SANDIA REPORT

SAND86–1085 • Unlimited Release • UC–60
Printed September 1986

Developments in Blade Shape Design for a Darrieus Vertical Axis Wind Turbine

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Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A02
Microfiche copy: A01

SAND86–1085
Unlimited Release
Printed September 1986

Distribution
Category UC–60

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Abstract

A new computer program package has been developed that determines the troposkein shape for a Darrieus Vertical Axis Wind Turbine Blade with any geometrical configuration or rotation rate. This package allows users to interact and develop a "buildable" blade whose shape closely approximates the troposkein. Use of this package can significantly reduce flatwise mean bending stresses in the blade and increase fatigue life.

Developments in Blade Shape Design for a Darrieus Vertical Axis Wind Turbine

Introduction

As the wind turbine industry enters an era without government tax credits, it becomes increasingly important that the cost per kilowatt hour of wind-produced power be substantially reduced. Wind turbines that are less expensive to manufacture but more dependable to operate are required in order to compete with other sources of energy. New turbine designs, therefore, must become less conservative and incorporate improved fatigue design and analysis techniques for increased turbine longevity.

Vertical Axis Wind Turbine(VAWT) blades, because of their large oscillatory loading conditions, are very susceptible to fatigue failure. When combined with the oscillatory loading, the mean loading due to centrifugal forces and gravity also contributes significantly to fatigue damage. One way of lowering mean stresses and extending the fatigue life is to design the blade such that its shape closely approximates an ideal shape called the troposkien or "skipping-rope" shape. This reduces the flatwise bending stresses due to centrifugal and gravitational forces as the blade tends to displace less from its original shape. Recently a methodology for designing an improved blade shape and thus lowering the mean stresses for VAWTs was developed at Sandia and is the subject of this report.

Development of Darrieus Blade Shape

It was realized early in the development of Darrieus VAWTs that the shape of the blade was important. G. J. M. Darrieus states in his 1931 U.S. patent of a VAWT that each blade should "have a stream-line outline curved in the form of a skipping rope."[1] More recently, in the early 1970's, the National Research Council of Canada independently developed the concept of a VAWT and noted that under the action of centrifugal forces, a perfectly flexible blade assumes the approximate shape of a catenary.[1] This is not precise, however, as a catenary is the shape formed by a perfectly flexible cable of uniform density and cross section hanging freely from two points. Once the cable is rotated about an axis through the end points, the shape deviates from the catenary and becomes a "troposkien." Figure 1 shows a comparison of a symmetric (gravity omitted) troposkien and a catenary for a VAWT blade of uniform density.

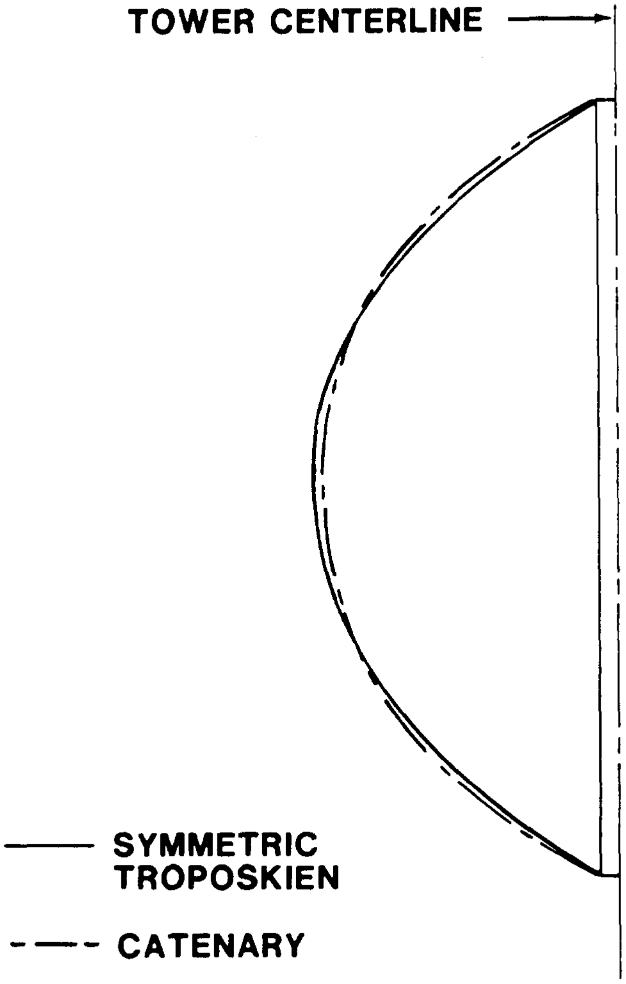

Figure 1. Symmetric Troposkein vs. Catenary Shape

In 1974, Blackwell and Reis, in their report, *Blade Shape for a Troposkien Type of Vertical-Axis Wind Turbine,*[1] defined the term troposkien as "the shape assumed by a perfectly flexible cable of uniform density and cross section if its ends are attached to two points on a vertical axis and it is then spun at constant angular velocity about that vertical axis." Since a VAWT blade is not perfectly flexible, it should be bent or formed as closely as possible into the shape it would become during rotation if it were flexible, thus minimizing the flatwise bending stresses. Blackwell and Reis developed the equations that geometrically describe a troposkien shape for a blade of uniform density and used an iterative solution of these equations in their computer program TROP. The equations were developed for only half the blade, and gravity effects were neglected in the solution; thus, the resulting troposkiens were symmetric about the equator. This was a good approximation for high-rotation-rate, small-diameter turbines like the Sandia 2-m turbine.[2]

In the late 1970's the iterative technique employed by Blackwell and Reis to define any uniform-density troposkien was extended by Sandia to include gravitational effects and blades of three different cross sections. These modifications were implemented in the computer program BENDO.

Current Sandia blade-shape designs have been based in general on the computer program DMG,[3] which formulates the blade shape as an approximation to the symmetric troposkien (as determined by BENDO). This approximation consists of three sections: a straight section at both the top and bottom portions of the blade and a circular arc through the equator that meets the straight sections tangentially. The DMG user inputs the height and diameter of the turbine rotor and the upper and lower blade-to-tower angles. DMG then determines the straight-circular arc-straight (S-C-S) geometry that approximates the symmetric troposkien for that particular turbine. Figure 2 shows a comparison of a symmetric troposkien and its S-C-S approximation for a VAWT blade of uniform density. The S-C-S approximation has an advantage over the catenary approximation in that the blade-to-tower angles can be made to match those of the troposkien. This tends to lower the flatwise bending stresses. When it was realized that gravity should be included in the troposkien formulation, the blade-shape design continued to be S-C-S approximations to a symmetric troposkien, but the blade-to-tower angles were adjusted to account for the blade sag.

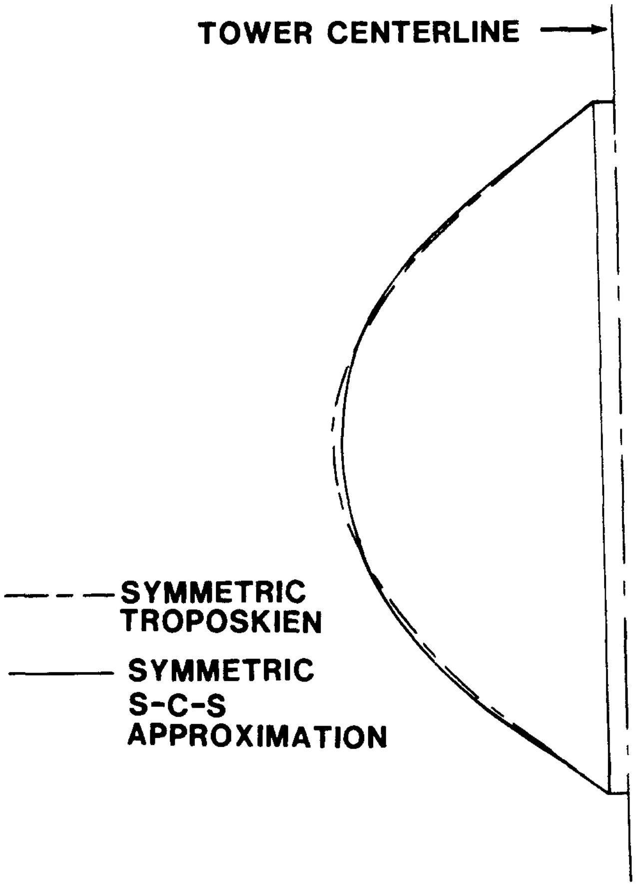

Figure 2. Symmetric Troposkien vs. Symmetric S-C-S Approximation

In the remainder of this report the definition of a troposkien shall be expanded to become "the shape assumed by a flexible structure of uniform or nonuniform density attached at its ends to a vertical axis such that when it is spun at a constant angular velocity about the vertical axis, no flatwise bending stresses occur in the structure." With the inclusion of nonuniform densities, the definition becomes more general and allows for design conditions where blades are constructed in multiple sections with varying geometrical or material properties and heavy joint sections. This is the case for the design of the Sandia 34-m Test Bed.* It should be noted that a troposkien shape for a particular blade or flexible structure is different for each rate of rotation when gravity is included. When gravity is excluded, the troposkien shape is the same for any rotation rate.

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*The 34-m Test Bed is a prototype VAWT being designed and constructed by Sandia. It has a rotor diameter of 110 ft (34 m) and an H/D ratio of 1.25. Each blade has five sections: a straight 48-in. chord section at each end of the blade, two 42-in. chord intermediate sections, and a 36-in. chord center section. The 48-in. chord has an NACA 0021 contour and the 36- and 42-in. chords have an SNLA 0018/50 contour.[4]

Development of New Troposkien Program

A recently developed troposkien shape-determination program called TROP-II[3] combines the previous developments of the programs TROP and BENDO and includes additional features and improvements. It employs the iterative technique developed by Blackwell and Reis to determine the troposkien shape and includes gravity, nonuniform blade densities, lumped masses, and the enforcement of a constant blade length. It also allows for the offset due to tower radius. These enhancements will enable the designer to produce blades that will more closely approximate exact troposkiens.

Figure 3 is a schematic that shows the loads on a perfectly flexible cable rotating at a constant angular velocity about a vertical axis Z. The distance from the Z axis to a point on the cable is indicated by R. R_{max} is the maximum distance from the Z axis to a point on the cable. This point is called the equator and always occurs where a tangent to the cable is in a vertical orientation. The loads acting along the length of cable are the centrifugal forces and the gravitational forces.

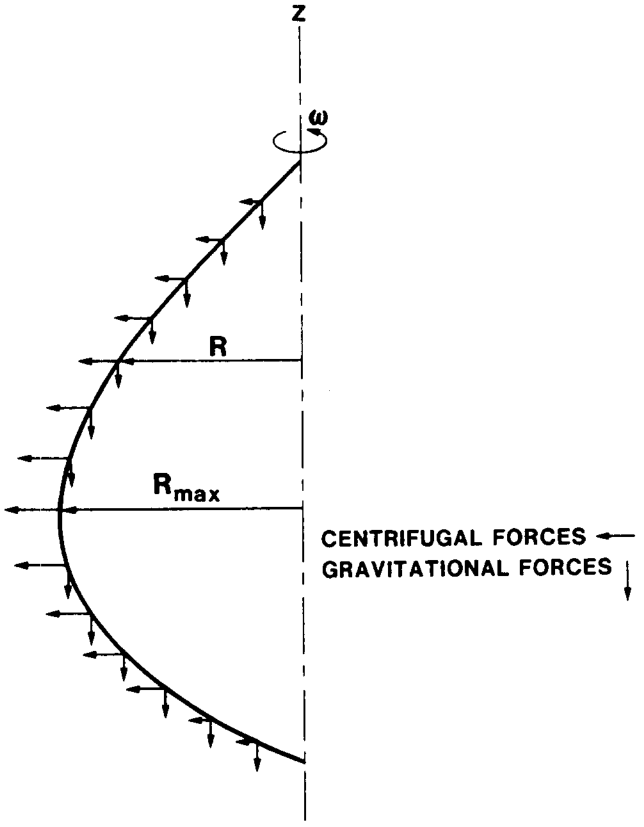

Figure 3. Loads on a Perfectly Flexible Cable Rotating About a Vertical Axis

Figure 4 is a free-body diagram that shows the loads on a section of the cable when it is rotating at a constant angular velocity. T_o is the tension in the cable at the equator and acts vertically downward. T is the tension at an arbitrary point P. Intermediate points on the cable section are designated as P_1, P_2, and P_3, and n is the number of cable segments between the equator E and the point P. Summing forces in the horizontal direction for this cable section results in

$$T \sin\theta = C \tag{1}$$

where C, the centrifugal force, can be formulated as

$$C = \int_0^S \sigma\, \omega^2\, R ds\ . \tag{2}$$

The quantity σ is the mass of the cable per unit length, and S is the length of cable between point E, the equator, and point P in Figure 4.

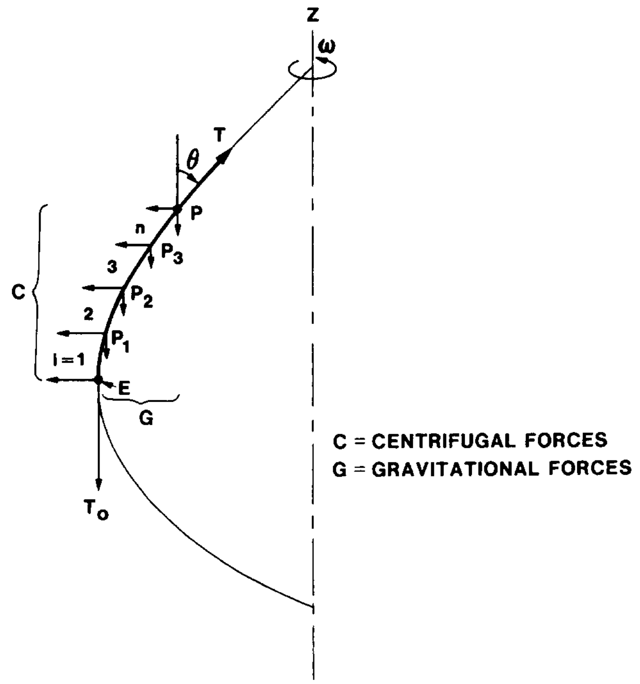

Figure 4. Free-Body Diagram of Section of Rotating, Flexible Cable

Summing forces in the vertical direction results in

$$T \cos\theta = T_o + G \tag{3}$$

where G, the gravitational force, can be written as

$$G = \int_0^S \sigma\, g ds \tag{4}$$

Here, g is the acceleration due to gravity.

Dividing Eq (1) by Eq (3) gives

$$\tan\theta = \frac{C}{T_o + G} \ . \qquad \textbf{(5)}$$

Holding the mass per unit length constant (thus making the gravitational force per unit length constant) and substituting Eqs (2) and (4) into Eq (5), one obtains

$$\tan\theta = \frac{\sigma\,\omega^2 \int_o^S R ds}{T_o + \sigma g s} \ . \qquad \textbf{(6)}$$

This is the same as Eq (6) in Reference 1, where it is solved after neglecting σgs and gravity. For the more general case of nonconstant mass per unit length (and thus nonconstant gravitational force per unit length) substitution of Eqs (2) and (4) into Eq (5) yields

$$\tan\theta = \frac{\omega^2 \int_o^S \sigma R ds}{T_o + g \int_o^S \sigma ds} \qquad \textbf{(7)}$$

This equation can be solved by breaking it up into a series of integrals as follows:

$$\tan\theta = \left\{\omega^2 \div \left[\left(T_o + g\int_o^{S_1} \sigma_1 ds\right) + \left(T_o + g\int_{S_1}^{S_2} \sigma_2 ds\right) + \ldots + \left(T_o + g\int_{S_{n-1}}^{S} \sigma_i ds\right)\right]\right\} \times \left\{\int_o^{S_1} \sigma_1 R_1 ds + \int_{S_1}^{S_2} \sigma_2 R_2 ds + \ldots + \int_{S_{n-1}}^{S} \sigma_i R_i ds\right\} \qquad \textbf{(8)}$$

where S_i is the length of cable from point E to point P_i. R_i is the distance from the Z axis to the midpoint of cable section i, and σ_i is the mass per unit length of cable section i.

The solution to Eq (8) is accomplished with the use of an iterative process. In this process the entire blade is broken into 40 segments. The blade length is computed using input parameters such as the rotor diameter and the H/D ratio. An initial value for T_o and the equator location are assumed and θ_i is then determined segment by segment from the equator to each end of the blade. After the first iteration, the ends of the blade end up at positions different from the blade-to-tower attachment points because T_o and the equator location were approximated. Depending on the position of the blade ends, T_o and the equator location are adjusted on the next iteration. This iterative process is continued until the blade ends are at the proper attachment points. Thus the troposkien is defined. During the iterative process the rotor diameter and blade length are held constant and slight changes in blade geometry are accommodated by modifying the rotor height and thus the H/D ratio.

The troposkien shape for a cable or blade of uniform density has a continuously changing radius of curvature. An example of this is shown in Figure 5, where the radius of curvature is plotted versus blade length for a troposkien of 37.5 rpm. A 42-in. blade section is used so that the troposkien roughly approximates a blade of the 34-m Test Bed. The high radius of curvature at the ends of the blade gradually diminishes towards the equator. When blade joints are included, the extra masses associated with the joints cause sudden changes in the radii of curvature of the troposkien at the joints. This is evidenced in Figure 6, which shows a plot of the radii of curvature along a troposkien at 37.5 rpm corresponding to the actual 34-m Test Bed geometry (including joints). The location of the joints is obvious by the sudden changes in radii of curvature which are due to the tendency of the blades to bulge outward at these positions. The effects of rotation rate on the troposkien shape when gravity is included are apparent in Figure 7. This figure shows troposkien shapes for different rates of rotation for a uniform-density blade of the Low Cost turbine scale.[5] The troposkien shape droops significantly at 5 rpm. As the rpm is increased, the troposkien shape sags less and less as centrifugal forces offset the gravitational forces. The effects of gravity are also apparent in Figure 8. This plot, which is to scale, compares the symmetric troposkien (gravity omitted) with the asymmetric troposkien (gravity included) at 37.5 rpm for the multiple-density blade of the Test Bed. The seemingly slight difference between the two shapes is important, as will be shown later. Designing a blade to the asymmetric troposkien can reduce the flatwise mean bending stresses significantly.

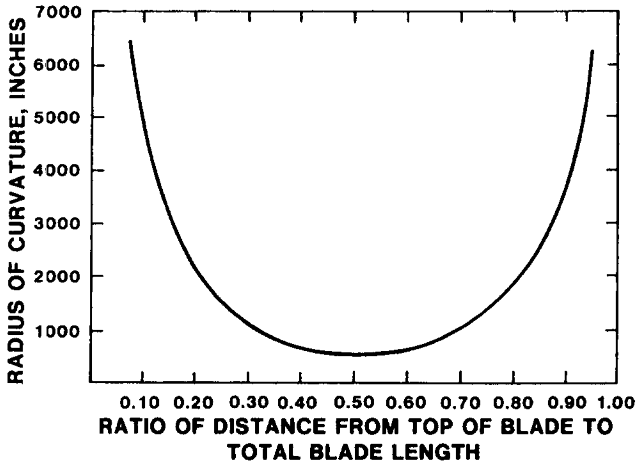

Figure 5. Radius of Curvature for the Troposkien of the 34-m Test Bed with a Uniform-Density Blade

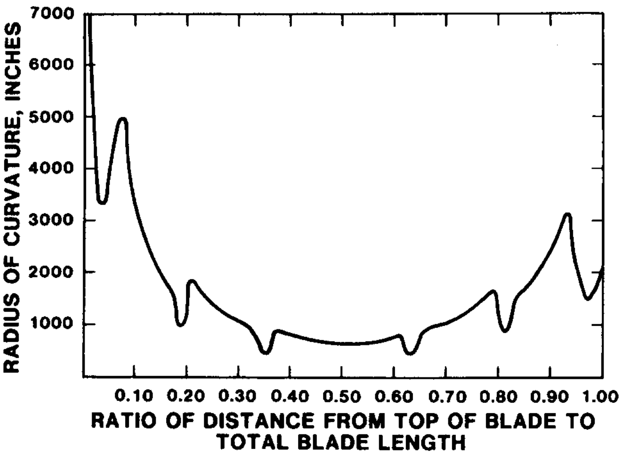

Figure 6. Radius of Curvature for the Troposkien of the 34-m Test Bed With Multiple-Sectioned Blade

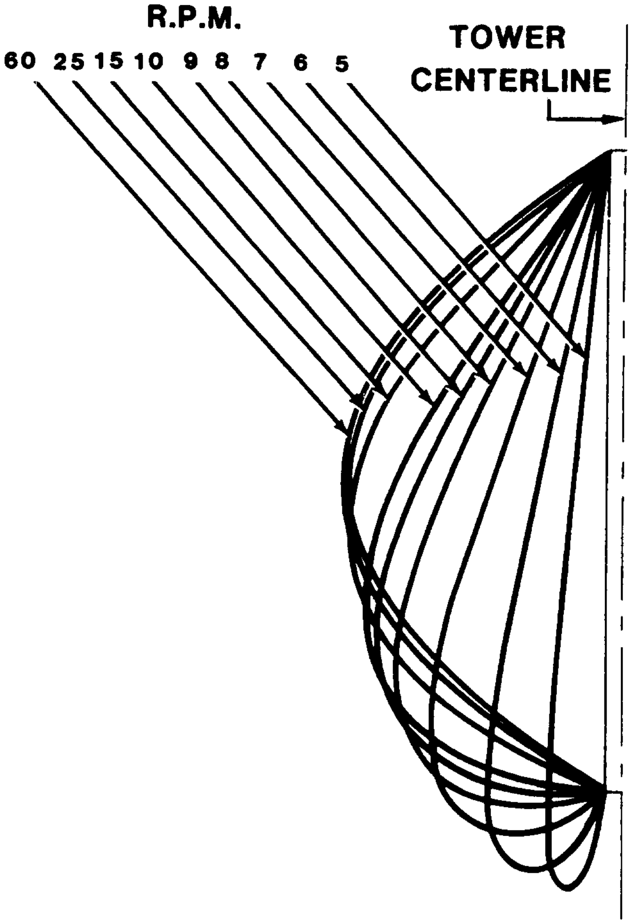

Figure 7. Effects of Rotation Rate on Troposkien Shape for a Uniform-Density Blade

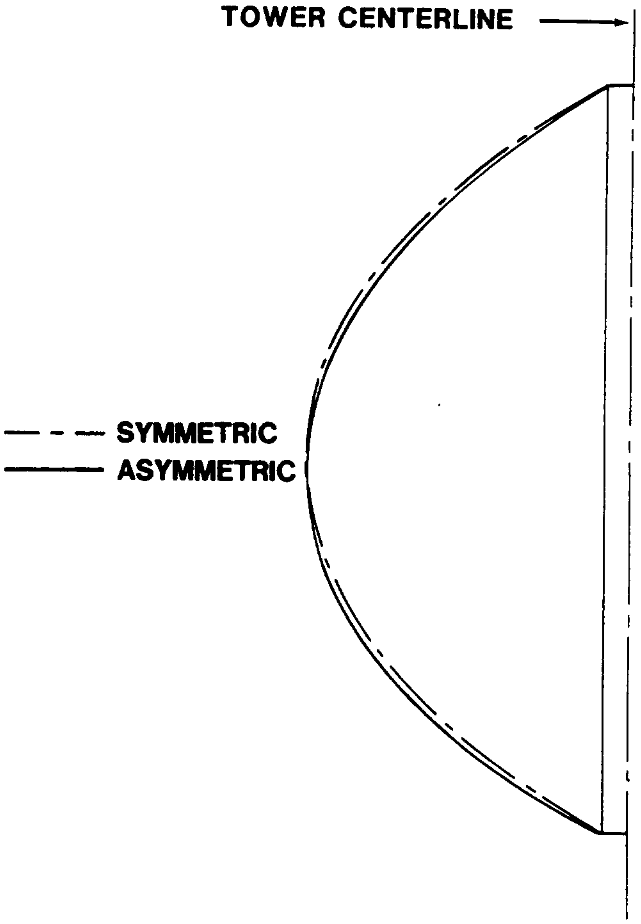

Figure 8. Symmetric Troposkien vs. Asymmetric Troposkien for the 34-m Test Bed at 37.5 rpm

Design of Blade Shapes

Methods Used for Design of Existing Blade Shapes

The computation of the troposkien, or ideal, shape of a VAWT blade for any configuration is the first step in the blade shape design process. The second step is designing a buildable shape that fits the troposkien as closely as possible. Constructing a blade bent exactly to a troposkien with its constantly changing radius of curvature would be very expensive. As previously noted, for either a symmetric or asymmetric troposkien a good approximation is an S-C-S shape. The Sandia 17-m research machine,[6] which was designed in 1976, has an S-C-S blade shape that approximates a symmetric troposkien. Figure 9 shows a plot of the flatwise mean stresses along the blade at 50.5 rpm for this machine as predicted by Sandia's forced response code FFEVD.[7] Because the blade is not shaped exactly to a 50.5-rpm troposkien and gravitational effects were not included in designing the blade shape, flatwise bending occurs. The peak flatwise mean stress of 9800 psi occurs at the lower root and is much higher than elsewhere along the blade. In the design of the DOE/ALCOA Low Cost turbine around 1980,[5] it was determined that gravity effects could easily be taken into account by rotating the S-C-S blade shape. This was done simply by modifying the blade-to-tower angles. For a symmetric troposkien approximation, the S-C-S shape attaches to the tower with identical angles, both top and bottom. In the case of the Low Cost turbine, the sag due to gravity was taken into account by determining the best fit S-C-S symmetric troposkien and then decreasing the angle at the top and increasing the angle at the bottom. These angle changes effectively "sagged" the blades and approximated gravity effects. The angles were chosen in a trial-and-error manner by determining the stresses for a series of blade configurations that differed only in the blade-to-tower angles. The angles that resulted in the lowest mean bending stresses were incorporated into the blade design. FFEVD predicts a flatwise mean stress distribution for the Low Cost turbine at 48 rpm, as shown in Figure 10. Bending stresses of up to 8000 psi occur, but the high stresses at the root are not evident.

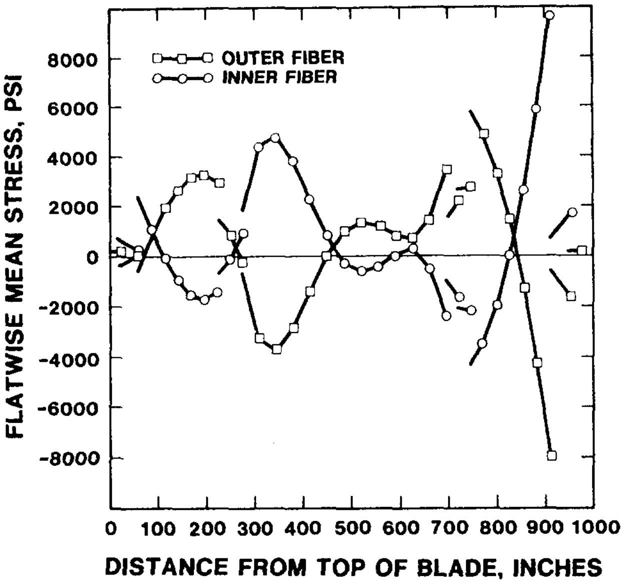

Figure 9. Flatwise Mean Stresses for Sandia 17-m Turbine at 50.5 rpm

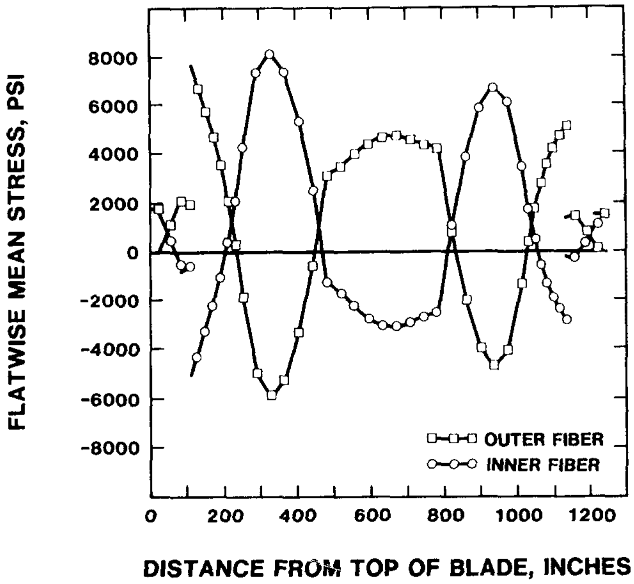

Figure 10. Flatwise Mean Stresses for the DOE/ALCOA Low Cost Turbine at 48 rpm

New Blade-Shape Design Methodology

A blade-shape design software package, TROPFIT,[3] has been developed that incorporates the previously discussed program TROP-II. This package allows the user to determine the troposkien shape for a particular blade and then develop a buildable approximation to this shape. TROPFIT contains several options that can be used in the troposkien approximation. One can still use the S-C-S approximation or incorporate any or all of the following options.

- Multiple radii of curvature along the blade
- Straight joint sections anywhere along the blade
- Slope discontinuities or "kinks" at the joints.

The motivation for including multiple radii of curvature and slope discontinuities in the design package resulted from the blade design of the 34-m Test Bed, where these approximating techniques were used. Figure 11 is a plot of the blade shape geometry for the Test Bed. Because the design called for five separate blade sections, use of multiple radii of curvature could easily be implemented. As shown in Figure 6, joints, because of their extra mass, cause sudden changes in the radius of curvature of the troposkien. These sudden changes can best be modeled by using slope discontinuities in the blade shape at the joints themselves. The "kinks" improve the troposkien approximation and substantially reduce the flatwise bending stresses when compared to an S-C-S approximation.

A simplified flowchart for TROPFIT is shown in Figure 12. The troposkien is first calculated by subroutine TROP-II and stored as a series of coordinates. Subroutine MSCFIT then takes these coordinates and, based on a three-point curve fit, computes the radius of curvature that best approximates each section of the troposkien. Straight sections are used for the sections nearest the tower, both top and bottom. This causes slope discontinuities at the joints, and MSCFIT determines the kink angles required for the geometry and stores this initial approximation. In TRACKIT, the user interacts to adjust the radii of curvature, kink angles, or section lengths to obtain a buildable geometry. TRACKIT then determines the new coordinates and stores these. Finally, the user-designed blade shape is used as a model in FFEVD, and a forced response calculation is carried out. The resulting centrifugal and gravitational bending stresses are compared to other designs in order to determine the "best" design.

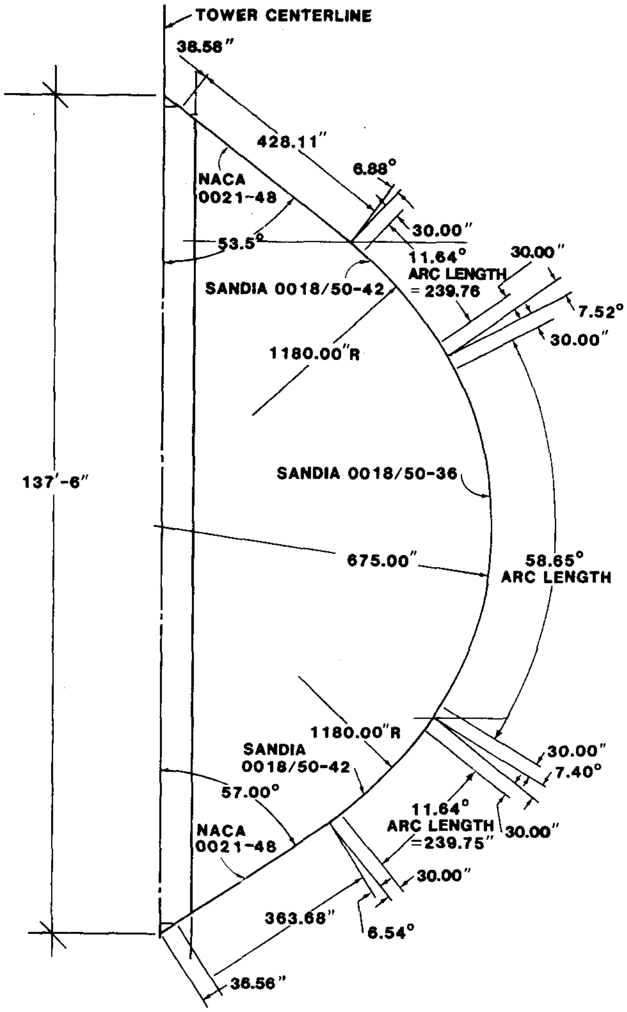

Figure 11. Blade Shape Geometry for 34-m Test Bed

Figures 13 through 17 are plots from FFEVD of predicted flatwise mean stresses along the blade lengths for the 34-m Test Bed at 40 rpm. The mean stresses for the troposkien itself are shown in Figure 13. Here, the inner and outer surfaces of the blade have the same stress distribution, which indicates that the blade has no flatwise bending. These mean stresses are the lowest obtainable for this blade. Figure 14 shows the flatwise mean stresses for the "best" S-C-S approximation. The top and bottom blade attachment angles were optimized to obtain 52° and 54°, respectively, resulting in stresses of up to 8700 psi, 7000 psi of which is due to bending as the blade shape tries to form itself to the troposkien.

During the blade design process for the Test Bed the radius of curvature and kink angles were modified with the help of TROPFIT to minimize the mean bending stresses. Figures 15 and 16 are the flatwise mean stress plots from intermediate blade shape designs for the 34-m Test Bed. In proceeding from the S-C-S approximation to the first intermediate design, multiple radii of curvature were incorporated. As seen in Figure 15, radii of curvature of 1100 in. for the intermediate sections of the blade and 660 in. for the center section were chosen. This design change reduced the peak bending stress from 8700 psi to 6700 psi.

For the second intermediate design, as shown in Figure 16, the peak mean bending stress was lowered to 5200 psi by using radii of curvature of 1300 and 660 in. and adding kinks at the joints of 3° to 4°.

The final blade design resulted in the plot of Figure 17. With radii of curvature of 1180 and 675 in. and kink angles of 6.5° to 7.5°, the peak mean bending stress was further reduced to 4300 psi. Thus, the maximum stress at 40 rpm is down from a peak of 8700 psi in the best S-C-S approximation (Figure 14) to 4300 psi in the final blade design (Figure 17). These stresses of the final design represent a significant decline in the typical flatwise mean bending stresses of Darrieus VAWTs and may increase the fatigue life of the blade by a factor of 2 to 4.

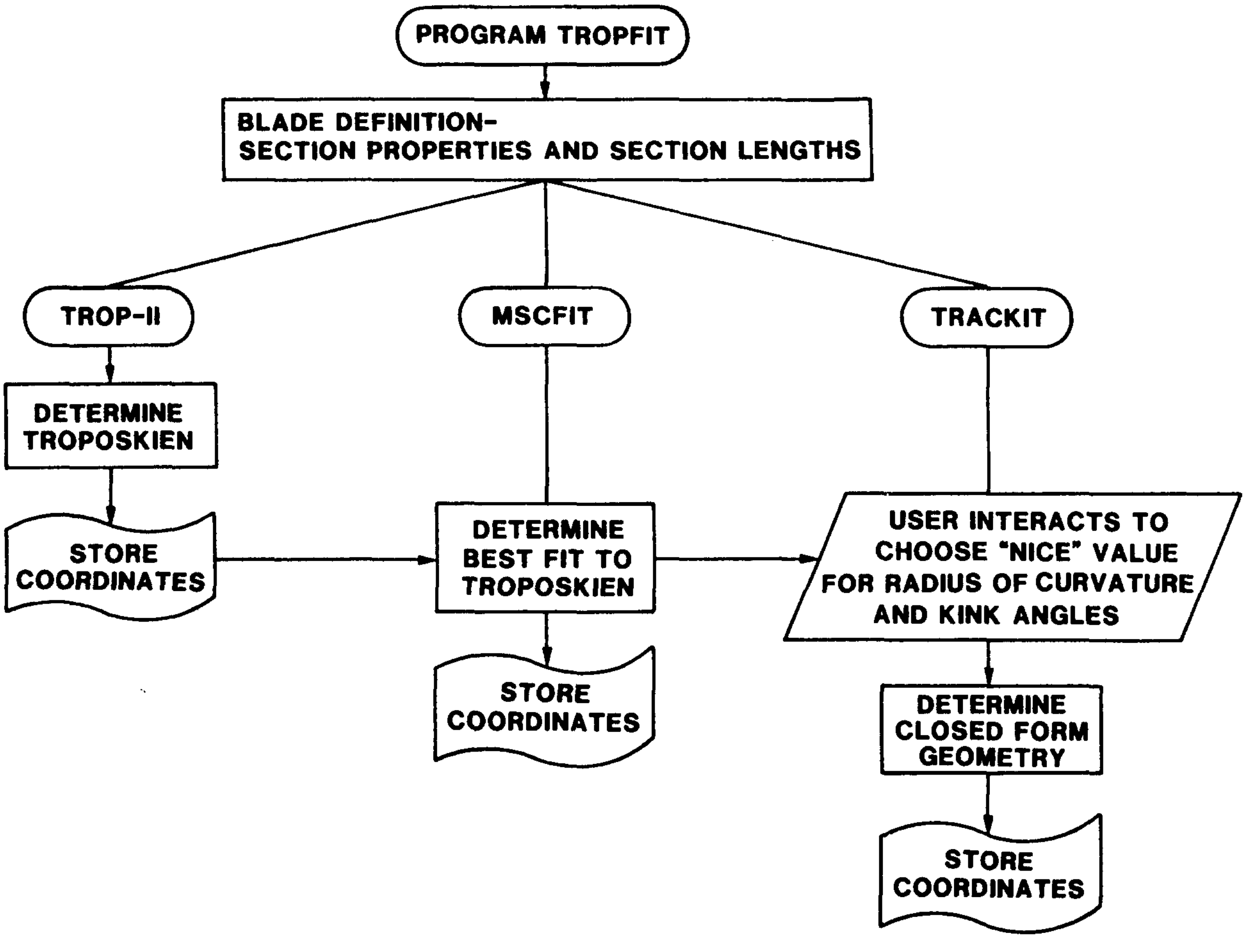

Figure 12. Flowchart for TROPFIT

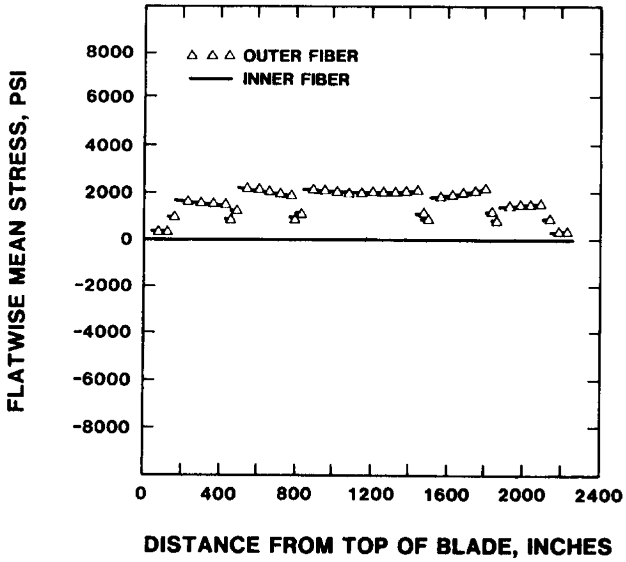

Figure 13. Flatwise Mean Stresses for Troposkien Blade Shape of 34-m Test Bed

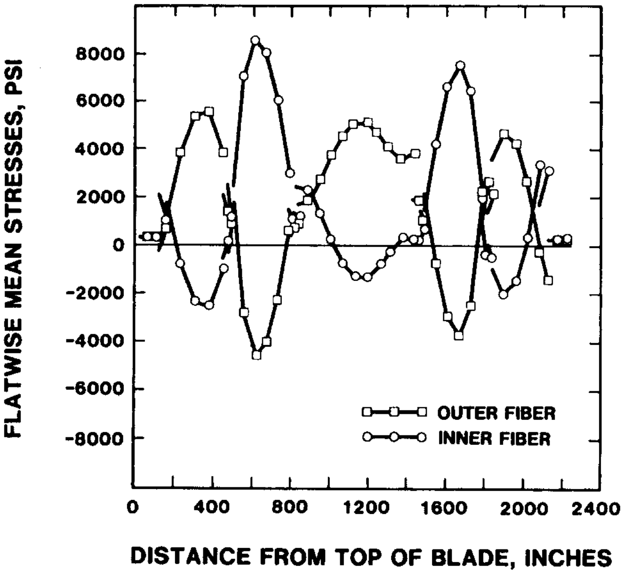

Figure 14. Flatwise Mean Stresses for S-C-S Blade Shape of 34-m Test Bed

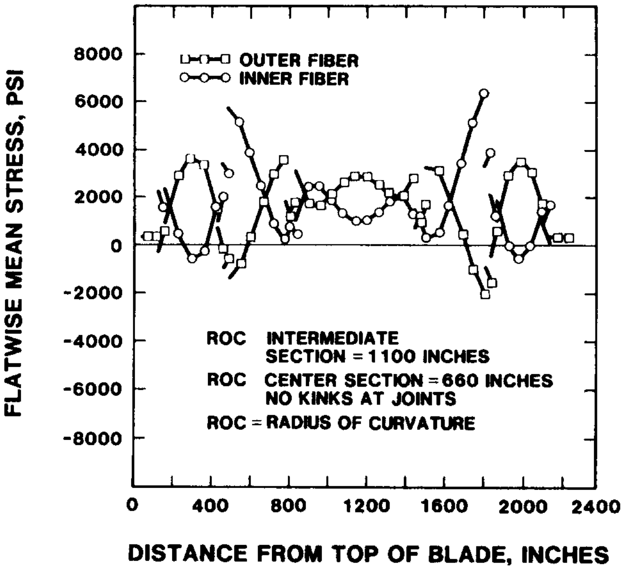

Figure 15. Flatwise Mean Stresses for First Intermediate Blade Shape for 34-m Test Bed

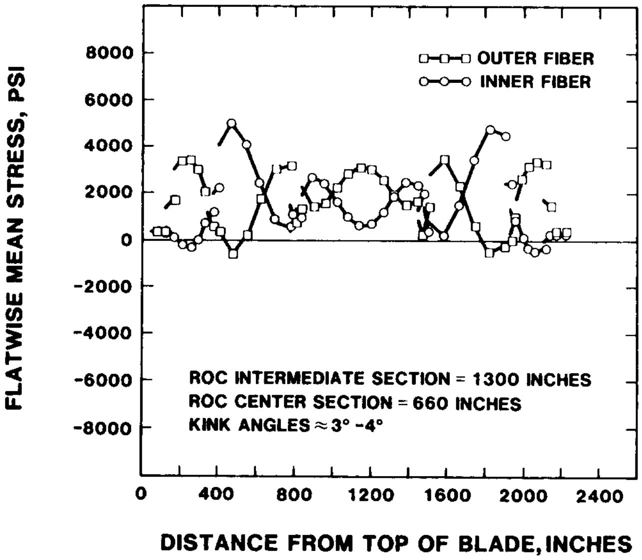

Figure 16. Flatwise Mean Stresses for Second Intermediate Blade Shape for 34-m Test Bed

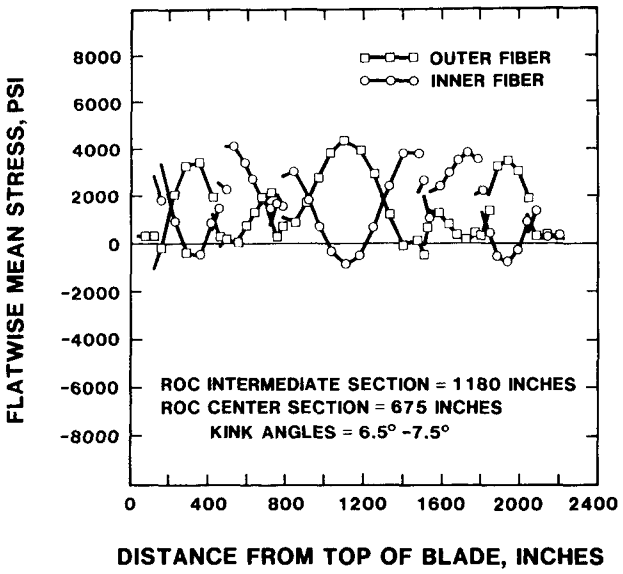

Figure 17. Flatwise Mean Stresses for Final Blade Shape of 34-m Test Bed

Summary

A program called TROP-II has been developed to determine the troposkien shape for a blade of any configuration at any rotation rate. This program has been incorporated into a blade-shape-design package called TROPFIT, which allows user interaction to develop a "buildable" blade shape that closely approximates an established troposkien. With the use of these programs, one can significantly reduce mean bending stresses in the blade and thus increase fatigue life. The practicality of the methodology was verified by applying it to the 34-m Test Bed.

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