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AEROELASTIC EFFECTS IN THE STRUCTURAL DYNAMIC ANALYSIS OF VERTICAL AXIS WIND TURBINES*

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ABSTRACT

Aeroelastic effects impact the structural dynamic behavior of vertical axis wind turbines (VAWTs) in two major ways. First, the stability phenomena of flutter and divergence are direct results of the aeroelasticity of the structure. Secondly, aerodynamic damping can be important for predicting response levels, particularly near resonance, but also for off-resonance conditions. The inclusion of the aeroelasticity is carried out by modifying the damping and stiffness matrices in the NASTRAN finite element code. Through the use of a specially designed preprocessor, which reads the usual NASTRAN input deck and adds appropriate cards to it, the incorporation of the aeroelastic effects has been made relatively transparent to the user. NASTRAN flutter predictions are validated using field measurements and the effect of aerodynamic damping is demonstrated through an application to the Test Bed VAWT being designed at Sandia.

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INTRODUCTION

The aeroelastic analysis of wind turbines is entirely similar to that done for subsonic aircraft wing structures, and most of the theory that has been developed for those structures carries over directly. The essence of aeroelastic behavior is that the aerodynamic loads depend on motions of the structure which change the angle of attack. As an example, for a horizontal wing structure, wing velocities in the vertical direction change the angle of attack in such a way that the motion is resisted by the induced aerodynamic loads. This type of motion produces aerodynamic damping. Alternatively, for wing torsion, the induced loads generally act to increase the motion, leading to a possible divergence or flutter condition.

In the case of flutter the oscillatory motion of the blade necessitates the use of unsteady aerodynamic theory. This theory introduces complex valued coefficients, which are functions of the reduced frequency (Strouhal Number), in the expressions for the aerodynamic loads. These coefficients alter the phase relations between the blade motions and the resulting aerodynamic loads, and can be very important in the prediction of flutter. For the analysis of divergence, which is a static phenomenon, the same equations apply, but the reduced frequency must be set to zero. Generally for VAWTs, flutter and divergence instabilities have not been an issue. However, during the design stage of a new turbine, it is always prudent to establish the flutter and divergence boundaries to avoid the catastrophic consequences associated with these phenomena.

For frequency response analysis aeroelasticity is important in establishing the level of aerodynamic damping. For VAWTs with high tip speeds aerodynamic damping can be substantial, leading to significant reductions in even the off-resonance response. Additionally, with the advent of modeling atmospheric turbulence, analysis procedures will have to accommodate dynamic response at all frequencies rather than just the integer multiples of the operating speed. Thus, to obtain accurate response levels near the natural frequencies of the rotor some reasonable estimate of the damping will be required. Since aerodynamic damping is at least as significant as the low level of structural damping that generally exists in VAWTs, it is important that it also be accounted for in the analysis.

The inclusion of the aeroelasticity is carried out by modifying the damping and stiffness matrices in the NASTRAN finite element code (using NASTRAN's "DMIG" input option). These modifications are incorporated with the Coriolis and Softening matrices required for modeling the rotating coordinate system effects. The stability and frequency response of the turbine are subsequently investigated using the appropriate NASTRAN solution procedure. Through the use of a specially designed preprocessor, which reads the usual NASTRAN input deck and adds appropriate cards to it, the incorporation of the aeroelastic effects has been made relatively transparent to the user.

A number of other investigators have addressed the issue of aeroelasticity in VAWTs [1,2,3] with good success. Although the approach is similar to the one used here, their work is based on a modal representation using generalized degrees of freedom. In addition, the phase relations between the structural motions and the induced aerodynamic loads are taken to be zero. The work presented here utilizes physical degrees of freedom, which simplifies the NASTRAN input of the aeroelasticity matrices. The phase relations between the structural motions and the induced loads, as prescribed by unsteady aerodynamic theory, are also retained.

The remainder of this paper includes sections which describe the theory used in the development of the aeroelasticity matrices, present and discuss specific results, and draw some conclusions.

AEROELASTICITY THEORY FOR VAWTS

In this analysis, a VAWT blade is visualized as a series of straight airfoil sections joined together to form the desired shape. The theory for the aeroelasticity of a wing structure is assumed to be applicable to each segment. An excellent presentation of the physics and the governing equations of subsonic aeroelasticity for wing structures can be found in [4]. The equations below are reproduced from that reference. As indicated above, unsteady aerodynamic theory is used in their development.

For subsonic flutter, the lifting force, L, and the moment about the center of twist, M, resulting from the motion of a blade segment, are given by

$$L = a_0 \rho V^2 b \left\{ -C\frac{\dot{u}}{V} + C\theta + [C(1-2a)+1]\frac{b\dot{\theta}}{2V} - \frac{b}{2V^2}\ddot{u} - \frac{ab^2}{2V^2}\ddot{\theta} \right\}$$

$$M = a_0 \rho V^2 b \left\{ d_1 \left[-C\frac{\dot{u}}{V} + C\theta + C(1-2a)\frac{b\dot{\theta}}{2V} \right] + d_2 \frac{b\dot{\theta}}{2V} - \frac{ab^2}{2V^2}\ddot{u} - \left(\frac{1}{8}+a^2\right)\frac{b^3}{2V^2}\ddot{\theta} \right\} \tag{1}$$

where, referring to Figure 1,

- a_0 is the coefficient of lift (per radian),
- ρ is the air mass density,
- V is the air speed,
- b is the half chord length,
- a is the fraction of b that the center of twist is behind the half chord point,
- d_1 is the distance the center of pressure is ahead of the center of twist,
- d_2 is the distance the rear aerodynamic center of pressure is ahead of the center of twist,
- C is the Theodorsen function,
- u is the vertical wing motion,
- θ is the rotational wing motion about the center of twist.

The terms which are proportional to the second time derivatives of u and θ represent "apparent mass" effects (additional mass due to air entrainment by the blade). Since the air mass density is so much smaller than that of the blade, these terms have been neglected in this analyis. Also, the half chord point and center of twist of the blade section are taken to be colinear, rendering the quantity, a, to be zero. Incorporating these considerations, the equations for L and M become

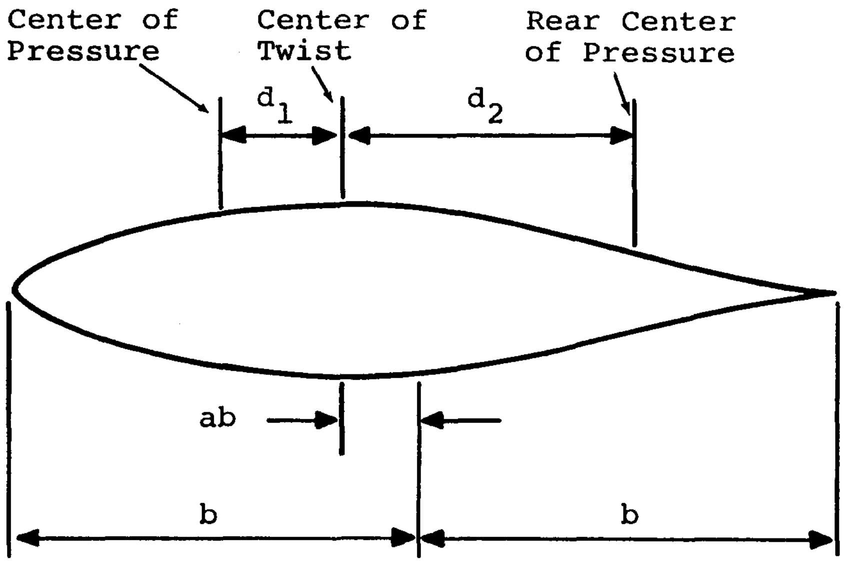

Figure 1. Blade Schematic.

$$L = a_0 \rho V^2 b \left[- C\frac{\dot{u}}{V} + C\theta + (1+C)\frac{b\dot{\theta}}{2V} \right]$$

$$M = a_0 \rho V^2 b \left[- d_1 C\frac{\dot{u}}{V} + d_1 C\theta + (d_1 C + d_2)\frac{b\dot{\theta}}{2V} \right] \tag{2}$$

Equation (2) can be specialized further by replacing V with $R\Omega$, where R is the radial distance from the tower to the blade location of interest, and Ω is the rotational speed of the turbine. With this approximation, only the relative air speed corresponding to the rotation of the rotor is taken into account in this aeroelasticity model. The free stream wind velocity is neglected. Also, for these computations, d_1 and d_2 are taken to be b/2 and -b/2, respectively. This places the center of pressure and rear center of pressure at the quarter chord and three quarter chord points, respectively.

The Theodorsen function, C, is of great importance for accurately predicting flutter in wing structures, but less so in VAWTs. It is a complex valued function of the reduced frequency, k, and therefore affects the phase relationships between the wing motions and the resulting aerodynamic loads. It is usually found in tabular form but can be reasonably approximated by

$$C(k) = \left[1 - \frac{.165k^2}{k^2 + (.0455)^2} - \frac{.335k^2}{k^2 + (.3)^2} \right]$$

$$-i \left[\frac{.165 \cdot .0455k}{k^2 + (.0455)^2} - \frac{.335 \cdot .3k}{k^2 + (.3)^2} \right] \tag{3}$$

where

$k = \frac{\omega b}{V}$ is the reduced frequency,

ω is the oscillatory frequency of the wing, i.e., the flutter frequency.

For flutter calculations, the value of ω used in the evaluation of the Theodorsen function should be set at the flutter frequency. As this frequency is not precisely known at the outset, some amount of manual iteration is required. To establish divergence conditions ω should be set to zero since divergence is a static phenomenon. For providing aerodynamic damping in frequency response computations, ω should be set to some characteristic frequency anticipated in the response, i.e. 3/rev.

In order to incorporate Equations (2) into NASTRAN, they are cast in a finite element form. This is accomplished using a Galerkin procedure. For the beam elements of which the VAWT blades are composed, the transverse and torsional degrees of freedom are assumed to vary linearly from one end of the element to the other. In the local element coordinate system, these motions are represented by

$$\begin{Bmatrix} u \\ \theta \end{Bmatrix} = \begin{bmatrix} 1-s & 0 & s & 0 \\ 0 & 1-s & 0 & s \end{bmatrix} \begin{Bmatrix} u_1 \\ \theta_1 \\ u_2 \\ \theta_2 \end{Bmatrix}$$

where the subscripts denote the motions at either end of the element, and s is the arc length measured along the element and normalized by the element length.

Inserting this approximation into Equations (2), premultiplying by the same linear shape functions, and integrating over the length of the beam element, the contributions to the element damping and stiffness matrices are obtained as shown below

<u>Damping Matrix</u>

$$-\int_0^1 \frac{B}{V} \begin{bmatrix} -C(1-s)^2 & (1+C)\frac{b}{2}(1-s)^2 & -Cs(1-s) & (1+C)\frac{b}{2}s(1-s) \\ -d_1C(1-s)^2 & (d_2+d_1C)\frac{b}{2}(1-s)^2 & -d_1Cs(1-s) & (d_2+d_1C)\frac{b}{2}s(1-s) \\ -Cs(1-s) & (1+C)\frac{b}{2}s(1-s) & -Cs^2 & (1+C)\frac{b}{2}s^2 \\ -d_1Cs(1-s) & (d_2+d_1C)\frac{b}{2}s(1-s) & -d_1Cs^2 & (d_2+d_1C)\frac{b}{2}s^2 \end{bmatrix} ds \qquad (4)$$

<u>Stiffness Matrix</u>

$$-\int_0^1 BC \begin{bmatrix} 0 & (1-s)^2 & 0 & s(1-s) \\ 0 & d_1(1-s)^2 & 0 & d_1s(1-s) \\ 0 & s(1-s) & 0 & s^2 \\ 0 & d_1s(1-s) & 0 & d_1s^2 \end{bmatrix} ds$$

where

$B = a_0\rho V^2 bL,$

L is the length of the element.

Note that the quantities, V, b, d_1, d_2, and C, may all be functions of s. The integrals are numerically evaluated using two-point Gaussian integration.

As NASTRAN's DMIG input option only allows one matrix to be input for each of the structural matrices, it is necessary to assemble all of the element contributions prior to NASTRAN input. Before this can be carried out, however, all of the individual element matrices must be transformed from the local frames in which they have been developed, to the global coordinate system.

Having provided these matrices to NASTRAN, flutter and divergence calculations are carried out using one of NASTRAN's complex eigenvalue solvers. Modes which are fluttering have negative damping coefficients, and divergent modes have null or negative frequencies. Frequency response analysis is accomplished in the usual manner using NASTRAN's frequency response solver.

PRESENTATION AND DISCUSSION OF RESULTS

To validate the analysis technique for predicting the onset of flutter, two test cases have been completed. First, the predicted flutter speed for a straight, uniform, cantilevered wing was compared to that obtained from an exact solution, and nearly perfect agreement was attained. Secondly, the flutter speed was computed for a specific configuration of the Sandia two meter VAWT, for which experimental flutter data has been obtained. The flutter prediction of 680 RPM is in good agreement with the observed value of 745 RPM, especially since the predicted result does not include any structural damping. The flutter mode was also correctly predicted.

Having established some credibility for the method, flutter predictions for the Sandia 34-m Test Bed VAWT design shown in Figure 2 have been made. A key innovation in this design is the variable blade section, which causes the rotor to stall at higher tip speeds. This permits higher operating speeds which reduce gear box loads and cost.

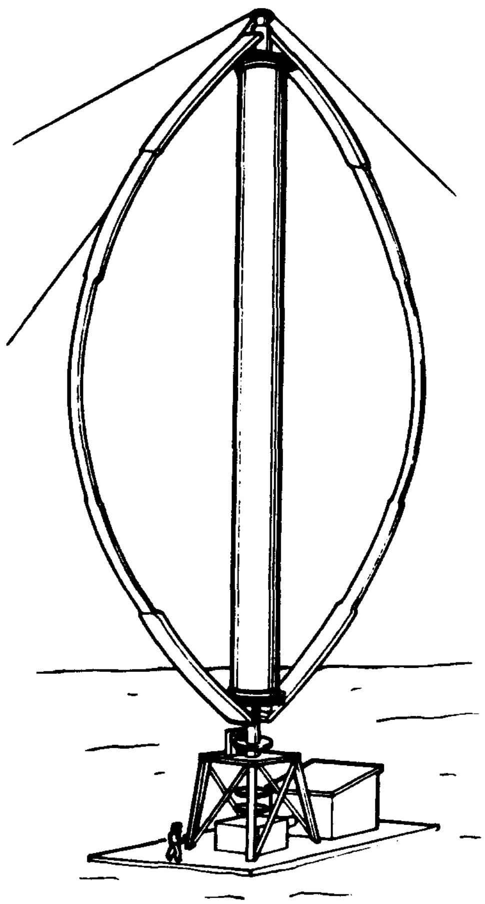

Figure 2. Artist's Concept of the Sandia 34-m Test Bed Design.

In Figure 3 the damping coefficient for the various modes of the turbine is plotted versus rotor RPM. The modes, which are characterized by their dominant behavior at 0 RPM, are identified by the labels to the right of the figure. The Pr or propeller modes are characterized by twisting motion of the rotor about the axis which is colinear with the tower. The F or flatwise modes primarily involve blade motion in the plane of the rotor with very little, if any, tower participation. The subscript, S, denotes symmetry in the motion of the two blades, and A, asymmetry. The B or butterfly modes consist of blade motion out of the plane of the rotor, which resembles the flapping of butterfly wings. This is usually coupled with some out-of-plane tower motion. And finally, the TI modes, or tower in plane modes, primarily involve tower motion in plane of the rotor.

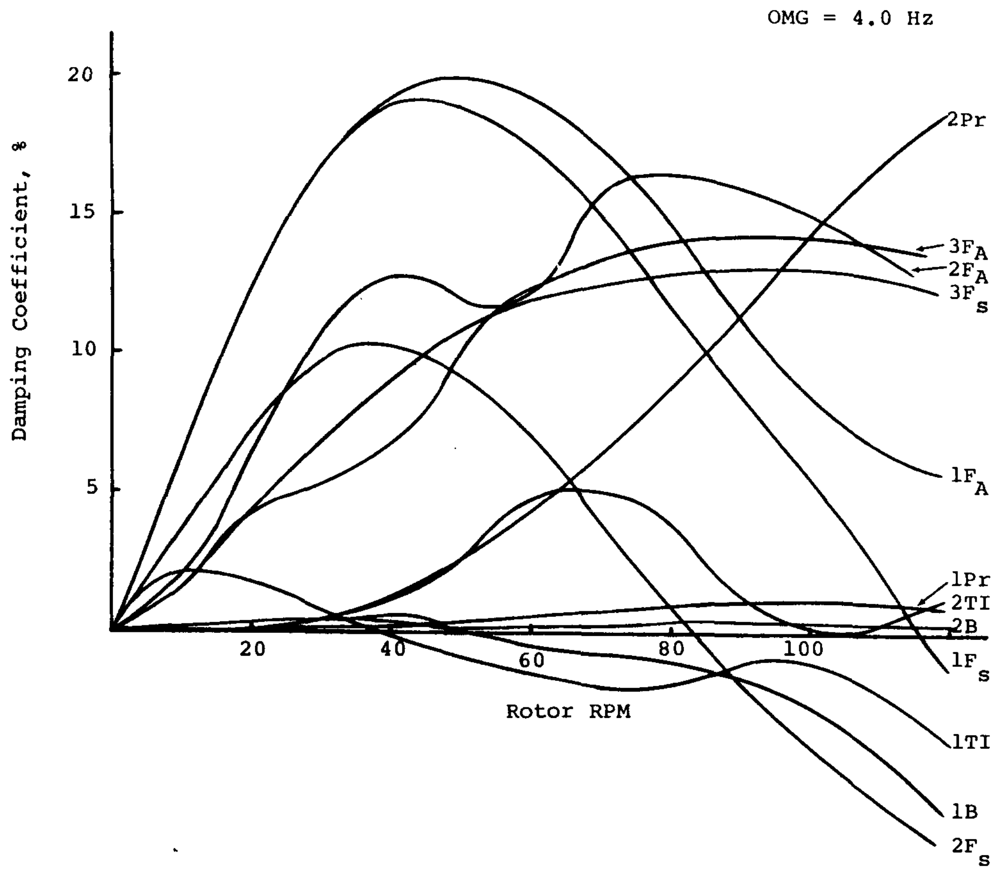

Figure 3. Damping Coefficients Versus RPM for the 34-m Test Bed, Aerodynamic Damping Only.

The damping coefficients shown in this figure correspond to percent of critical structural, rather than viscous damping. However, they derive totally from aeroelastic effects, i.e., no structural damping has been included. In computing these curves the oscillatory frequency, ω, was set at 4 hz, which corresponds to the frequency of the $2F_S$ mode as it crosses the axis at 82 RPM. Generally the flatwise modes are substantially damped over a large range of RPMs and eventually become unstable as they cross the axis. Other modes, such as the 1B and 1TI, become unstable at a relatively low RPM and remain modestly so out to higher rotational speeds. These are not as crucial as they might seem since, as will be shown, a small amount of structural damping stabilizes them. The mode that actually establishes the flutter speed is the flatwise mode that first goes unstable. As shown in Figure 3, this corresponds to the $2F_S$ mode and, consequently, the flutter speed for the Test Bed is predicted to be approximately 82 RPM. This is well above the operating speed range of 28 to 40 RPM.

In Figure 4 damping coefficients similar to those of Figure 3 are shown, except that in Figure 4, structural damping at a level of 2 percent of critical has been included. This level is consistent with values reduced from data taken from Sandia's two-meter VAWT [5]. In general, the primary effect of including the structural damping is that the curves for the various modes are raised by approximately the amount of damping specified. This tends to stabilize the 1B and 1TI modes and increases the flutter speed to 89 RPM.

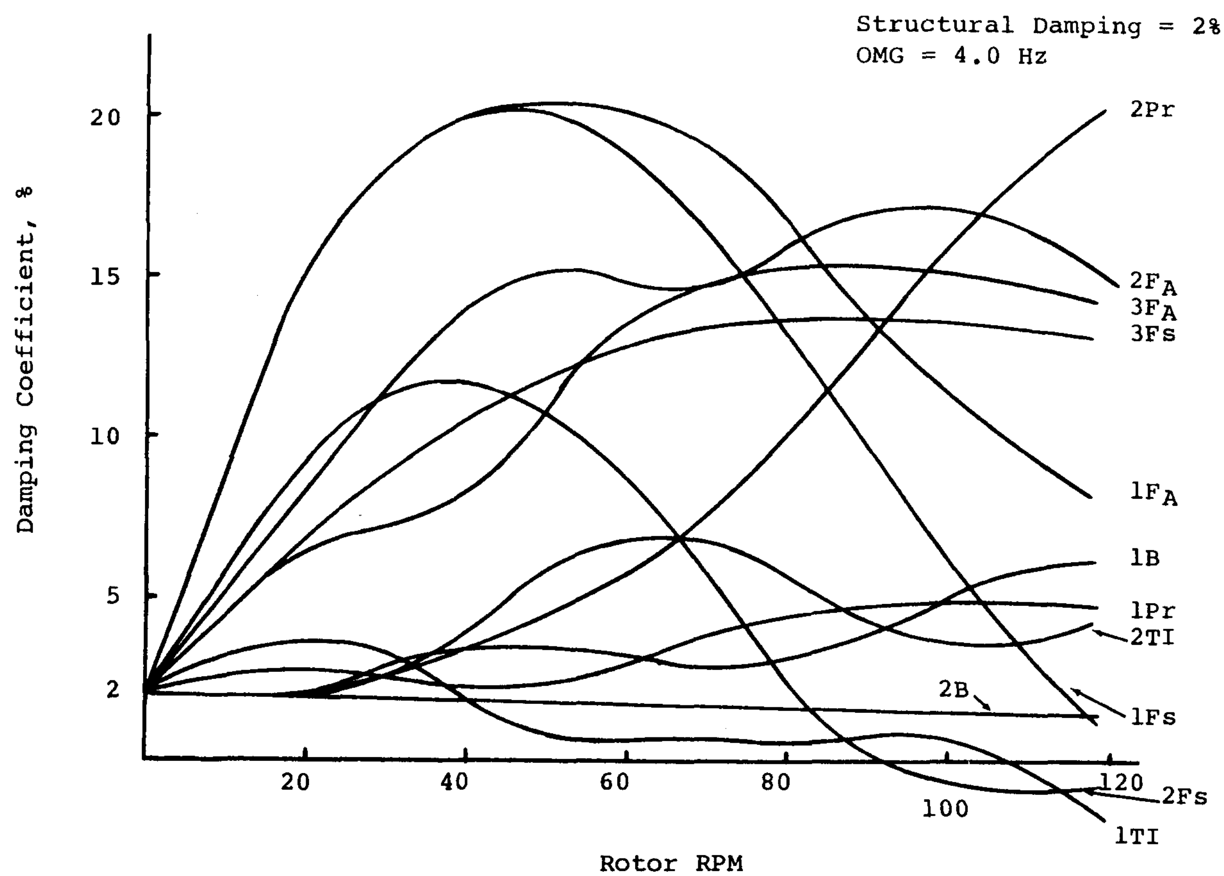

Figure 4. Damping Coefficients Versus RPM for the 34-m Test Bed, Aerodynamic Plus Structural Damping.

In an attempt to discern the role of the Theodorsen function in analyzing the aeroelastic behavior of VAWTs, ω was set to zero. For this value, the Theodorsen function is real rather than complex and has a value of unity. In this case, the predicted flutter speed becomes 84 RPM rather than 82, a modest difference.

However, damping factors are approximately 20 percent greater than previous values, which may lead to some degree of unconservatism in the predicted structural response.

To investigate the divergence characteristics of the Test Bed, the fanplot shown in Figure 5 was produced using a value of zero for ω. Actually the fanplot proved to be relatively insensitive to the value of ω used. The dashed P lines denote the forcing frequencies that are present at each RPM as a result of the rotor turning in a steady wind. Recalling that divergence is indicated by a natural frequency dropping to zero, there is no indication of divergence or even its onset from this figure. The descent of the frequency of the 1B mode is a result of the whirl instability rather than aeroelastic divergence.

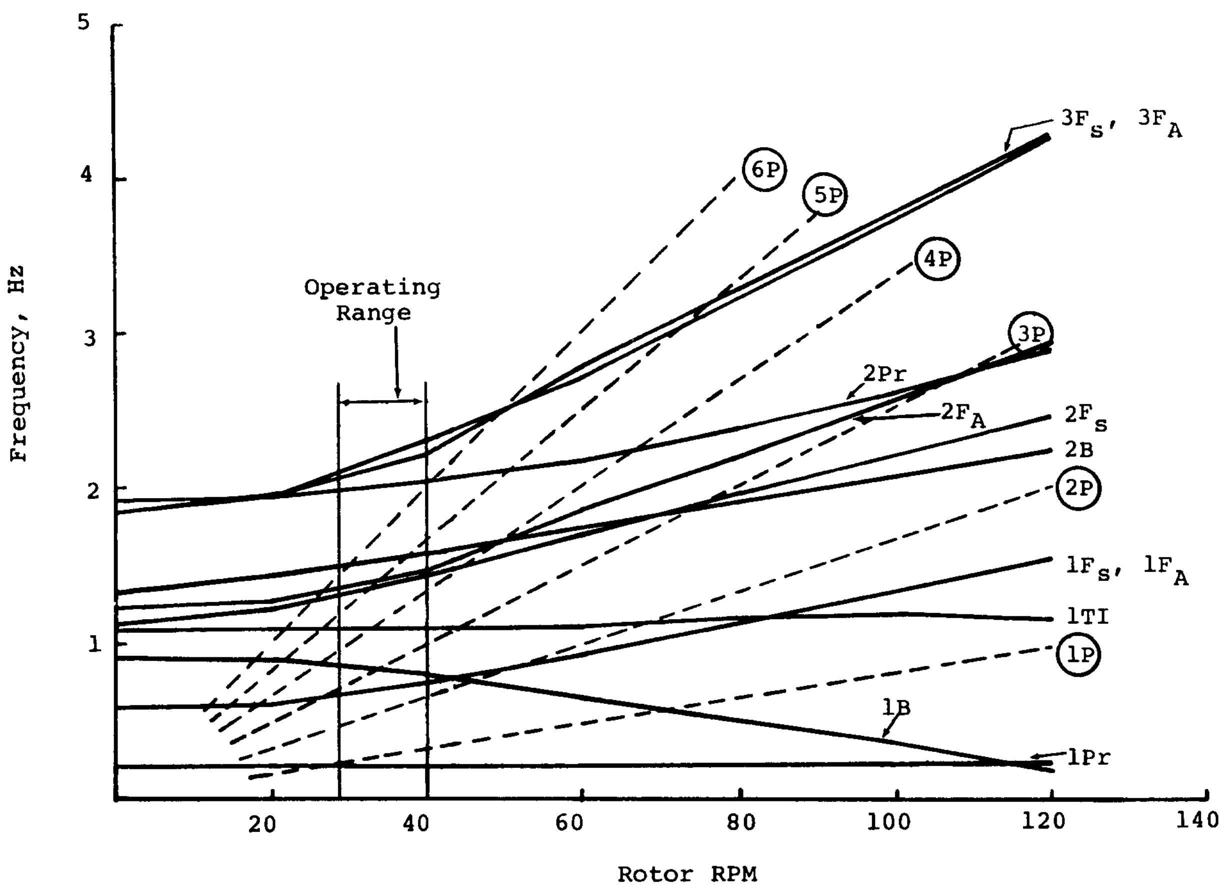

Figure 5. Fanplot for the 34-m Test Bed.

The effect of aerodynamic damping on the off-resonance response of a VAWT was determined by computing the response of the 34-m Test Bed with and without the aeroelasticity, at a rotational speed of 40 RPM. Results for the blade flatwise RMS stress versus vertical location are provided in Figure 6. The curves shown correspond to a wind speed of 20.11 m/s (45 MPH). As indicated, the aerodynamic damping provides an RMS peak stress reduction of approximately 20 percent. If the flatwise vibratory stresses happen to drive the fatigue life of the blade, this reduction would substantially increase its life.

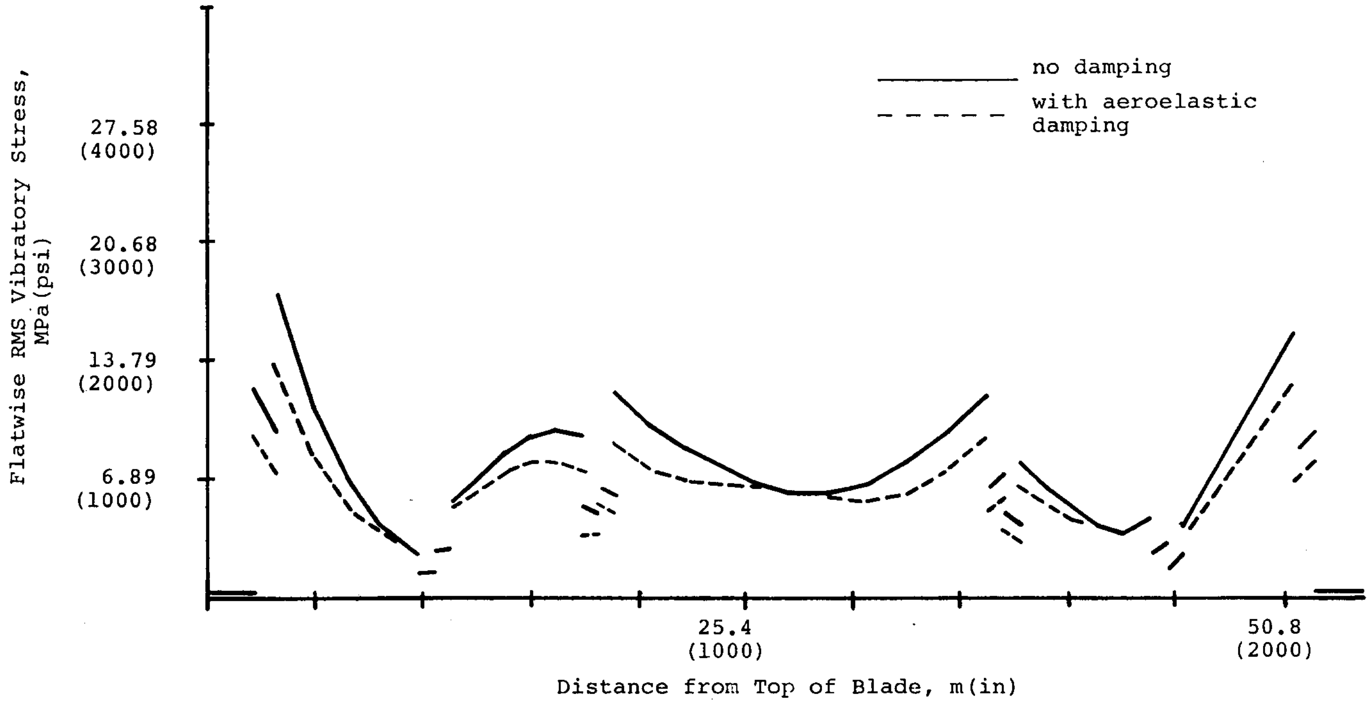

Figure 6. **Effect of Aerodynamic Damping on Flatwise RMS Vibratory Stresses for the 34-m Test Bed.**

CONCLUSIONS

Aeroelasticity can produce unstable behavior in VAWTs associated with the phenomena of flutter and divergence. The occurrence of divergence, however, is unlikely because of the additional torsional stiffness afforded the blade by its attachment to the tower at each end, in contrast to the cantilever design of an aircraft wing. Additionally, it is anticipated that the whirl instability point would always occur prior to the onset of divergence. The possibility of flutter is not as remote as divergence. However, predicted flutter speeds tend to be two to three times that of the operating speed. In any case, for a new turbine design, it is always prudent to establish the flutter speed in order to avoid the serious consequences of flutter, should it occur. The method described here provides a relatively simple and accurate means of accomplishing this.

The same method also provides a simple way to incorporate aerodynamic damping in frequency response analyses. As shown, aeroelasticity can produce damping factors associated with flatwise blade motion as high as 20 percent of critical. At these levels, even the off-resonance response can be significantly reduced. This suggests that an additional benefit of VAWT designs with higher tipspeeds may be a reduction in flatwise blade response due to higher damping levels.

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