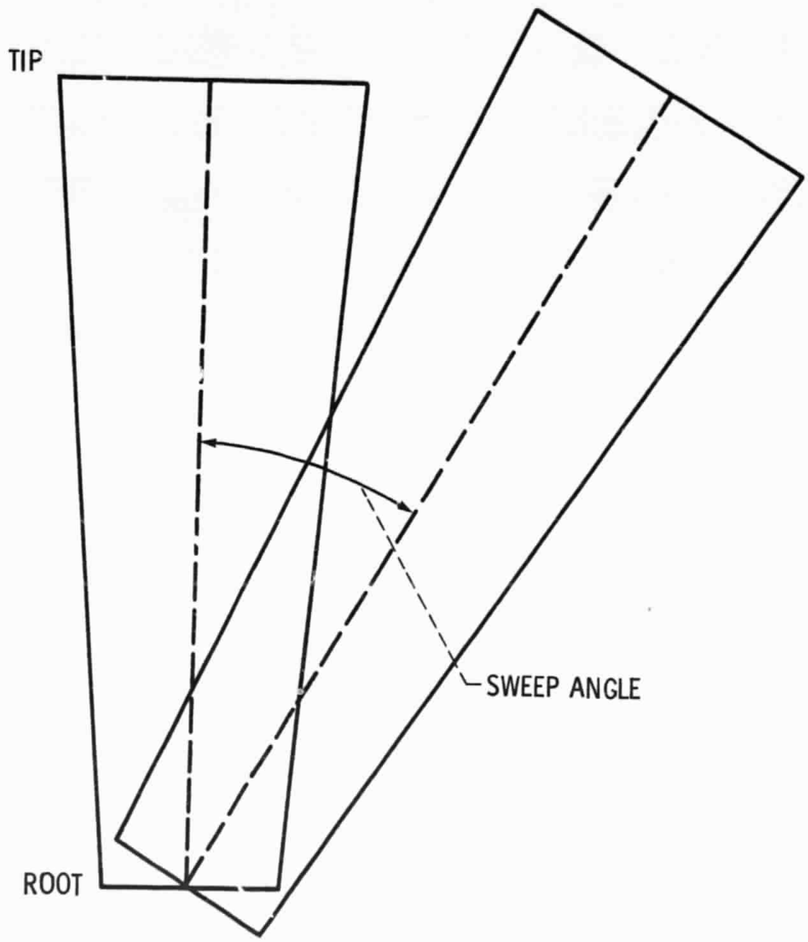

Figure 3. - Blade planforms, swept and unswept.

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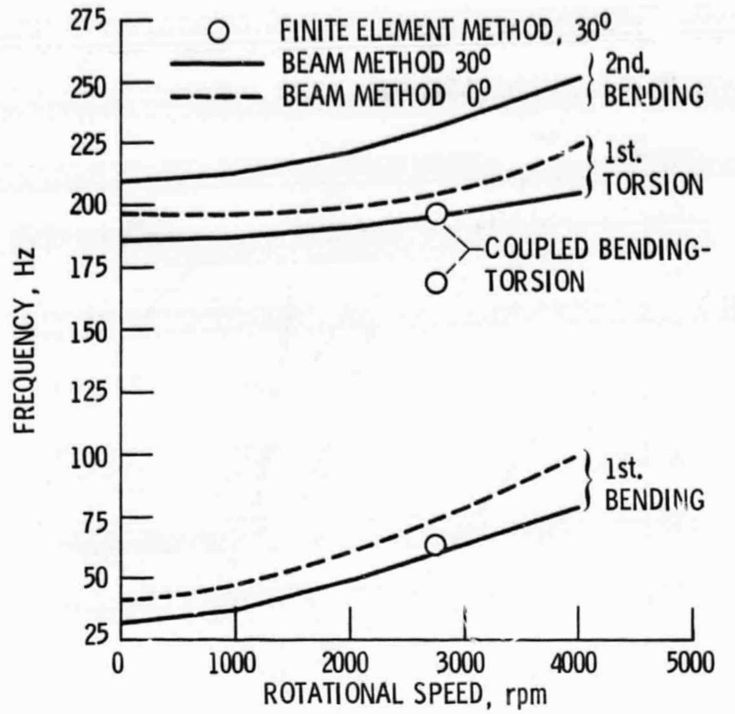

Figure 4. - Campbell diagram.

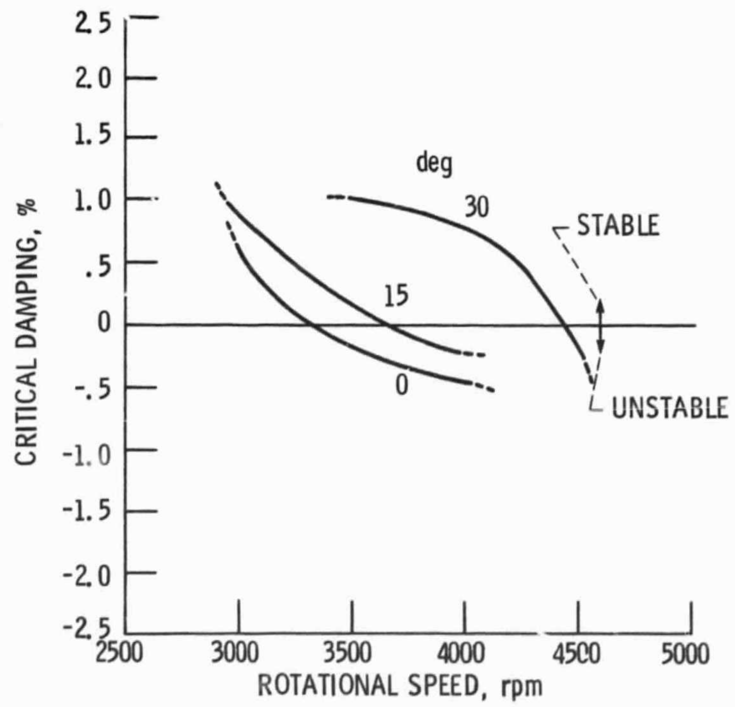

Figure 5. - Torsion mode damping, M = 0.43.

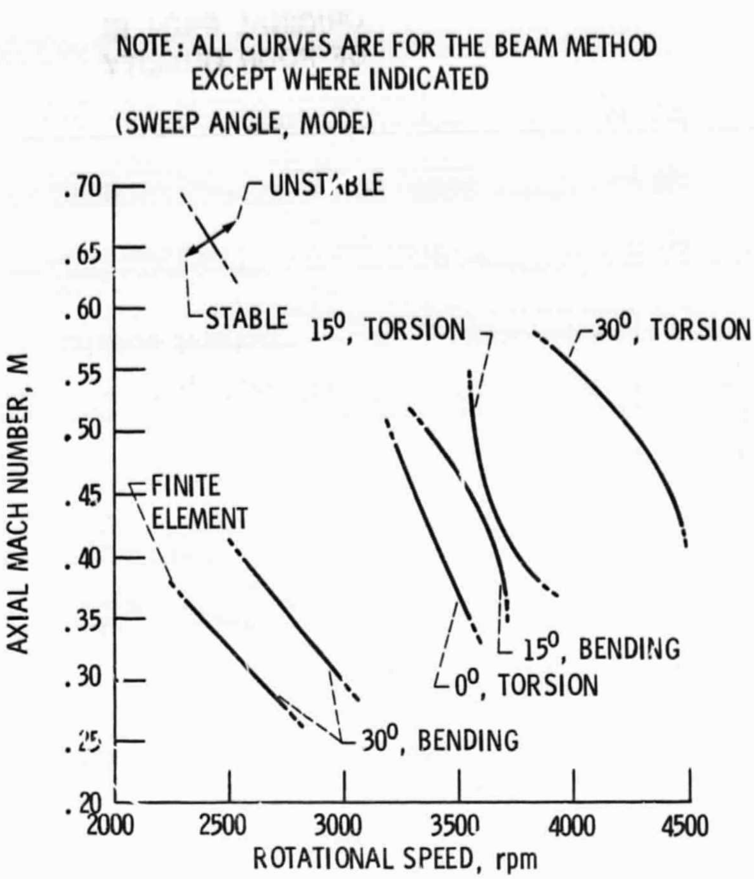

Figure 6. - Flutter boundaries.

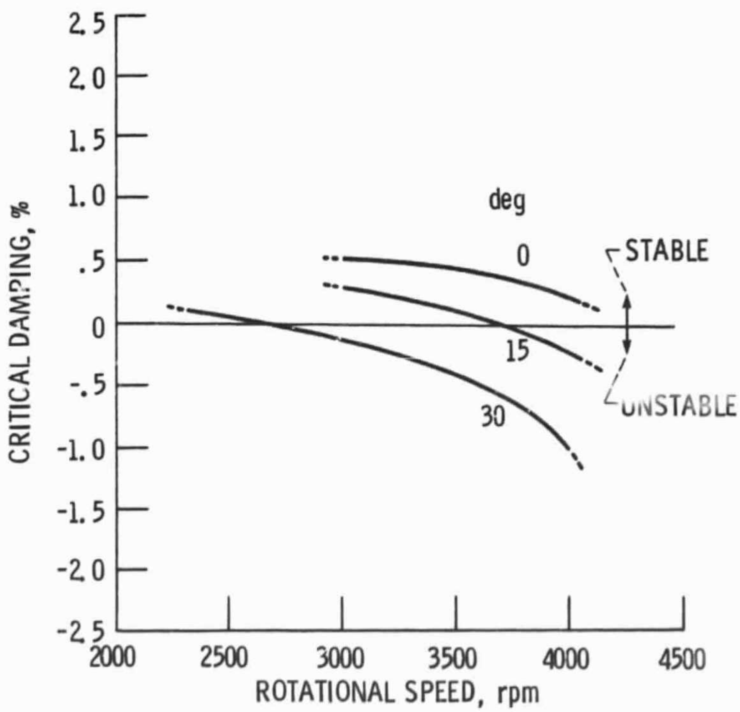

Figure 7. - Bending mode damping, M = .43.

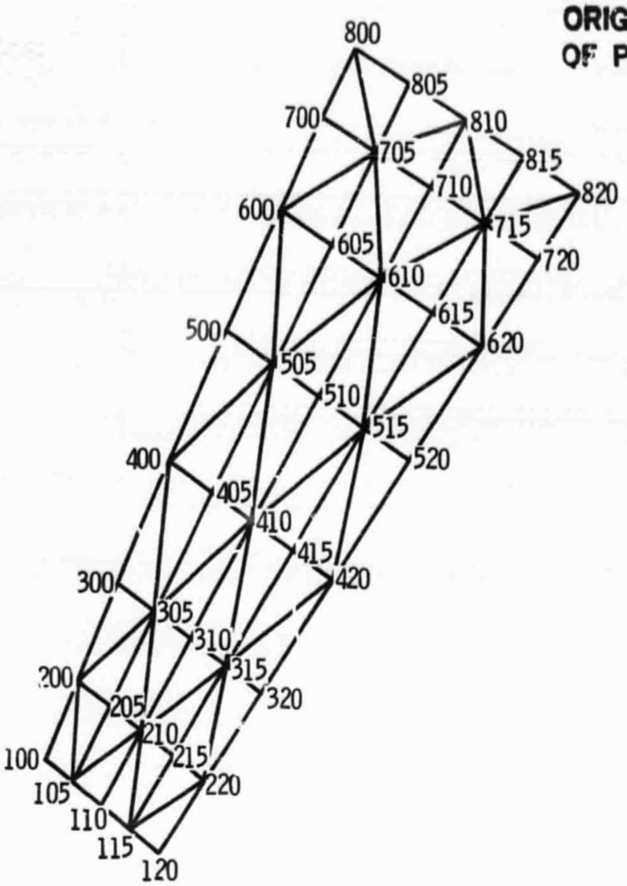

Figure 8. - Finite element model.

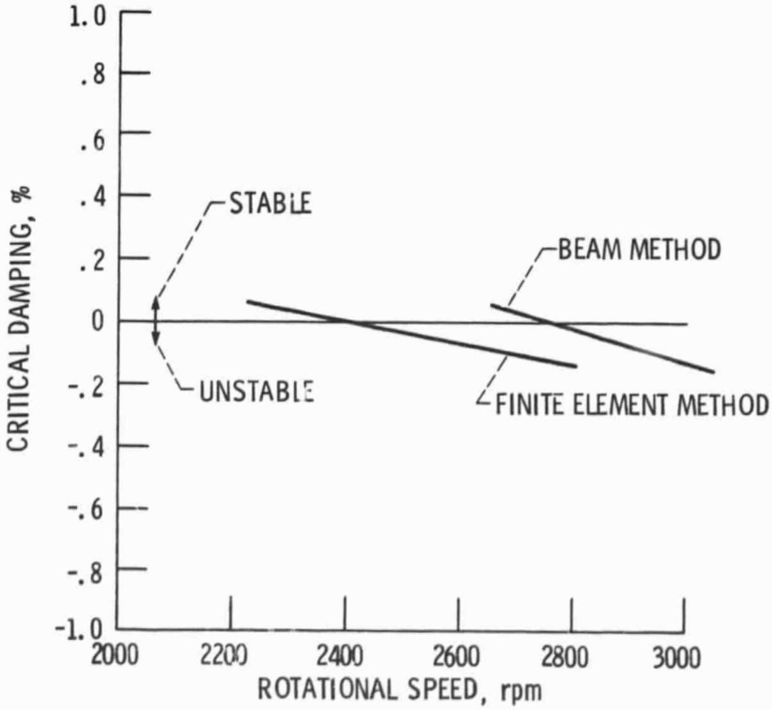

Figure 9. - First bending mode damping, M = 0.35.