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DOE/NREL Advanced Wind Turbine Development Program

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ABSTRACT: The development of technologically advanced, high-efficiency wind turbines continues to be a high-priority activity of the U.S. wind industry. The National Renewable Energy Laboratory (formerly the Solar Energy Research Institute), sponsored by the U.S. Department of Energy (DOE), has initiated the Advanced Wind Turbine Program to assist the wind industry in the development of a new class of advanced wind turbines. The initial phase of the program focused on developing conceptual designs for near-term and advanced turbines. The goal of the second phase of this program is to use the experience gained over the last decade of turbine design and operation combined with the latest existing design tools to develop a turbine that will produce energy at $0.05 per kilowatt-hour (kWh) in a 5.8-m/s (13-mph) wind site. Three contracts have been awarded, and two more are under negotiation in the second phase. The third phase of the program will use new innovations and state-of-the-art wind turbine design technology to produce a turbine that will generate energy at $0.04/kWh in a 5.8-m/s wind site. Details of the third phase will be announced in early 1993.

1. INTRODUCTION

The Advanced Wind Turbine Program is currently in its second phase. In Phase II, each of the contractors is required to evaluate a promising existing turbine, propose design improvements for the same turbine, fabricate two prototypes of the improved turbine design, and test these prototypes in a demanding wind site. The contractors must demonstrate that their designs have met the cost of energy (COE) and reliability goals during these tests. Later, under Phase III, contractors will be required to start their design process with a completely new approach that must use innovative design concepts capable of meeting the much more challenging COE goal. The development of this class of turbine will require the latest design tools, extensive component development testing, and the use of advanced materials.

This paper will describe the complete program, the turbines currently being designed, the innovative design techniques, and the evaluation testing planned for the prototypes. It will also contain the results of preliminary tests that have already been conducted on "preprototype" turbines.

2. BACKGROUND

Wind generation of electricity for delivery to the electric grid must compete with other utility sources of electricity in a complex world of financing, tax credits and penalties, competing cost formulas, and set-asides. Despite the actual complexity of the energy market, relatively new technologies such as wind turbines must still compete on a pure COE basis with the well-developed fossil fuel infrastructures for the production of electricity. Wind systems can only grow by eliminating perceptions of poor reliability and availability through technological developments, innovation, and improvement. Wind turbine operators have made great strides to eliminate these perceptions using current technology, but that is not enough. Existing wind turbines produce electricity at $0.07–$0.09/kWh. Decreases on the order of 50% are needed to help make wind energy competitive. New advances in aerodynamics, materials, generators, controls, and design tools must be incorporated into turbine designs to make wind-generated electricity competitive with conventional energy sources.

3. ADVANCED WIND TURBINE PROGRAM

The next 5 years are critical for the U.S. wind industry. Market opportunities are multiplying as utilities, state and local governments, and the public are becoming more aware of the potential for wind power. The wind industry must place itself in a position to take advantage of these opportunities. The DOE programs are designed to assist industry activities in meeting these challenges. First, existing wind plant operators and developers must remain healthy and competitive. Second, new products that combine the best of existing designs with new research and technology must be ready for deployment in the near term. Third, a next generation of utility-grade wind turbines must be developed for the year 2000 and beyond.

The goal of the Advanced Wind Turbine Program is to assist U.S. industry in incorporating advanced wind turbine technology into utility-grade wind turbines for the near term (1993–1995) (Near Term Product Development [NTPD] Program), and to provide the next generation of utility-grade wind turbines for the mid-term (late 1990s) (Next Generation Product Development [NGPD] Program). The NTPD Program is in progress with three contractors developing prototype turbines. The technical advances incorporated in these turbines will be the main topic of this report.

The NGPD Program is split into two parts. The first part, entitled the Innovative Subsystems Project, will focus on development of innovative subsystems or components that can be designed separately from the full turbine, bench tested, and proof-of-concept tested on a full-scale turbine. The second part, entitled Turbine Development Project, will focus on the development of utility-scale turbines and produce prototype machines for field testing.

These programs will help introduce new products into the marketplace, support the development of new jobs domestically, help create greater stability and strength in the wind industry by attracting utility participation, broaden the national use of wind energy, and increase competitiveness in the international marketplace.

NEAR-TERM PROTOTYPE DEVELOPMENT

Under the NTPD Program, three contractors are developing prototype wind turbines. R. Lynette and Associates has already deployed the WC-86 machine, which incorporates several design improvements from the earlier ESI-80. Atlantic Orient Corporation is developing the 15/50, a dramatic improvement over the Enertech 44/60 turbine after which it is designed. And, Northern Power Systems is developing the NPS 250, which sports a redesigned rotor.

4.1 WC-86

R. Lynette and Associates (RLA), located in Redmond, Washington, U.S.A., is developing a 275-kW, 26.3-m, downwind, teetered rotor turbine based on the ESI-80 design. The ESI-80 design was developed as the next generation of the ESI-54 in the early 1980s and enjoyed partial success. Most of the failings of the ESI-80 were caused by simple engineering oversights, poor attention to design details, or a poor knowledge of extreme loads. With a thorough re-engineering effort, a better knowledge of the design loads, and an optimum blade redesign, RLA believes this design will be a robust and reliable turbine with improved energy production, suitable for utility-scale power generation. Redesigning the ESI-80 has allowed RLA to take advantage of the substantial operating history of this machine, retain component designs that proved reliable, and focus redesign efforts on those areas of the turbine that were unreliable [1].

Simplicity and Performance Improvements: Figure 1 illustrates RLA's WC-86 turbine along with the basic design specifications. Simplicity has been maintained throughout the machine with the fixed pitch and free yaw configuration. The rotor diameter has been increased from 24.5 m (80 ft) to 26.3 m (86 ft). Proven wood composite material has been used to design a more aerodynamically efficient blade that incorporates the new, NREL-developed S8XX thick family airfoils (Figure 2). Use of the new airfoils plus an optimized planform has resulted in a substantial increase in performance. Figure 3 compares the original ESI-80 power curve with the measured

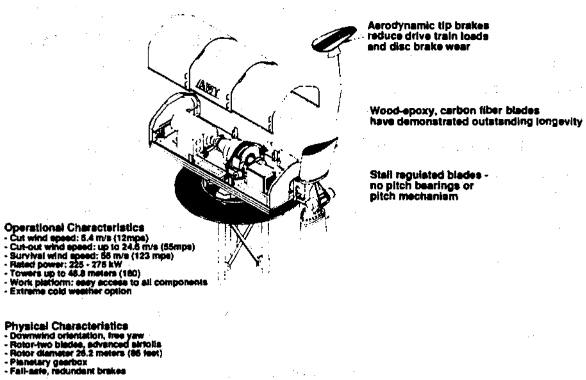

Figure 1: R. Lynette and Associates WC-86 Turbine

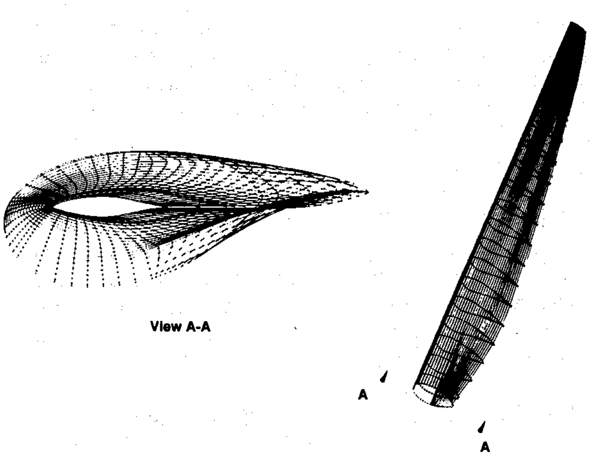

Figure 2: RLA WC-86 Wood Epoxy Blade

power curve of the WC-86. A percent improvement curve is shown in the same figure and illustrates a dramatic 70% improvement at 8 m/s.

Tip Vanes: One key to the success of any stall-regulated turbine is a reliable aerodynamic brake. RLA has retained the tip vane concept and uses it both as a fail-safe brake and as an active brake for normal shut-down operations. The ESI-80 tip vane proved to be very effective when used in both these braking modes. The vane is mounted at the tip of the blade and allowed to pivot about a hinge line that is perpendicular to the chord line located at the leading edge. The vane is held in a low-drag orientation with an electro-magnet and released either by a control system command or centrifugal forces. When released, the vane is forced to rotate into a high-drag orientation (parallel to the leading edge) by centrifugal forces and aerodynamic forces.

The ESI-80's tip vanes principal failings were insufficiently sized hinge pins, overweight fiberglass vanes, and unreliable slip rings. The slip rings are used to transmit electrical power from the nacelle to the rotor. RLA re-engineered all these problem parts while retaining the successful features of the system. Slip rings have been replaced with a split rotating transformer that transmits electrical power to the rotor using magnet coupling. The split feature allows wind turbine technicians to easily remove the transformer coils in the unlikely event of failure. The split, rotating transformer was supplied by Atlantic Orient Corporation for the same application in its new turbine design, which is discussed later.

The tip vane has been redesigned into a low-drag, lightweight, composite structure. The new vane has been tested in a wind tunnel to confirm its low drag in the undeployed orientation (parallel to the tip path) and to determine its maximum drag in the deployed orientation. These force measurements were also helpful in accurately simulating the deployment transient loads that were needed to design the hinge structure. RLA has conducted rotor performance tests that prove that the tip vanes actually enhance production at low to moderate wind speeds and reduce peak power at cut-out wind speeds (23 m/s). Figure 4 shows the tip vanes during wind tunnel testing.

Low-Speed Shaft Brake: A low-speed shaft brake was incorporated into the WC-86 to eliminate braking loads in the gearbox and improve the reliability of the brake. The new system is a more traditional multiple caliper disk brake, which is spring applied and released by air pressure. The brake will experience light duty because the tip brakes will provide the primary braking energy for all normal high-wind shut-downs, but it is sized to be capable of stopping the machine in all normal and abnormal operating conditions.

Prototype Tests: RLA will initially deploy at least two prototypes. Both of these turbines will be located in a very turbulent site in the Tehachapi, California, wind farms. The first one was installed in February 1993. The next prototype will incorporate all the experience gained during assembly and

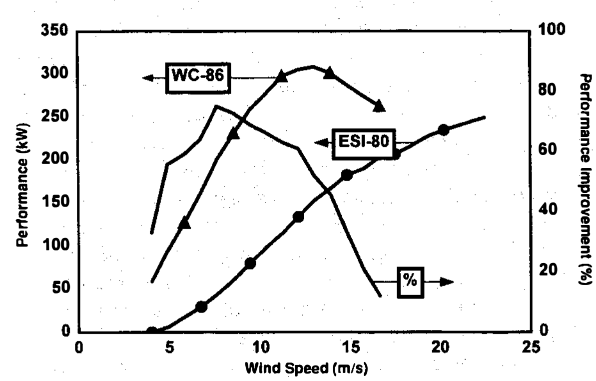

Figure 3: RLA WC-86 Performance Improvement

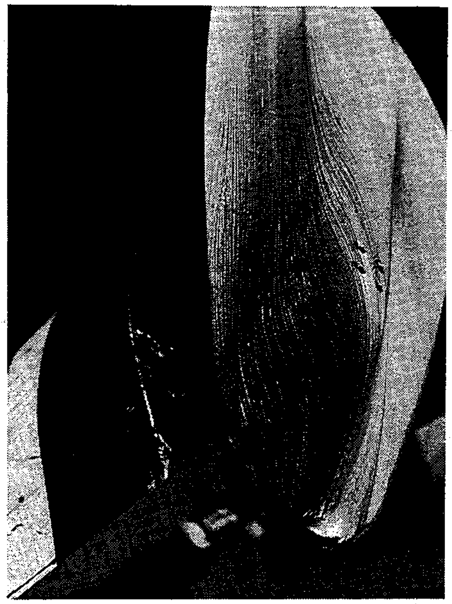

Figure 4: RLA WC-86 Tip Vane Wind Tunnel Test

testing of the first. The second prototype is expected to be installed in the late fall of 1993.

4.2 AOC 15/50

The Atlantic Orient Corporation (AOC) is located in Norwich, Vermont, U.S.A. The AOC has developed an improved and simplified version of the Enertech 44/60 called the AOC 15/50 (15-m diameter with a 50-kW rating) [2]. Figure 5 illustrates this new design and lists some of the major specifications. This down-wind, three-bladed turbine design is suited for remote applications, small wind farms, and even large wind farms where sufficient land is available. Its integrated main frame/gearbox/generator eliminates many of the critical bolted joints found in conventional turbine designs and creates a very efficient load path from the rotor to the tower top. The new configuration has allowed AOC to reduce the material needed for a safe design. The integrated drive train has also eliminated maintenance-prone couplings between the gearbox and the generator.

Several other features have been added to the machine without increasing the complexity. An optional yaw damper has been added for turbines located in turbulent sites. The damper is a passive hydraulic system that limits yaw rates and hence gyroscopic loads. In most sites, with average turbulence, this device will not be needed. A cast tower top plate has been added to further improve the efficiency of the load path. A fail-safe electrodynamic brake was developed using passive electrical components. The tip vanes are electromagnetically retained, much like the RLA tip brakes. As mentioned earlier, AOC developed a split rotating transformer that is used to transmit tip brake control power from the nacelle to the rotor. Finally, AOC has developed a new wood epoxy composite blade using the new NREL S809 thick family airfoils. Like RLA, AOC has dramatically improved its performance by increasing its rotor diameter while retaining a modest peak power. This approach limits the size of the generator and the gearbox required, yet improves the performance in the most probable energy-producing wind speed range. Figure 6 shows this new blade, and Figure 7 shows the improved power curve.

Component Fatigue Testing: The new wood composite blade was supplied by Gougeon Brothers Inc. Static and fatigue tests were conducted at the NREL fatigue test facility [3]. Fatigue loads were applied at a spanwise location, which exercised the majority of the inboard portion of the blade. Load sequences (blocks) were applied repeatedly while the cyclic amplitude was increased. Failure occurred at 55,733 cycles for load amplitude ratios of R = 0.1, with maximum loads of 2/3 (68%) of design failure strength. Analysis shows that this blade would probably exceed the Danish Standard and has allowed AOC to quantify the blade design limits.

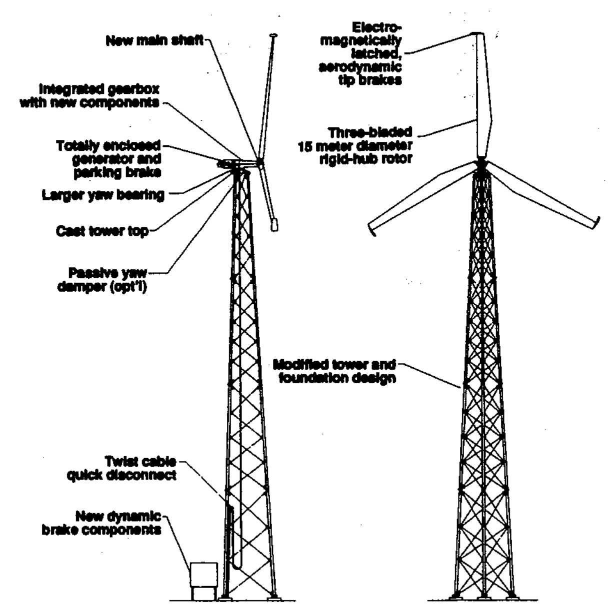

Figure 5: Atlantic Orient Corp. 15/50 Turbine

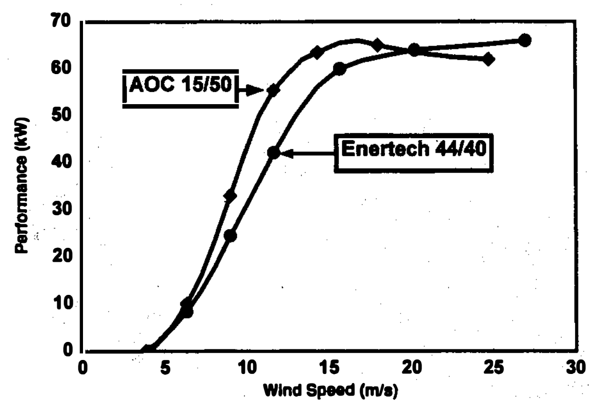

Figure 6: AOC 15/50 Blade Layout

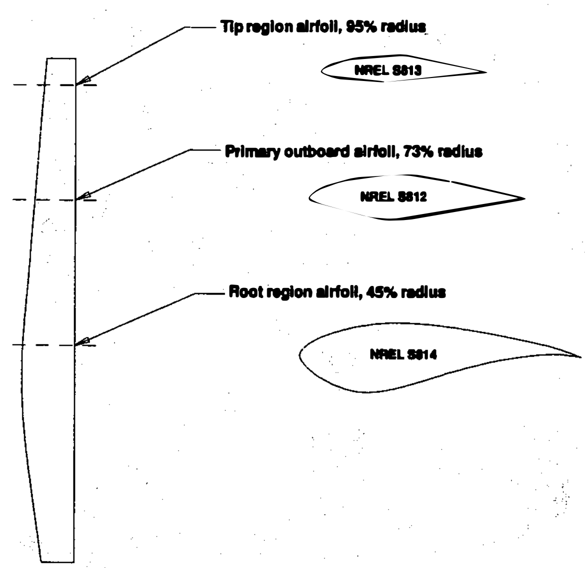

Figure 7: AOC 15/50 Performance Improvements

Because the tip brakes are so important in the safe and reliable operation of the machine, AOC decided to fatigue test them under simulated conditions. Figure 8 shows a spin test stand that is designed to cycle the tip brakes through a sequence of start-ups, deployments, and shut-downs. This system will realistically simulate operating loads and allow AOC to subject the system (including the rotating transformer) to a lifetime of deployments before the prototype has been field tested. This test stand may also be used to test cold weather icing conditions.

A test stand has been designed to simulate high yaw rate loading cycles on the entire load path from the hub joint through the yaw bearing to the tower top. The generator will be used as a motor to drive the gearbox and main shaft while simulated thrust and gyroscopic loads are applied using pneumatic cylinders. These extreme load conditions will be simulated until AOC design engineers are satisfied that there are no design weakness.

Prototype Tests: At least three prototypes will be deployed. The first will be deployed at the U.S. Department of Agriculture (USDA) Agricultural Research Station in Bushland, Texas, U.S.A. The second will be installed at a severe cold weather site on top of Mount Equinox, Vermont, where winter icing is common. This site is operated by Green Mountain Power, a Vermont utility. The last will be installed in an extremely turbulent site in the Palm Springs, California, wind farms.

4.3 NPS 250

Northern Power Systems (NPS) is located in Moretown, Vermont, U.S.A. Northern's wind turbine design experience dates back to the mid-1970s when its researchers developed the High Reliability 2-kW (HR-2) turbine [4]. Northern's last design was the North Wind 100-kW machine (NW-100) [5]. The 250-kW, two-bladed, teetered, up-wind machine that NPS is developing under the current DOE contract is a scaled-up version of the NW-100. Figure 9 illustrates this turbine and lists some of its key features.

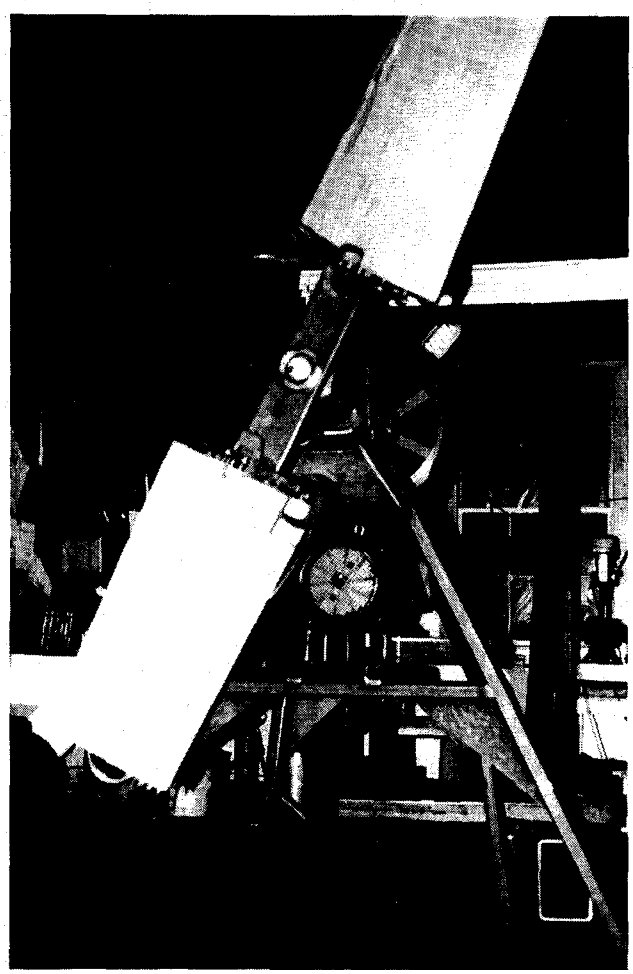

Figure 8: AOC 15/50 Tip Brake Test Stand

Most of the NPS work has been focused on the rotor design. Learning from the successes and failures of the NW-100, Northern researchers have eliminated the full span pitch control system used in that design and substituted aileron controls. They have designed a more robust hub that incorporates teeter and an active teeter brake. The blade is a hybrid composite that combines skins and spars, fabricated using filament winding techniques, with a flow-through hub section. Figure 10 shows an exploded view of how the various components will be assembled into an efficient low-cost blade. Figure 11 illustrates the hub saddle, which captures the blade center section in a wrap-around elastomeric blanket. The flow-through hub will eliminate all costly and inefficient blade root joints, which have been the site of past blade failures in some turbines. With this hub design, all the critical loads, such as flapwise bending, in-plane gravity, and centrifugal loads, are isolated in the rotor structure. Only torque, thrust, and unbalanced loads are transmitted through the hub to the nacelle structure.

Ailerons: The most important new development featured in this turbine is the ailerons. These devices deflect in the downwind direction and act as spoilers or drag brakes when aerodynamic brakes are needed. When power modulation is needed, above rated wind speed, the ailerons can be deflected through small angles to increase or decrease power. Small

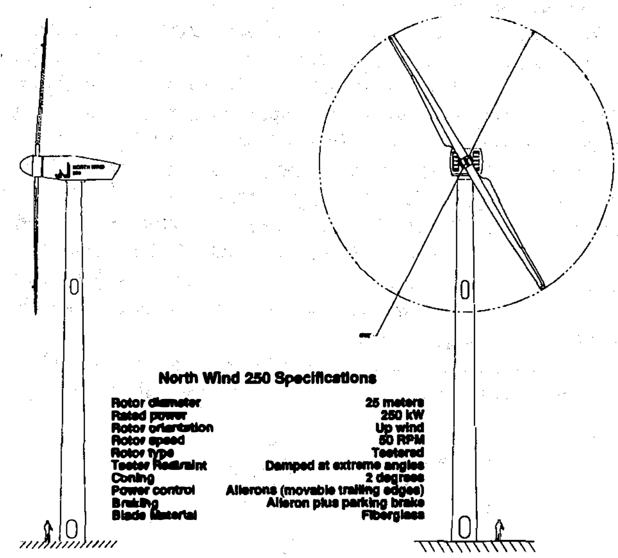

Figure 9: Northern Power Systems 250-kW Turbine

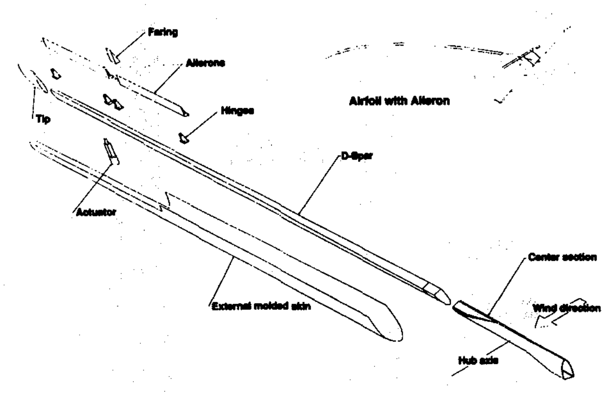

Figure 10: NPS 250 Blade Assembly

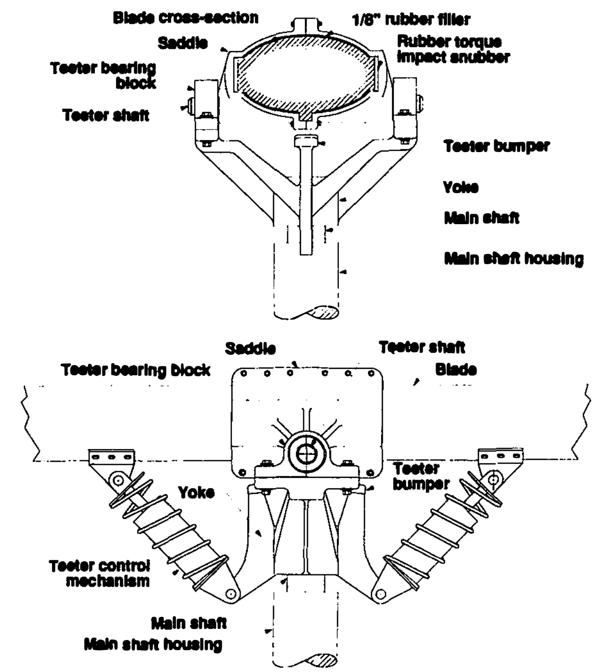

Figure 11: NPS 250 Teetered Hub Assembly

positive deflections (upwind) will increase camber, which will increase lift (and drag). Small negative deflections (downwind) will decrease camber and decrease lift. Because only 30% of chord and span is used to accomplish the needed control, the actuation loads and actuators are small. This approach does not require costly joints in the load-bearing spar of the blade.

Figure 12 shows tests being conducted at the Wichita State University wind tunnel on an airfoil with an aileron. These tests were run to measure the airfoil performance under a wide range of angles of attack and aileron deflection angles. Results have helped NPS aerodynamicists optimize the aileron configuration. Ailerons such as these have been tested on NASA's 40-m MOD-0 test bed and three different NPS test turbines ranging in size from 2 to 20 m [6]. Each of these tests has shown that ailerons can be used effectively in controlling rotor speed. A parking brake will still be required for maintenance and bringing the rotor to a complete stop, but, as in the case of RLA and AOC, the aerodynamic brake will be used as the primary braking device.

Prototype Tests: NPS has tested the aileron concept on one three-bladed turbine and two two-bladed, teetered turbines. Tests for a prototype turbine will begin in the fall of 1993. The test site will be located on a wind farm in Altamont Pass, California.

5. CONCLUSIONS

The DOE/NREL Advanced Wind Turbine Program has initiated the development of three promising new turbine designs. Each of the designs has taken advantage of years of operating experience with similar turbines. Using current technology and more advanced design tools, the three companies have improved on designs that were deployed in the mid-1980s. The new designs all show dramatic performance, reliability, and COE improvements. They are all being subjected to comprehensive component test programs and multiple prototype field test programs. When these efforts are complete, these turbines will represent some of the most extensively engineered wind turbines in the world.

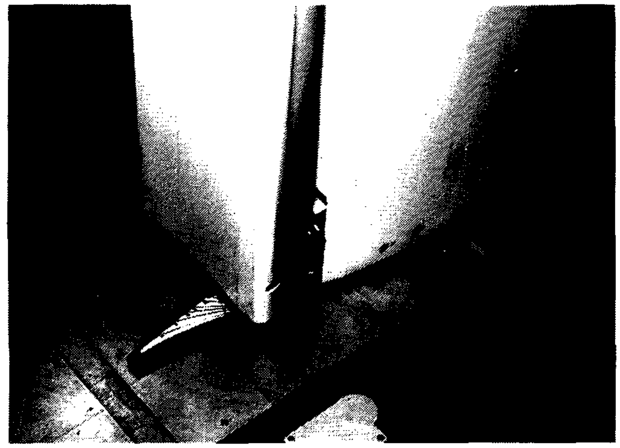

Figure 12: Aileron Blade Wind Tunnel Tests

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