OVERVIEW OF VERTICAL AXIS WIND TURBINE (VAWT) BLADE DESIGN PROCEDURES*

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The design of a VAWT blade section involves primarily the selection of a manufacturing technology, establishing structural integrity, and obtaining acceptable aerodynamic performance. In this paper, a survey is presented of the practices which have been applied for designing VAWT blades in the past. Through this presentation, an attempt is made to discuss strengths and weaknesses of the existing procedures. Where appropriate, discussion is provided on planned or suggested future work in developing improved design tools.

Selection of Manufacturing Technology

This important first step in the design process is governed almost entirely by qualitative issues. Table I lists the features we at Sandia Laboratories have found to be desirable when selecting a manufacturing technology.

It is unlikely that a technology exists which excels in all of these characteristics. Thus, the judgment of the designer is required to make a final selection. Obviously, the relative importance of the items in Table I depends on the particular application. For example, short-term availability may dominate blade selection for a research machine, corrosion resistance for machines destined for coastal use, and so forth. Blade cost, however, should almost always be of primary importance.

In past VAWT blade construction, many manufacturing technologies have been used. These technologies include: aluminum extrusions (hollow and solid), machined aluminum, aluminum extrusion/fiberglass composites, fiberglass/steel, fiberglass, roll-formed and welded steel (straight sections only), advanced composites, and plywood. Of all these, aluminum extrusions have been the most widely used because they possess many of the desirable characteristics of Table I. However, the other listed technologies and promising new proposals (such as composite pultrusions and formed steel blades) should remain as potentially superior candidates to extrusions in certain applications.

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Structural Design

Following selection of a manufacturing technology, critical structural dimensions of the blade section must be determined. At Sandia Laboratories, structural performance is evaluated primarily with numerical (finite element) models. The Canadian National Research Council (NRC)[1*] has evaluated designs using experimental measurements on scaled wind tunnel models. Both of these methods have been applied on prototype machines which yielded acceptable structural performance.

Considering analytical techniques, blade analysis has focused on static, dynamic, and flutter (aeroelastic) issues. The basic approach has been to design the blade first to static requirements followed by checking and fine tuning (if necessary) to preclude undesirable dynamic or flutter effects.

Static finite element blade models have been developed for quasi-static centrifugal and aerodynamic normal operating loads, gravity loading, and parked-rotor blade collapse in gale-force winds. The MARC nonlinear finite element package has been favored for these problems because of significant geometric-non-linearities which occur in the VAWT blade due to the effects of centrifugal stiffening for normal operating loads and large deformations which occur in parked rotor blade collapse.

Table II summarizes the criteria which have been used to determine static acceptability. Typical results for quasi-static blade stresses predicted by MARC are shown in Fig. 1.

The suitability of quasi-static analysis requires system natural frequencies to be well above the load excitation frequencies. Finite element models (using SAP IV primarily) have been constructed to examine resonant frequencies of the complete blade/tower/tiedown system. Typical results from such an analysis, in this case the Sandia 17 meter rotor with two extruded blades, are shown in a fan plot (Fig. 2). Due to the collective effects of conservative static requirements (Table II), the support of the blade at both ends, and the inherent stiffness of the tiedown cable support system, these resonant frequencies are quite high relative to typical excitation frequencies.

This tends to justify the use of quasi-static models. However, efforts are in progress to construct a complete forced-response dynamic model to replace the quasi-static analysis. This is appropriate because economic factors are motivating reduction of conservatism in the static requirements, a trend toward larger rotor height-to-diameter ratios, and

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*References listed at end of paper.

consideration of alternate blade manufacturing technologies. These changes can lower system resonant frequencies and thereby increase the risk of relying only on static analysis tools.

Aeroelastic flutter instability has been observed[1,2] on VAWT blades. Approximate analyses[3] and experimental data on scale models[1] have indicated that blades meeting the static requirements with section properties similar to aluminum extrusions will have critical flutter speeds well above normal operating speeds. However, there are destabilizing factors which may lower the flutter speeds if alternate sections are considered with substantially different properties than aluminum extrusions. These factors include: the ratio of aerodynamic forces to blade mass and elastic stiffness, the ratio of blade bending to twisting stiffness, and the ratio of blade stiffness to tower torsional stiffness. Efforts are in progress both analytically[4] and experimentally (at Sandia Laboratories) which should yield more quantitative data on the influence of these and other factors on flutter speed.

Aerodynamic Design

Aerodynamic design of the blade section is related to the structural suitability of the blade through the shape of the section and the blade chord.

Most Darrieus blades have utilized symmetrical NACA 0012, 0015, or 0018 airfoils, the last two digits representing the percentage ratio of blade thickness to chord. Of these three high lift to drag ratio sections, the 0018 has the advantage (used on the Canadian 200 kW Magdalen Island rotor) of a somewhat higher ratio of flatwise to edgewise stiffness which can improve structural performance. There are insufficient data to clearly distinguish the subtle differences in aerodynamic performance which probably exist between these three airfoils. At Sandia Laboratories, we have favored the 0012 and 0015 airfoils primarily because of a relatively large data and experience base for these airfoils. Undoubtedly, future research should yield a more definitive answer for the most appropriate airfoils, including investigation of series besides the 0012, 0015, and 0018.

A much more significant variable influencing the structural, aerodynamic, and economic performance of a blade is the blade chord, or, more generally, the ratio of blade chord to rotor radius. In general, reducing the chord to radius ratio causes structural section properties of the blade to deteriorate rapidly (see Fig. 3), and the resulting lower rotor solidities also reduce overall aerodynamic performance. These effects tend to drive design toward higher chord to radius ratios. However, blade costs tend to increase as chord to radius ratio increases, which poses a classical trade-off problem for the designer. For extruded aluminum blades on two-bladed rotors, current design practice suggests that the "best" solidity is in the range of 10 to 15%. Based on the trade-offs involved in this selection, it is apparent that different blade technologies may well yield a different optimum solidity, so the 10 to 15% practice should not be interpreted as a design invariant.

Concluding Remarks

The available practices for designing VAWT blades have been applied in designing blades which have provided excellent service on research-oriented machines. However, this is a developing technology and all conceivable phenomena are not included in the analyses. Future efforts at Sandia Laboratories will be directed toward improvement of existing techniques guided by experimental data and operating experience. The output of such an effort can lead to a reduction of technical risks and conservatisms required to cover analysis uncertainties.

References

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Table I. - Qualitative Issues Governing Selection of Manufacturing Technologies for VAWT Blades

Economics
- Low Raw Material Costs
- Low Labor Intensity
- Low Tooling Costs

Mechanical Properties of Materials
- Endurance Limits
- Yield Strength
- Density
- Ductility
- Stiffness
- Corrosion Resistance
- Weldability or Joinability

Formability
- Capability to Fabricate High Moment of Inertia, Low Weight Sections (1/4 Chord Balance <u>Not</u> Required)
- Capability to Form Curved Blade Sections
- Blade Root Attachment and Shipping Joint Hardware Compatability
- Size Limitations on Chord and/or Blade Length

Availability
- Short-Term R&D Time Requirements
- Long-Term Raw Material Supply
- Energy Intensity for Fabrication and Raw Materials

Table II. - Static Structural Performance Criteria

- Quasi-static vibratory blade stresses less than 10^8 cycle endurance limit (approximately 6000 psi for 6063-T6 aluminum extrusions) at normal operating rpm in 60 mph winds.

- Quasi-static blade angle-of-attack changes due to aerodynamic loading less than 3° at normal operating rpm in 60 mph winds.

- Parked upwind blade survival for 150 mph static gusts.

- Parked gravitational stresses below 40% of yield.

- Blade survival (no yield) at operating rpm + 20% in 80 mph winds (accident conditions).

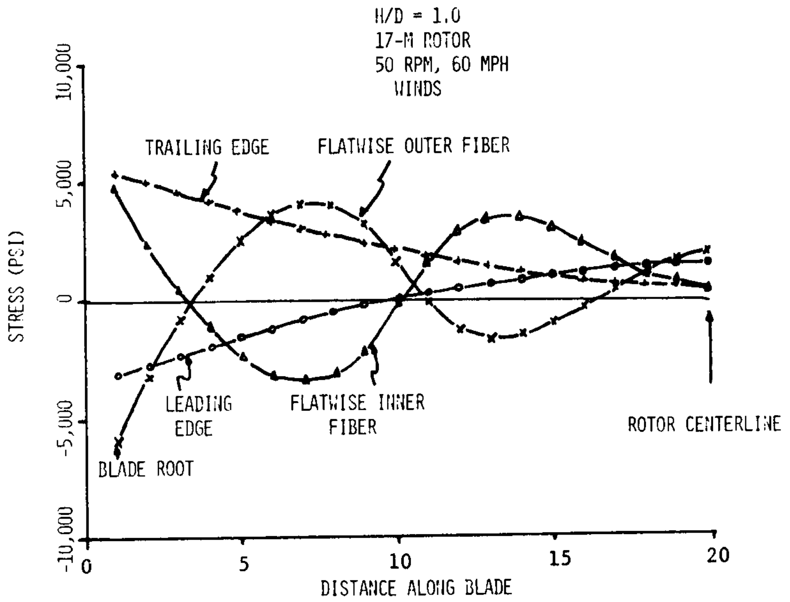

FIGURE 1. Results from MARC Showing Variations in Blade Section Stresses Between the Blade Root and Rotor Centerline. Loading Corresponds to Maximum Aerodynamic and Centrifugal Loads Which Occur in a Revolution at 50 rpm in 60 mph Winds (17-m Rotor).

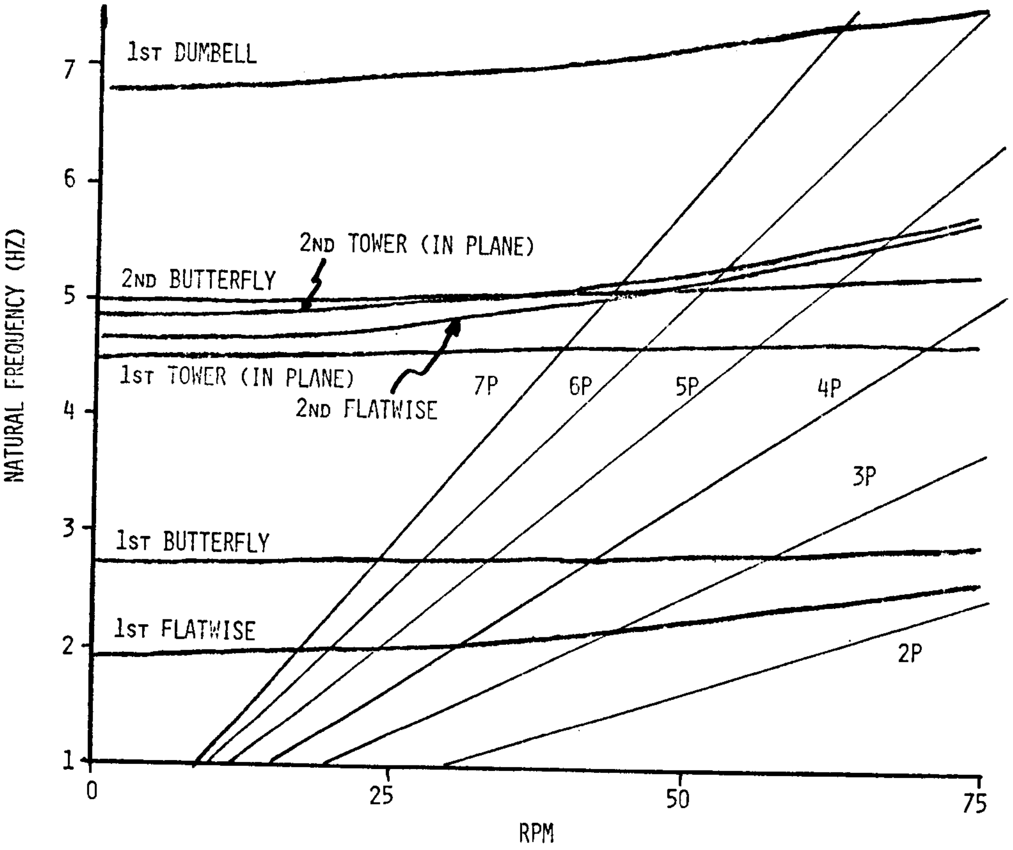

FIGURE 2. System Resonant Frequencies for the Sandia 17 Meter Rotor,

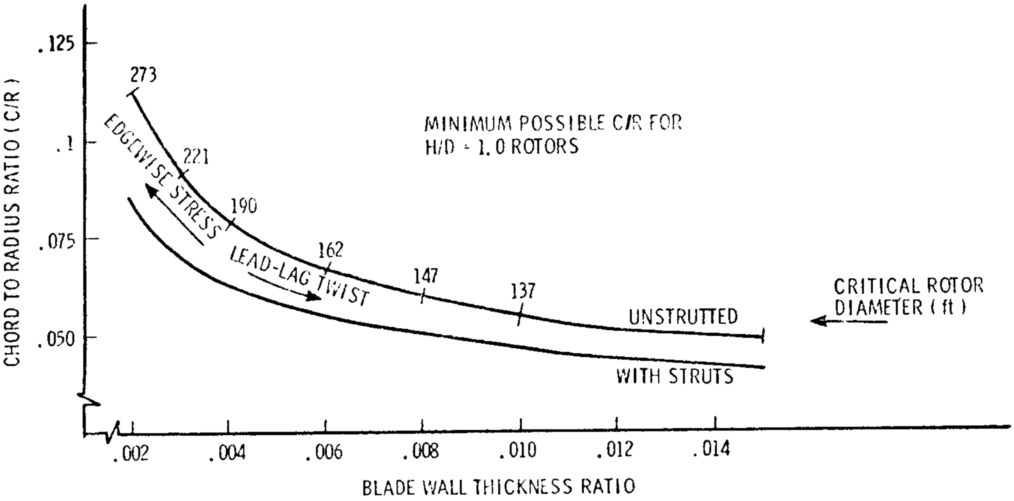

FIGURE 3. The Minimum Possible Chord-to-Radius Ratio for Aluminum Extrusions Satisfying the Criteria of Table II. Blade Wall Thickness Ratio is the Ratio of Wall Thickness to Chord Length. The Effect of Support Struts is Shown. "Critical Rotor Diameter" is the Rotor Diameter Above Which Gravitational Loads Become Excessive.