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Tailored Airfoils for Vertical Axis Wind Turbines

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TAILORED AIRFOILS FOR VERTICAL AXIS WIND TURBINES*

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ABSTRACT

The evolution of a family of airfoil sections designed to be used as blade elements of a vertical axis wind turbine (VAWT) is described. This evolution consists of extensive computer simulation, wind tunnel testing and field testing. The process reveals that significant reductions in system costs-of-energy and increases in fatigue lifetime may be expected for VAWT systems using these blade elements.

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INTRODUCTION

Wind energy conversion systems (WECS) which operate on aerodynamic lift principles have typically used airfoil sections which were designed exclusively for aeronautical applications. These sections were used because they were the only ones available having a data base of sufficient depth to give designers confidence in their aerodynamic loads and performance predictions. However, systems using these standard airfoils produced energy at costs greater than desired and exhibited cyclic stress characteristics which decreased reliability and caused early fatigue lifetime estimates to be questioned. These negative aspects prompted consideration of airfoils which were intended specifically for WECS applications. This paper details one evolution of blade element airfoil sections which were designed exclusively for use in the vertical axis wind turbine (VAWT) environment. The process includes:

1. Determination of desirable section characteristics.
2. Numerical design of blade element sections.
3. Field test (small scale) of computer-generated sections.
4. Wind tunnel test (static) of chosen sections.
5. Field test (large scale) of a typical section.
6. Wind tunnel test (dynamic) of chosen sections.

Items 1 through 4 were completed as of late 1983. They have shown that 10-20% reductions in cost-of-energy (COE) and fatigue life improvements may be obtained through design of airfoils having the exclusive purpose of serving as VAWT blade element airfoil sections. The last two activities are currently underway. The first three of the above six-step process are described in detail in Reference 1. They will be reviewed here only.

DETERMINATION OF DESIRABLE SECTION CHARACTERISTICS

The approach taken to identify airfoil properties which would favorably affect turbine operation was indirect. Turbine economic (Ref. 2) parametric studies were conducted using artificial VAWT aerodynamic performance descriptions. Attempts were then made to match, through performance code modeling, the assumed performance descriptions of those configurations demonstrating the lowest COEs. The rated powers of the hypothetical turbines examined fell into the 100-500-kW range. The aerodynamic performance codes used were of the double-pass conservation of momentum multiple streamtube type (Refs. 3 and 4). These codes require blade element airfoil section data as input information. These data were artificially constructed for symmetrical sections, fed into the performance codes and the output examined. Adjustments were made to the input section data until predicted VAWT performance resembled the performance figures representing the low COE systems. Qualitatively, the blade element airfoil section typically should have: 1) modest values of maximum lift coefficient with relatively sharp stall, 2) low zero lift drag coefficients, and 3) wide drag buckets. The finally adjusted section data became the objective section characteristics.

NUMERICAL DESIGN OF BLADE ELEMENT SECTIONS

The design of the actual sections was accomplished using the popular airfoil design/synthesizer code of R. Eppler (Ref. 5) by a Sandia National Laboratories (SNL) consultant, G. M. Gregorek of Ohio State University. This code, known as PROFILE, functions by combining a boundary layer model with a conformal mapping technique to generate airfoil geometries which have prescribed velocity distribution characteristics. PROFILE makes accurate calculations of section drag as long as the Reynolds number (Re) is greater than 0.2×10^6 and the flow is not separated. For highly separated flows, data taken from wind tunnel tests on NACA 00xx sections, and assumed to be independent of shape and Re, were used. The mid-stall region was represented by curves faired between the Eppler predictions and the universal test data. These computations are referred to as the "Three-Source Section Data".

The "tailored" airfoil sections were expected to operate at values of Re between roughly 1 and 3 million. A group of sections having the desirable characteristics noted above and operating in this Re range are the natural laminar flow (NLF) airfoils. These are defined as airfoils which can achieve significant extents of laminar flow (>30% of chord) solely through favorable pressure gradients. The most popular (and least expensive) VAWT blade construction technique is aluminum extrusion. This process can produce surface finishes and hold tolerances which are close to those of the more expensive composite construction techniques used for high-performance sailplanes which successfully use NLF. It was believed that blades manufactured by extruding aluminum would provide a proper surface for maintaining the desired extents of natural laminar flow (Ref. 6).

Three sections were designed with conservative laminar flow extents which were to be approximately 50% of chord at near zero values of angle-of-attack, α. The sections were also symmetrical. This feature would allow for a less complicated comparison with currently used blade element sections, even though cambering appears to offer some advantages in VAWT design. The sections had three values of thickness: 15, 18 and 21% of chord. The first value is typical of existing blade elements while the higher values are desirable from the structural viewpoint. Figure 1 shows the 15% t/c design. The section was designated SAND 0015/47, the 47 indicating the percent of chord which was to support laminar flow. The cross section of the NACA 0015 is superimposed in Figure 1 for comparison. The geometrical differences between the two airfoils may be summarized in noting that the NLF profile has a smaller leading edge radius and a maximum thickness farther aft than the NACA 0015, and it also has a slight reflex toward the trailing edge. The 18 and 21% sections are qualitatively similar.

Figures 2 and 3 give lift and drag coefficients for the SAND 0015/47, as well as those for the most popular current VAWT blade element, the NACA 0015, as calculated by PROFILE. The calculated effects of surface roughness are shown in Figure 4. Note that while roughness degrades NLF performance, they can remain superior to NACA sections of the same thickness and under similar conditions.

FIELD TEST (SMALL SCALE)

Prior to this time, no NLF airfoil was known to have been used in a wind turbine application. It was advisable to demonstrate that this could be successfully accomplished as early as possible. The first section designed, the SAND 0015/47, was chosen for this demonstration, and the vehicle was the SNL 5-m diameter research VAWT. Testing indicated that when compared to the NACA 0015 bladed version of the 5-m diameter turbine (see Figures 5 and 6):

1. Efficiencies (C_p) remain nearly constant over a wide range of tip-speed ratio ($R\omega/V_\infty$);
2. Maximum (rated) power level is lower;
3. Break-in (power-producing) tipspeed ratio (TSR) is the same;
4. Peak efficiency is lower.

Points 1 and 2 are considered positive. The nearly constant power coefficient feature of this constant rotational speed turbine means there is little change in operating efficiency over a reasonable range of wind speeds. Lowering the rated power level allows for reduced capital costs by not having to build in capacity which would be used only a few percent of the turbine's operating time while not significantly changing net energy capture. The drive train with a lower power rating also has a lower tare

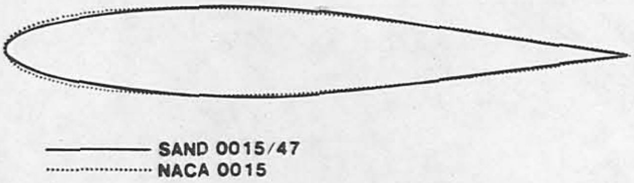

FIGURE 1. CROSS-SECTIONS OF SAND 0015/47 AND NACA 0015 AIRFOIL SECTIONS

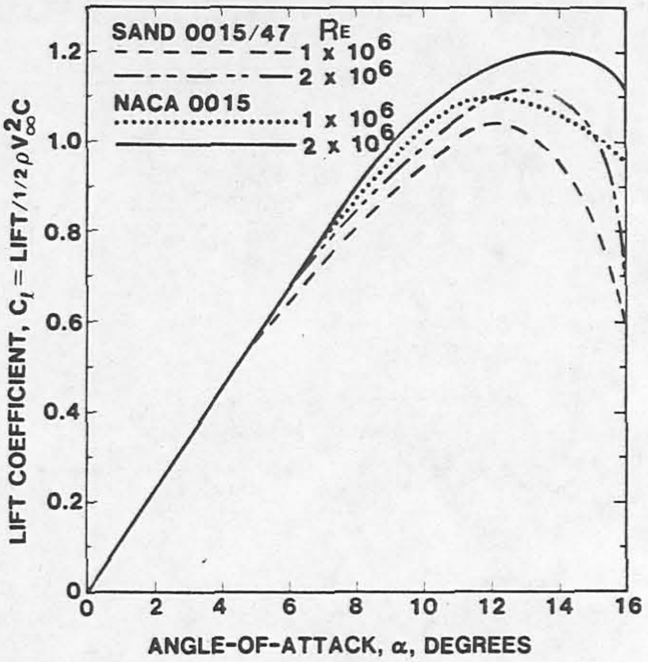

FIGURE 2. COMPARISON OF CALCULATED LIFT COEFFICIENTS FOR SAND 0015/47 AND NACA 0015 AIRFOIL SECTIONS

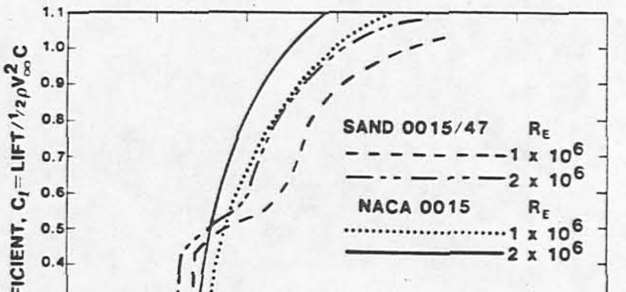

FIGURE 3. COMPARISON OF CALCULATED DRAG COEFFICIENTS FOR SAND 0015/47 AND NACA 0015 AIRFOIL SECTIONS

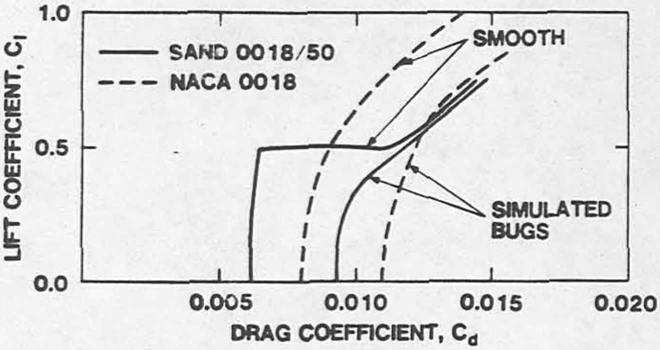

FIG. 4. EFFECT OF SURFACE ROUGHNESS ON SAND 0018/50 AND NACA 0018 AIRFOIL SECTION AT $Re = 1.5 \times 10^6$.

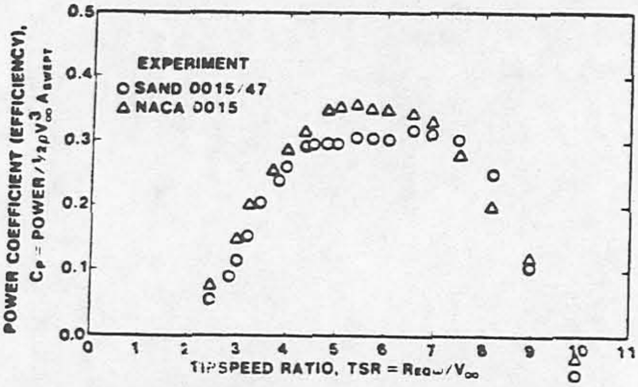

FIG. 5. POWER COEFFICIENT VS TIPSPEED RATIO FOR SNL 5-M DIAMETER VAWT, ω = 175-RPM, SAND 0015/47 AND NACA 0015 SECTION BLADES.

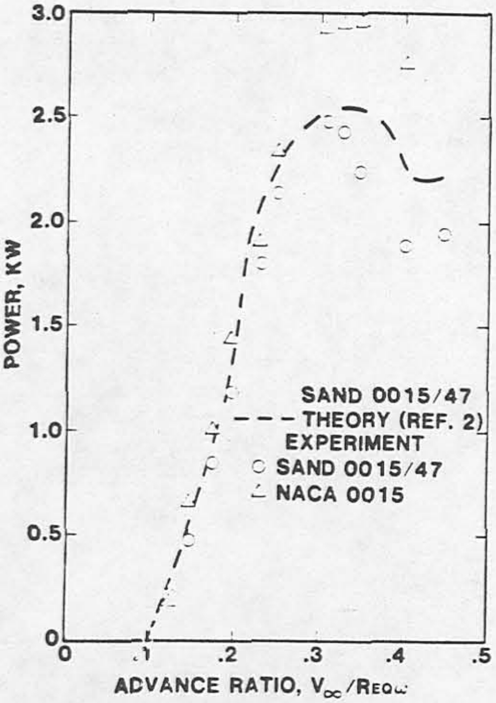

FIG. 6. AERODYNAMIC POWER VS ADVANCE RATIO FOR SNL 5-M DIAMETER VAWT, ω = 175-RPM, SAND 0015/47 AND NACA 0015 SECTION BLADES.

rating, which increases energy capture over the entire operating range and offsets the high windspeed energy capture reductions due to the lowered rating.

The no-change in breakeven TSR was believed to be due primarily to the low values of Re for this test. It was also felt that the lower peak efficiency is attributable, at least in part, to the low Reynolds number.

The lowered peak efficiency found with the SAND 0015/47 blades was a negative factor. This quantity could be raised by using a section whose drag bucket was somewhat wider than that of the SAND 0015/47 but which had approximately the same zero-lift drag coefficient as the earlier profile. This may be accomplished by adding thickness to the 15% t/c airfoil. The 18 and 21% t/c sections were designed with this goal in mind.

The SAND 0018/50 was extruded in a 15-cm chord, bent to the troposkein approximation shape for the SNL 5-m diameter research turbine, and tested. The measured performance of these blades was generally disappointing. Not only was the objective of increased peak efficiency not met; efficiencies over the entire range of tipspeed ratios were substantially down relative to those measured when the turbine was operating with the 15% NLF sections. A reexamination of the predicted airfoil flowfield characteristics showed that the SAND 0018/50 was subject to a relatively large extent of separated flow at low values of α, when operating at Reynolds numbers typical of the 5-m diameter research turbine. The PROFILE code substantially underpredicts the drag in this separated region, the reason being that the author (Eppler) believes that no user of the code would be interested in any airfoil design having significant separation. Consequently the design would be automatically discarded, and its drag value would be irrelevant. This characteristic was unknown at the time the 5-m test was being formulated. The poor performance on the 5-m led to the running of a very short noncomprehensive wind tunnel test on both the SAND 0018/50 and the SAND 0015/47 using specimens of the 15-cm chord extrusions. The test was conducted in the Ohio State University's 15-cm x 56-cm wind tunnel at Re 1.8×10^6 in order to verify that the 0.18 t/c airfoil's poor performance was in fact due to excessive separation at low Re, not due to a design flaw which would manifest itself at full scale. The results are summarized in Figures 7 and 8. It is apparent that Eppler predictions of drag for the SAND 0018/50 at this higher Reynolds number are quite reasonable, and that further consideration of this section is justified.

One favorable result of the 0018/50 small scale testing was the determination of

3. Maximum lift coefficients ($C_{\ell max}$) were slightly higher than anticipated.

4. Recovery to higher lift coefficients after the post-$C_{\ell max}$ drop occured later than expected.

Figure 10 illustrates observations 3 and 4.

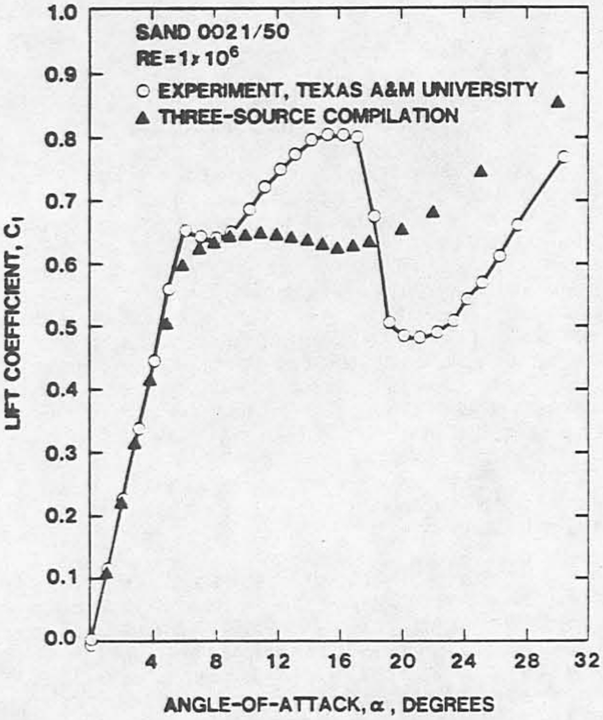

FIG. 10. C_l VS α, SAND 0021/50.

FIELD TEST (LARGE SCALE)

The next step in the blade evolution was large scale field testing. This step was to take place using full benefit of the earlier simulations, and small scale field and wind tunnel testing, but overall program scheduling and test slippages forced the design of the large scale field test to take place without the benefit of the static wind tunnel test results. Consequently the blade set design for the SNL 17-m diameter research VAWT was completed using the original three-source section data described earlier. The design was subjected to three ground rules. They were:

1. The root sections (those nearest the tower) were to be of NACA 0015. Performance simulations with blades having NLF airfoils along their entire span indicate that energy costs are higher than with blades having higher maximum lift coefficients and gentler stall characteristics near the tower.

2. The NLF airfoil section chord would be identical to that of the current version of the SNL 17-m turbine. This was to keep the NLF bladed turbine geometrically similar to the baseline 17-m, i.e., 2 blades, 61-cm chord, height-to-diameter of unity (H/D = 1), and a solidity of 0.146.

3. The NLF airfoil section would be the SAND 0018/50. The SAND 0021/50 was excluded on the basis of its performance characteristics not having any experimental verification, either in a wind tunnel or in the field operating as a VAWT blade element. The SAND 0015/47 was not considered as it was a predecessor design to the 0018/50.

The aerodynamic design used the tool developed by Kadlec (7). Based upon the double-pass multiple streamtube code first reported by Paraschivoiu (3) and coupled with the Gormont (8) dynamic stall model, this code allowed each rotor blade to be divided into 21 equal vertically dimensioned elements each having any chord and any airfoil section.

The aerodynamic performance of some eight geometrical combinations, each at three different turbine angular velocities, was calculated. The 24 resulting sets of aerodynamic performance parameters were then used as input data to the SNL VAWT economic estimation model (2), and system COEs were calculated. A 6.26-m/s (14-mph) average Weibull ambient wind distribution was used. The current version of the 17-m, operating at 50.6 rpm, was considered to be the baseline case. Calculated costs-of-energy for the 23 nonbaseline cases ranged from 9% below the baseline to 34% above. Allowing the economic code to optimize angular velocity resulted in a turbine rpm of 66.7 and a system COE which was 10% below that of the baseline case. This turbine had blades whose center 62% vertical projection used the SAND 0018/50 with the remaining (extremities) portion being comprised of NACA 0015 airfoil sections. The blades were fabricated and installed during April 1984.

No test results are available at this writing; however, Figure 11 gives current predictions (Ref. 3) of aerodynamic power versus advance ratio for the hybrid bladed turbine operating at its COE optimum angular velocity. The blade element airfoil section data used here does include the results of the static wind tunnel test series. The deviations from the assumed stall region section behavior results in the optimum angular velocity dropping from 66.7 to 63.2 rpm. Shown for comparison is the baseline case, also COE optimized for its blade element airfoil section. The annual energy production of both turbines is the same, but it can be seen readily that the NLF bladed version produces more of its energy

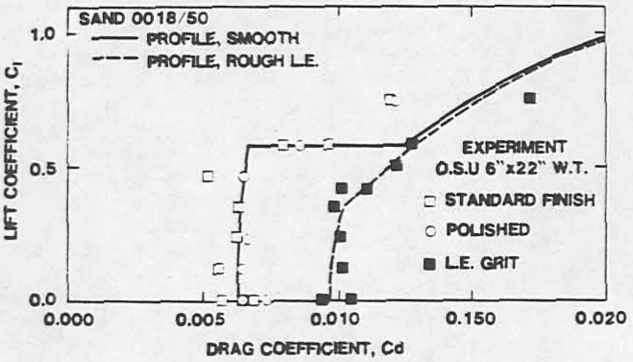

FIG. 7. EXPERIMENTAL AND ANALYTICAL DRAG POLARS, SAND 0018/50 AIRFOIL SECTION, Re = 1.8 x 10^6.

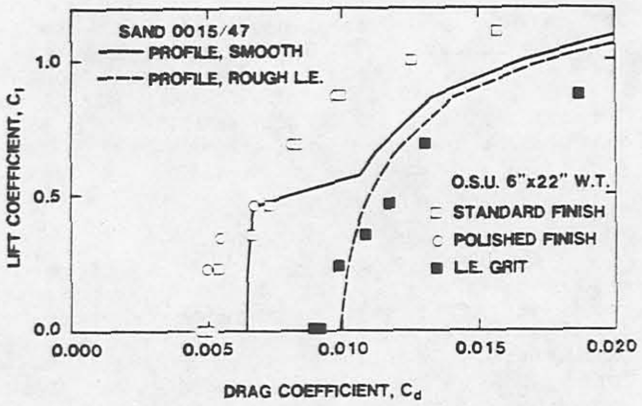

FIG. 8. EXPERIMENTAL AND ANALYTICAL DRAG POLARS, SAND 0015/47 AIRFOIL SECTION, Re = 1.8 x 10^6.

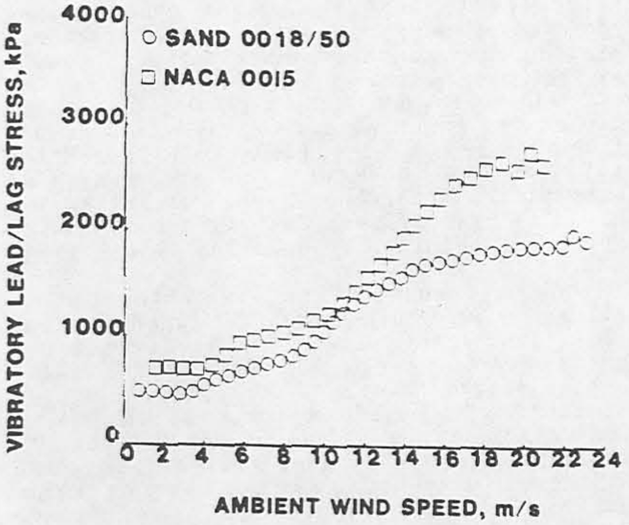

FIG. 9. MEASURED LEAD/LAG VIBRATORY STRESSES SNL 5-M VAWT, SAND 0018/50 AND NACA 0015 BLADE AIRFOIL SECTIONS, ω = 162.5 RPM.

the high wind speed vibratory stress behavior. Shown in Figure 9, the NLF blade lead/lag stress does not increase nearly as rapidly with increasing wind speed as does the NACA 0015 bladed version. This feature, believed due to the section's being an NLF profile, has extremely important implications in the area of reduced fatigue and increased turbine lifetime. It is also believed that this feature does not depend qualitatively upon Re, as computer simulations at higher values of Reynolds numbers indicate that similar trends exist.

STATIC WIND TUNNEL TEST SERIES

Airfoil data in the mid-to-late stall region are of particular importance to vertical axis wind turbine system design. Much of each turbine blade operates in this region in high wind conditions. It is in these winds that maximum power levels are reached. The blade performance in the stall region determines the actual rating of the turbine, the turbine regulation characteristics, and the required drive train and generator capacities. Since the final design of a system is too important to be allowed to depend on estimated section performance, a test series was initiated to determine the actual performance of the three SNL NLF designs.

The objectives of the wind tunnel test were two fold: 1) to obtain force and moment data on the sections, and 2) to measure the pressure distribution on the surface of the airfoils. The tests were run in the Texas A&M University's 2.13 m x 3.05 m (7 ft x 10 ft) Low Speed Wind Tunnel. The airfoil models had nominally 30 cm chords and were instrumented with 70 static pressure ports. An 80-port wake rake was in place 1.25 chords behind each section. Each model was mounted vertically such that it nearly intersected both the tunnel ceiling and floor. Data were obtained for α's between 0 and 180° for Re's 0.2, 0.5, 1.0 and 1.5 x 10^6. Lift and moment were obtained through integration of the blade surface pressures. Drag was calculated by integration of both surface and wake rake pressures. Limited balance measurements were made to supplement the pressure integrations. Some oil and smoke flow vizualization runs were also conducted to assist in interpreting the quantitative measurements.

The following observations may be made from this test.

1. Extents of laminar flow were up to 60-65% of chord, rather than the 45-50% expected.

2. Low α drag coefficients were consistent with PROFILE predictions and the OSU wind tunnel test results.

at lower relative wind speeds than does the baseline turbine.

Calculated aerodynamic torques for the two turbines are plotted in Figure 12. The lower average and RMS vibratory torques produced by the hybrid bladed turbine are apparent. The lower average torques imply reduced transmission costs while the lower vibratories will bring about increased fatigue lifetimes.

WIND TUNNEL TEST (DYNAMIC)

Unsteady aerodynamics is an inherent feature of VAWT operatiion. Turbine peak loads are the result of one of these unsteady effects, dynamic stall. A wind tunnel test series is currently underway using the SAND 0015/47 and 0018/50 sections where α histories, Reynolds and Mach numbers, and reduced frequencies consistent with a 34-m diameter, 500-kW VAWT are being duplicated. Models will be fabricated from a graphite/epoxy compound cast to proper contours in precisely machined molds. Models will have 11.4-cm chords and will be tested in the Ohio State University's 15-cm x 30-cm variable pressure wind tunnel. Pressure taps serving an electronically scanned pressure system or surface mounted piezoresistive transducers will be used. Oscillations will be driven by electric or hydraulic motors over four α ranges: ±14°, ±19°, ±30° and ±53°. Reduced frequencies, $k = \dot{\alpha} c/2V_\infty$, will be 0.01, 0.05 and 0.25. Four values of Re will be considered: 0.5, 1.0, 2.0 and 4.0 x 10^6. Air density will be adjusted to maintain a nominal Mach number of 0.15. Software and hardware development are well underway and first data are expected in September 1984.

SUMMARY

The development of a family of airfoil sections specifically intended for use as blade elements on a vertical axis wind turbine has been described. The product of extensive numerical modeling and wind tunnel testing, these sections have a strong potential for reducing VAWT systems cost-of-energy and increasing system reliability and lifetime.

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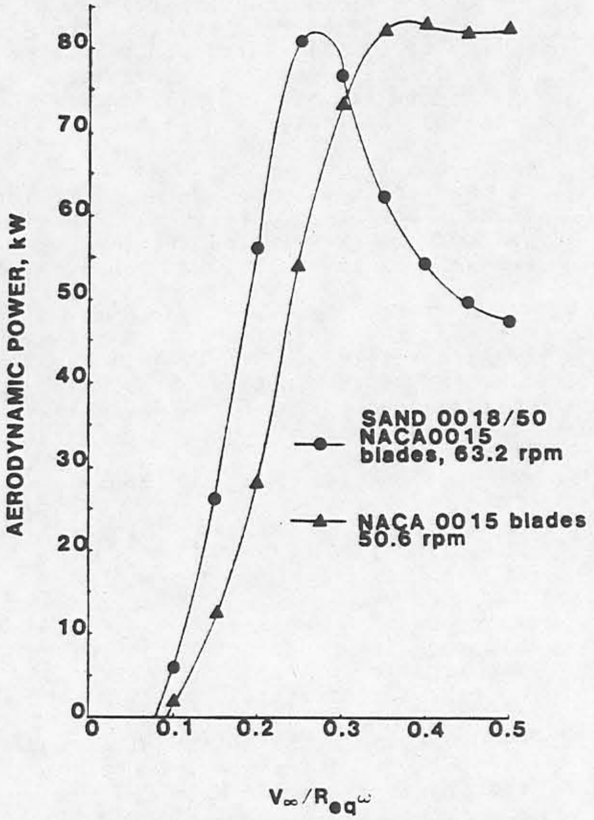

FIG. 11. CALCULATED AERODYNAMIC OUTPUT POWER, SNL 17-M DIAMETER RESEARCH VAWT, 61-CM CHORD, HEIGHT/DIAMETER = 1.0, EQUAL ANNUAL ENERGY PRODUCTIONS, 1500-M MSL.

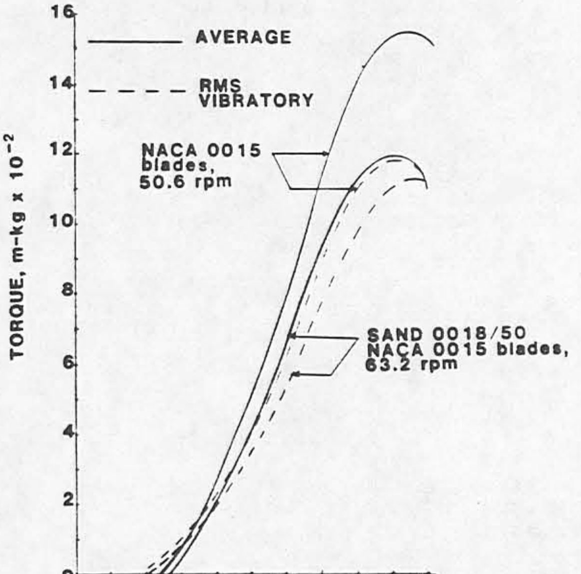

FIG. 12. CALCULATED AVERAGE AND RMS VIBRATORY TORQUES, SNL 17-M DIAMETER RESEARCH VAWT, 61-CM CHORD, HEIGHT/DIAMETER = 1.0, EQUAL ANNUAL ENERGY PRODUCTIONS, 1500-M MSL.

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