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Tie-Down Cable Selection and Initial Tensioning for the Sandia 17-Meter Vertical-Axis Wind Turbine

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TIE-DOWN CABLE SELECTION AND INITIAL TENSIONING FOR THE SANDIA 17-METER VERTICAL-AXIS WIND TURBINE

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ABSTRACT

The rationale used for selection of tie-down cables for the Sandia 17-meter turbine are presented, discussed and implemented. The effects of initial cable tension on the response of the tie-down system is evaluated and discussed in terms of resulting sag, blade interference and response linearity.

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FIGURES

TIE-DOWN CABLE SELECTION AND INITIAL TENSIONING FOR THE SANDIA 17-METER VERTICAL-AXIS WIND TURBINE

I. Introduction

There are two principle considerations in the design of a cable tie-down system for the vertical axis wind turbine. The first is that of establishing geometric, physical and mechanical properties of the system for adequate load carrying capability and tower stiffening. These properties include the number of cables, the cable elevation angle, cable density, active cable area and cable stiffness. The second consideration in the design is that of determining initial cable tension and sag to insure sufficient blade clearance and load retention after tower deflection. These two aspects of design are actually coupled together due to the dependence of cable stiffness on initial tension. The dependence is nonlinear and therefore difficult to handle, especially when the nonlinearities become large. With proper selection of cable properties and initial tensions the nonlinear effects can be minimized, thus permitting independent treatment of the two phases. This approach will be used here.

This report discusses the initial tension phase of the tie-down design for the 17 meter turbine. Since field adjustments may be required to compensate for thermal, creep and dynamic effects, response curves should prove to be useful. Results of the first design phase for this turbine will also be presented.

II. Phase I Design Results

1. Even symmetrically distributed numbers of cables have a significant erection advantage over odd, or unsymmetrically distributed numbers of cables. This is because even numbers of cables can be mounted and tensioned in pairs rather than all at once. Four cables, at equally spaced azimuth positions, were selected for the 17 meter, VAWT tower tie-down. Two cables offer stiffness in only one vertical plane, and six cables were judged to be too many for cost and appearance reasons.

2. The cable elevation angle was selected as that which gave a maximum horizontal stiffening effect to the blade support tower and a minimum bending moment at the base of the tower. This angle is approximately 35° measured from a horizontal plane.*

3. Cable "outriggers" at the top of the tower were eliminated because of relatively small stiffening effects, undesirable translation-rotation coupling at the top of the tower and added costs. They were not needed to reduce the blade-cable strike probability because of the relatively shallow cable elevation angle of 35°.

4. A minimum cable-tower horizontal stiffness at the top of the tower of approximately 9000 lb/in. was established for the four-cable tie-down system.[1] This resulted in approximately a one inch, downwind, horizontal deflection at the top of the tower in an 80 mph wind. (This is considered to be the maximum wind speed in which the turbine will be permitted to operate.)

In order to meet this stiffness requirement, the following wire rope was selected.

Name and Construction: galvanized bridge strand, 7 strand
Linear Weight: 2.07 lb/ft
Active Cross Sectional Area: 0.596 in.
Effective Elastic Modulus: 25.0 x 10 psi
Breaking Strength: 122,000 lb

*This result is from unpublished work, where it was found to be independent of geometric scaling.

III. Phase II Design - Initial Tension

Because of the nonlinear coupling of cable geometry (sag) and mechanical properties with cable tension, it is possible for results of this phase to effect preliminary design, above. This design feedback can be eliminated, however, if cable tension is high enough to minimize non-linear effects, as will be demonstrated.

There are several features of the cable tension-sag problem which are worth discussing separately. The first is the relationship between tension and midpoint sag in a cable which connects two fixed points in space. These two points are the top of the undeflected blade support tower and the ground connection, see Figure 1.

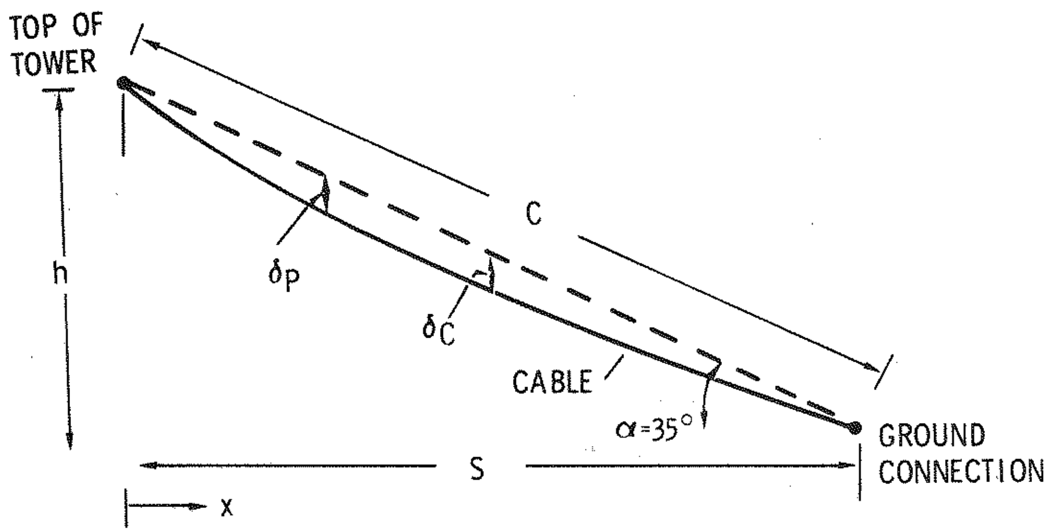

Figure 1. Cable Geometry

The midpoint sag in the cable is given by the parabolic approximation[2]

$$\delta_c = \frac{wC^2}{8T} \cos \alpha \qquad (1)$$

where α is the elevation angle of the undeflected cable, T is the chordwise component of the cable tension (directed along a line connecting the cable endpoints) and w is the linear weight of the cable. Material stiffness is absent from this equation because elastic deformation has a small effect upon equilibrium of the cable. To further illustrate this point, consider a cable as in Figure 2, but with the ground connection replaced by a roller over which the cable passes before attaching to a weight, W. The equation relating sag and tension is the same in this case as it is for the cable connecting two fixed points. If elastic deformation is suddenly permitted in the cable of Figure 2, the weight, W, simply moves downward without any change in cable sag. If the roller is then fixed in space and the weight is removed, the situation displayed in Figure 1 is recovered.

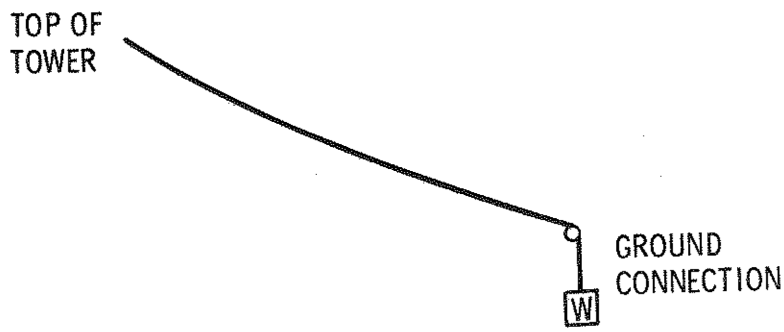

Figure 2. Counterweighted Cable

Another feature of the cable tension-sag problem which is of interest is the relationship between cable midpoint sag and sag at some other point. This relationship is

$$\delta_p = \frac{4\delta_c\, x\,(S - x)}{C^2 \cos^2\alpha} \qquad (2)$$

where x is measured as shown in Figure 1. For the cable selected for tie-down of the 17 meter turbine, midpoint sag and sag at the point closest to the passing blade are shown in Figure 3. The point on a blade which comes closest to a sagging tie-down cable lies approximately at the intersection of the straight, circular arc and strut blade sections.

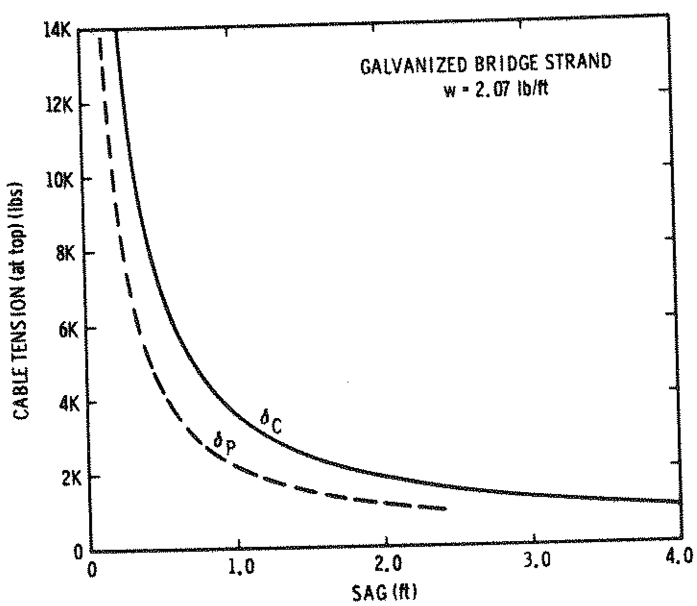

Figure 3. Cable Tension Versus Midpoint and Strike Point Sag

The next question which arises is what happens to the tension and sag in a cable when there is relative motion between the two end points. For the purposes of this report, the relative motion between the end points will be permitted by keeping the ground connection fixed and allowing horizontal motion, ΔC_h, at the top of the tower in the plane of the deflected cable. When this motion occurs, part of it is due to elastic stretch (or contraction) in the cable, and part is due to a change in the cable geometry (sag). See Reference 2 for a more complete discussion. After some algebraic manipulation, the relationship between cable stiffness and sag[2] is given by

$$K = \left[\frac{C}{AE} + \frac{512\,\delta_c^3}{12(1 + b)wC^3 \cos \alpha}\right]^{-1} \tag{3}$$

where

$$b = \frac{8}{3}\left(\frac{\delta_c}{C}\right)^2$$

and A and E are the cable's cross sectional area and effective modulus. Equation (1) could be used to relate K to cable tension. The nonlinearity of (3) is apparent.

When sag is very small, stiffness is nearly constant and is dominated by elastic stretch. When sag is large, stiffness can be quite small as cable loads tend to pull sag out before inducing cable stretch.

For the 17 meter turbine, the cable stiffness, mid-point sag relation is illustrated in Figure 4. Since the cable stiffness is not constant with δ_c, it is not possible to obtain the loss (or gain) of cable tension due to a tower deflection. Concern should be primarily with tension loss because this will be accompanied by increased sag and a greater probability of a blade strike. As the tower deflects, tension is lost, sag is increased and the effective stiffness changes.

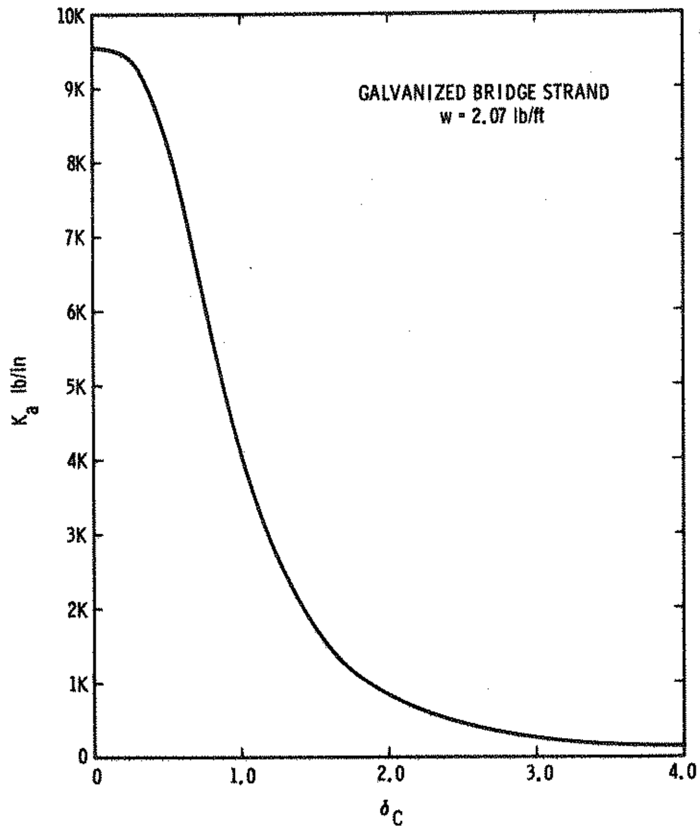

Figure 4. Cable Stiffness Versus Midpoint Sag

To calculate the tension loss directly, the load-deflection relationship must be integrated. Expressing the cable stiffness, K, in terms of cable tension, T, gives

$$K = \frac{dT}{dC} = \left[\frac{C}{AE} + \frac{w^2 C^3 \cos^2\alpha}{12T^3 (1 + b)}\right]^{-1} . \tag{4}$$

Integration of this equation can be simplified greatly (yielding approximate results) if one recognizes that small changes in C produce large changes in T. Since a solution will be sought where changes in T are minimized, C may be considered constant for the integration and subsequent numerical evaluation. Rearranging Eq. (4) gives

$$dC = \left[\frac{C}{AE} + \frac{w^2 C^3 \cos^2\alpha}{12T^3 (1 + b)}\right] dT \tag{5}$$

and integration of this gives

$$\Delta C = \left[\frac{C}{AE}\,(T_f - T_i) - \frac{w^2 C^3 \cos^2\alpha}{24\,(1 + b)}\left(\frac{1}{T_f^2} - \frac{1}{T_i^2}\right)\right] \tag{6}$$

where ΔC is the change in chord length, and T_i and T_f are the initial and final cable tensions, respectively. Equation (6) can also be written in terms of the change in cable tension, $\Delta T = (T_f - T_i)$ as

$$\Delta C = \left[\frac{C\Delta T}{AE} + \frac{w^2 C^3 \cos^2\alpha}{24\,(1 + b)}\,\frac{\Delta T\,(\Delta T + 2T_i)}{T_i^2\,(\Delta T + T_i)^2}\right]. \tag{7}$$

Numerical results of Eq. (7) are presented in Figure 5 for the 17 meter turbine tie-down cable where cable tension change, ΔT, is shown as a function of cable chord length change, ΔC, and horizontal deflection, ΔC_h. Also shown is the 9000 lb/in. linear cable stiffness, K_s, (Phase 1, pt. 4) used in the composite tower, tie-down analysis. As indicated in the figure, nonlinear effects become increasingly larger with deflection. It is also evident that the higher the initial cable tension, the greater the permissible deflection before nonlinear effects become strong. From the figure, cables with initial tensions of 12, 000 lb or greater behave in a nearly linear fashion for horizontal deflections, ΔC_h, up to about 1 in.

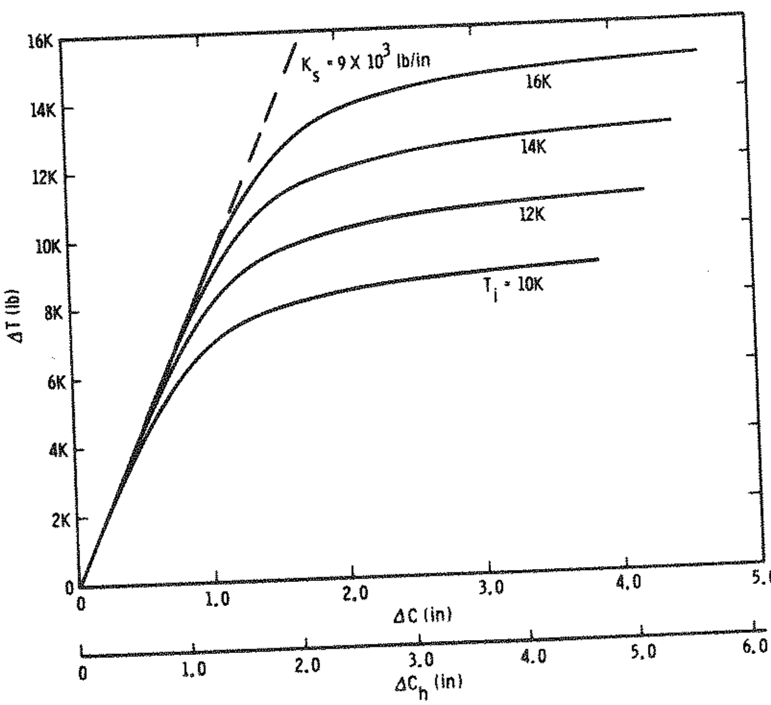

Figure 5. Cable Tension Change Versus Chord Length Change and Tower Deflection

Two additional figures may be useful. Figure 6 shows the dependence of final cable tension, T_f, on ΔC and ΔC_h. Figure 7 shows the dependence of the cable sag at the strike point, δ_p, on the deflections. Results in both figures are presented for various values of initial cable tension. Note, in Figure 7, that for a given initial tension, T_i, the final sag, δ_p, increases rapidly with displacement. This suggests that selection of initial cable tension be based on a minimum acceptable clearance between the sagging cable and a passing blade. For example, if this minimum clearance is selected as 5 feet of separation in the vertical direction, approximately 1 foot may be due to cable sag after tower deflection (the rest would be an allowance for blade deflection and rigid body separation).

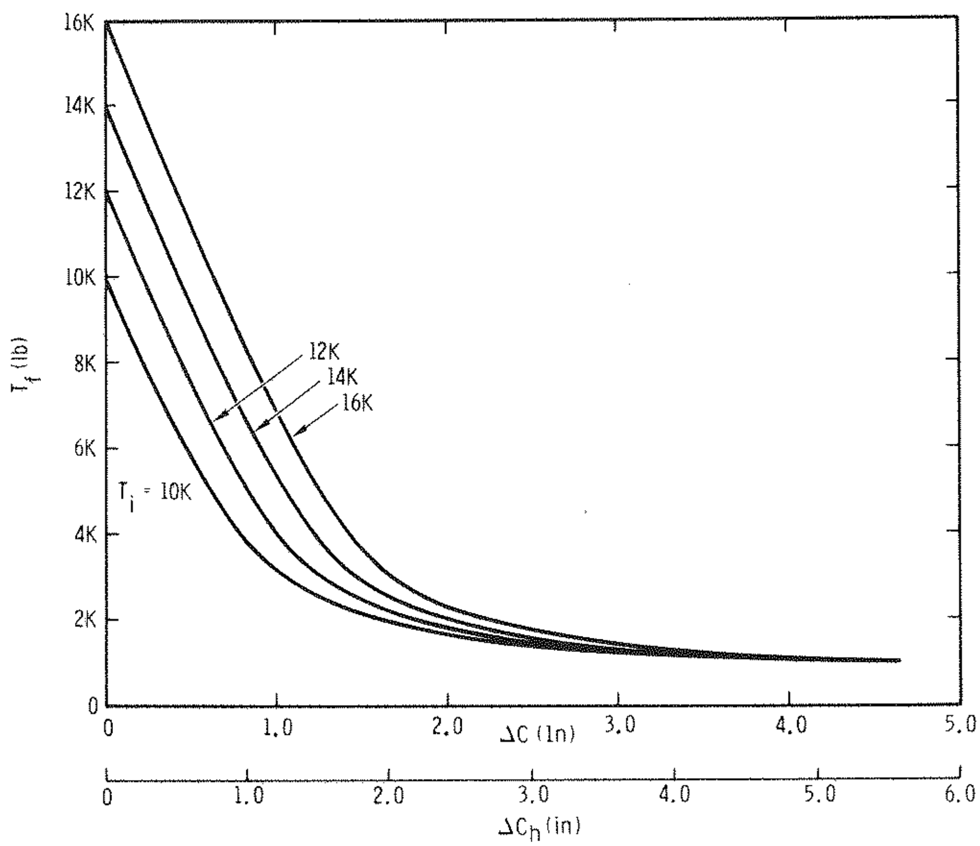

Figure 6. Final Cable Tension Versus Chord Length Change and Tower Deflection

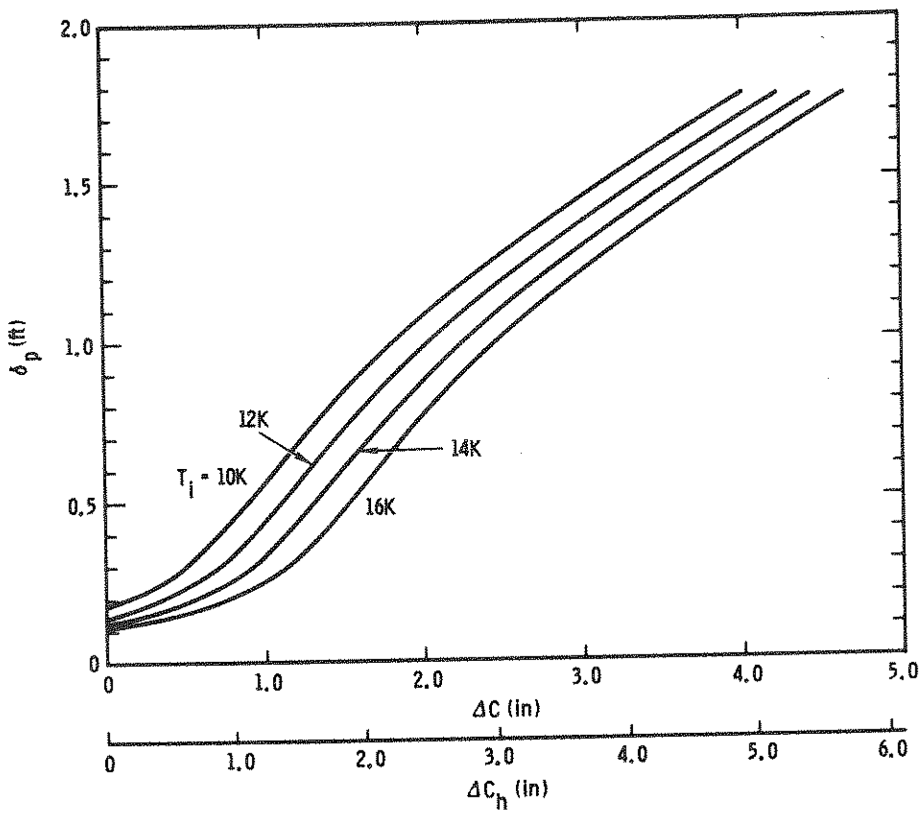

Figure 7. Strike Point Sag Versus Chord Length Change and Tower Deflection

From Figure 7, if a horizontal tower deflection, ΔC_h, of 2.5 in. is allowed (conservatively) then for a strike point sag to be 1 foot or less, the initial cable tension should be 12,000 lb or more. If a deflection, ΔC_h, of 3 in. is allowed, then 16,000 lb or more of initial cable tension is required to keep the strike point sag 1 foot or less. For the 17 meter turbine, a 12,000 lb initial cable tension is selected. This value provides a relatively small strike point sag (0.3 ft) when the horizontal tower deflection is approximately 1 in., and the response remains nearly linear.

IV. Summary

While the initial cable tension-cable sag-tower deflection interaction can be highly nonlinear, proper selection of cable properties and initial tension for a specified performance can practically eliminate the nonlinearities. The dependence of final, strike point sag upon tower deflection has been demonstrated. Since tower deflection, under steady state conditions, is a function of wind speed, it is possible to ease cable tension under light wind conditions (from a tension value selected to cover all wind possibilities) thereby reducing bearing loads and life. It may also happen that undesirable dynamic effects in the cables arise under certain operating conditions. In this case, cable tension may have to be adjusted to "tune" the cables such that resonant frequencies. Numerical results contained in this report will provide guidance for this operation.

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