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Non-Technical Summary Report

By
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Washington University Technology
Associates, Inc.
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WASHINGTON UNIVERSITY TECHNOLOGY
ASSOCIATES INC., ST. LOUIS, MISSOURI

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SERI TECHNICAL MONITOR:

RICHARD MITCHELL

PREFACE

Washington University Technology Associates is pleased to submit this Nontechnical Report on The Yawing of Wind Turbines With Blade Cyclic Pitch Variation under Solar Energy Research Institute Division, Subcontract No. XH-9-8085-3 and Midwest Research Institute Prime Contract No. EG-77C-01-4042.

We wish to thank the Solar Energy Research Institute for awarding the subcontract for this work to the WUTA Corporation. This work was directed and administered for SERI by Dr. Irwin Vas, Branch Chief--Wind Energy Branch. Mr. Richard Mitchell had program management responsibility for the work and was assisted by Mr. Peter South, acting as Principal Engineer. The subcontract was administered by Ms. Lori Miranda.

The report covers the contract performance period of September 15, 1979 to December 15, 1980. The principal investigator for this program was Dr. Kurt H. Hohenemser. Dr. Andrew H. P. Swift designed the wind tunnel model, performed part of the analytical work and all of the experimental work, including its evaluation. Dr. David A. Peters served as coinvestigator for dynamic analysis. Mr. Patrick F. Rice administered the project, designed the instrumentation system, and contributed to its implementation. Mr. William Stein of Astral Wilcon replaced the late Mr. Warren A. Strutman for the design and construction of the 7.6-m-diameter test wind turbine which has many components in common with the Astral Wilcon 10B machine. Mr. Rice edited and processed the Final Report and prepared and edited the Nontechnical Summary Report. Mr. James E. Bulfin assisted in drafting the summary report and served as an engineering technician during the study. Mrs. Kathleen Windish processed the text for the Final Report and the Nontechnical Summary Report.

The original contract performance period and funding level was increased in order to enhance instrumentation, thereby enabling measurement of critical dynamic loads of the test wind turbine. Measurement of performance as well as measurement of dynamic loads was required to determine whether the innovative concept had the potential for cost-effective wind energy conversion.

On June 28, 1980, lightning strikes severely damaged the instrumentation and recording system. It took over a month to repair the damage and to replace destroyed components of the instrumentation system. Despite the time lost in July and the unusually hot and windless month of August, the contract goal to analyze and verify by atmospheric experiments the yaw characteristics and power output of a wind turbine with blade cyclic pitch variation has been achieved.

This summary report contains highlights of the methodology employed and the results obtained from the study. The analytical and test work, within the bounds of the available test data, has shown the innovative concept to be viable. Blade cyclic pitch variation does not degrade system performance.

Performance may, in fact, be enhanced by the application of the concept because the machine rapidly adapts to changes in wind direction.

Richard Mitchell
SERI Technical Monitor

SECTION 1.0

NON-TECHNICAL SUMMARY

The purpose of the study "The Yawing of Wind Turbines With Blade Cyclic Pitch Variation", conducted under SERI Subcontract No. XH-9-8085-3, was to determine whether blade cyclic pitch variation could be adopted from rotorcraft technology and successfully applied to the yawing of horizontal axis wind turbines.

The methodology selected to test the innovative design concept included 1) computer-aided predictive analytical studies of performance, 2) small scale wind tunnel tests, operating without power extraction and, 3) full size 10 kW-rated atmospheric testing with microcomputer aided statistical data acquisition and processing.

The analytical studies, wind tunnel tests and atmospheric testing on a 10 kW-rated machine showed that the concept was viable; blade cyclic pitch variation has demonstrated potential for cost effective wind energy conversion.

1.1 INTRODUCTION

Most wind turbine designers have selected three or four-bladed rotors rather than the more cost-effective two-bladed rotor because of the higher aerodynamic and gyroscopic loads usually associated with the two-bladed rotor configuration. This study investigated the use of "blade cyclic pitch variation" as a method to compensate for these loads on a two-bladed wind turbine.

The term "cyclic pitch variation" is taken from rotorcraft technology. For rotorcraft with cantilever blades, cyclic pitch variation removes the aerodynamic and gyroscopic pitching and rolling moments on the airframe which otherwise would be very high. For rotorcraft with hinged or teetering blades, cyclic pitch variation compensates blade flapping and keeps the blade tip path plane approximately normal to the rotor shaft, in addition to providing a means for rotorcraft control.

To our knowledge, cyclic pitch variation has not been applied to horizontal axis wind rotors prior to this study. The lack of cyclic pitch variation in horizontal axis wind turbines with cantilever blades exposes these machines to higher aerodynamic and gyroscopic loads than necessary. These loads are particularly evident in two-bladed wind turbines with cantilever blades because the unbalanced aerodynamic and gyrosocpic blade moments produce substantial two per revolution loads and vibrations in the nonrotating structure. The NASA MOD-OA and MOD-1 two-bladed wind turbines with cantilever blades avoid excessive gyroscopic effects by using a slow yaw gear drive. As a consequence, the machines cannot follow rapid wind direction changes. Edgewise wind components of substantial magnitude can occur and can cause increased dynamic blade loads. To relieve the ill-effects of edgewise wind components, individual blades or pairs of opposing blades have been used in large two-bladed wind turbines built in the forties and fifties. They are incorporated in the latest US, German and Swedish designs of megawatt size two-bladed wind turbines.

The horizontal axis wind turbine study incorporated two features: The application of blade cyclic pitch variation adopted from rotorcraft technology, and the use of yaw angle control, not only for wind direction following, but also for rotor speed or torque control. Cyclic pitch variation in a two-bladed rotor relieves the blades of all the gyroscopic and odd-harmonic aerodynamic root moments. This makes rapid yaw rates of a two-bladed rotor possible without causing vibratory hub moments and without causing appreciable angular excursions of the blade tip path plane. Due to the allowable rapid yaw rates of wind turbines with blade cyclic pitch variation, the two conventional separate control systems - yaw control for wind direction following and blade feathering control for rotor speed and torque regulation - can be replaced by a system with only a single control variable, the rotor yaw angle.

The concept can be implemented in various ways. One way is to use active blade cyclic pitch control adopted from rotorcraft technology in combination with a freely yawing nacelle. Another way is to use passive blade cyclic pitch variation in combination with a yaw gear drive. A third way is to use passive cyclic pitch variation in combination with an adjustable tail vane for a freely yawing nacelle. The last method was selected for this study because it was the simplest and most reliable. Passive cyclic pitch variation is particularly simple for a two-bladed rotor. The blade pair is free to pitch about the common cyclic pitch axis without the need of a linkage. The blade axes have a small built-in prelag angle with respect to the cyclic pitch axis so that imbalancing gyroscopic or aerodynamic moments cause cyclic pitch variation that removes the imbalance.

Of several possible wind turbine configurations considered for this study, the configuration chosen on the basis of cost-effectiveness and simplicity had the following characteristics:

- A two-bladed, emasculated, hub moment free rotor with passive cyclic pitch variation, located upwind of the mast.
- A movable tail boom that could be rotated from a position essentially perpendicular to the rotor plane (zero furl angle) to a position essentially parallel to the rotor plane (90° furl angle).
- A power actuator that could adjust the tail boom furl angle (the angle between rotor axis and tail boom) in response to rotor speed signals.
- A self-excited alternator with constant electric load for stand alone grid-independent operation.

1.2 THE MODEL TESTS

The concept was first studied with a small scale wind tunnel model operating without power extraction. Although the model and the full scale machine were not geometrically similar, the near equality of the blade prelag angles and of the blade Lock numbers resulted in the same ratio (1.7) or rigid blade body mode frequencies over rotational frequencies. Thus, the blade cyclic pitch dynamics of the model and the full scale rotor were the same outside the blade stall regime.

The model could be tested in the free yaw mode with a tail vane or in the fixed yaw mode without a tail vane. The yaw angle could be changed during test runs. The purpose of the first series of small scale wind tunnel model tests, conducted in October, 1979, was to gain initial yawing experience with a wind rotor having passive cyclic pitch variation. A second series of tests was conducted in April, 1980 to obtain quantitative data on starting capability and to determine operating parameters at higher wind speed.

Results of the first wind tunnel model test series indicated that rotor rpm could easily be controlled by yawing the rotor out of the wind. These tests were conducted in the fixed yaw mode and the yaw angle was changed (and fixed) incrementally. The rotor was autorotating. The rotor self-started soon after starting the wind tunnel and ran smoothly without visible flapping in both yawed and unyawed positions, except that beyond 50° yaw angle some cyclic pitch stop pounding occurred for high wind speeds and rotor speeds. This was presumably related to a slope discontinuity and caused by progressive blade stall. The full scale rotor did not produce this phenomenon because of the much higher stall margin.

In the free yaw mode, the model started easily and demonstrated a high degree of stability about the yaw axis. Transient testing was performed by forcibly yawing the model 20° away from equilibrium and then releasing it. The model returned rapidly to the equilibrium position with almost no overshoot. The cyclic pitch amplitude remained within the $\pm 9^{\circ}$ limit during the rapid yaw rate test.

During the second series of tests conducted in April, 1980 the model reliably started with zero yaw angle at about 8 mph wind speed. When running, it could be quickly stopped by applying 90° yaw angle. It did not start at this yaw angle up to the highest tested wind speed (24 mph). The blades showed no motion up to 15 mph wind speed when stopped with 90° yaw angle but flapped in an irregular manner at 24 mph. The rotor started at 20 mph for 80° yaw angle but did accelerate beyond the stop pounding phase. A yaw angle of 80° for the model was not attainable without severe stall. We expected the full scale rotor to start at 80° yaw angle and to rapidly pass through the initial brief stop pounding phase to normal operation.

The small scale model tests demonstrated 1) smooth operation of the rotor with passive cyclic pitch variation up to yaw angles of 50°, 2) good controllability of rotor speed by yawing, 3) easy starting between 0 and 80° yaw angle, 4) good damping of yaw transients and, 5) capability of high yaw rates without vibrations. The model also demonstrated that blade-stall-related stop pounding may occur with involvement of the blade coning mode. The blade airfoil and its pitch settings were not too well defined in the test model; the tunnel wall effect was substantial. For these reasons only a qualitative evaluation of the model tests was made and no attempt was made to compare the model test results with the results of predictive analysis.

1.3 ANALYTICAL STUDIES

Analytical studies were conducted in support of the design of the atmospheric test turbine. Performance analysis for zero yaw angle used conventional methods and assumed steady wind speed and wind direction. The emphasis was on establishing trends with configuration changes. Rough estimates were made with respect to the steady state yaw characteristics because of the lack of an accepted analytical method applicable to yawed conditons. The prediction of natural frequencies was hampered by ill-defined structural properties of the blades, nacelle and tower. Potential linear aeroelastic instabilities were analyzed with the originally assumed structural properties. Corrections were believed to be unnecessary since no linear aeroelastic instabilities were uncovered up to very high rotor overspeed. Analysis has not been performed on the stall related nonlinear cyclic pitch stop pounding condition observed during the second wind tunnel model test series.

Tower, rotor, and boom dynamics were analyzed using a finite element method developed at Washington University by David A. Peters and Timothy W. H. Ko. Results of these analyses are described in Section 5 of report SERI/TR-8085-15. 3.

1.4 ATMOSPHERIC TESTS

When considering the best approach to a quantitative experimental study of a wind turbine with blade cyclic pitch variation, the question arose whether to use wind tunnel tests with a large wind tunnel model with adequate Reynolds number or atmospheric tests. The advantage of wind tunnel tests was that the steady flow characteristics could easily be compared to analytical results. The disadvantage was that a realistic simulation of the effects of variable wind velocity and direction was not feasible. Also, it was unlikely that we could have obtained an early time slot in one of the larger wind tunnels. Therefore, atmospheric testing appeared to be the only practical approach. Due to the random variability of wind speed and wind direction, statistical data collection and processing was the preferred method of atmospheric testing.

1.4.1 Test Site

The 2000 acre Tyson Research Center owned by Washington University was selected for the site testing of the atmospheric equipment. The test turbine was located close to the high point of a ridge that extended in the north-south direction. The 25 ft diameter wind turbine was mounted on top of a 60 ft tower and was effectively open to the wind in all diretions. The instrument shed, the power winch and gin pole for raising and lowering the tower were located to the north of the tower on the ridge. The entire research park was enclosed by a fence and had only one access, controlled by a guard.

1.4.2 Atmospheric Test Equipment Configuration

The 25 ft diameter rotor was composed of two fiberglass blades, each weighing only 31 lb. These were attached to an aluminum blade retention structure which, in turn, was attached to the hub via Rulon bearings and a steel pin. A taper-lock bushing retained the hub assembly to the main shaft.

The rotor drove a shaft-mounted two-stage speed increaser having a total gear ratio of 15:1. The output shaft of the speed increaser carried a pulley and a timing belt which drove the alternator. The alternator was supported by a bracket bolted to the rear face of the speed increaser. The total speed step-up with the pulleys and the speed increaser was 25:1. A tach generator (also used as a starting motor) was shaft-mounted to the speed increaser output shaft. A slipring unit for transmitting strain gage signals through the rotating system was mounted to an extension of the rotor shaft at the rear of the speed increaser.

The alternator was a truck unit rewound for 240 V operation. The three-phase ac output of the alternator was rectified to dc and applied to a resistive load bank.

The 204 in long aluminum tail boom was adapted from a commercially available lamp post. It was attached to the nacelle by a steel pin through Rulon bearings and actuated by a 12 V dc linear actuator.

The main structural element of the nacelle was an 8 X 5.3 in I-beam. The I-beam transmitted the gravity moment of the tail boom and vane, the rotor and rotor support, and the rotor thrust and torque to the yaw post. The yaw post was welded to a flange and bolted to the underside of the I-beam.

1.4.3 Modified Unarco-Rohn Tower

To facilitate maintenance and calibration of the rotor and nacelle instrumentation, the Unarco-Rohn S.S.V. 60 ft tower was modified so that it could be tilted from the vertical position to a position about 6° from horizontal. Two of the three tower legs were hinged.

Although the development of the tower tilting mechanism involved considerable effort and cost, substantial overall cost and time savings were achieved. The ease of erecting the tower without a professional crew, installing the machine on the tower without a crane, installing the electrical system, and performing numerous instrumentation and maintenance tasks for the machine without the repetitive need for a costly "cheery picker" more than justified the time and cost required to develop and implement the tilting tower feature. Tower tilting from horizontal to vertical position and vice versa took about 15 minutes, including insertion or removal of the 12 leg flange bolts. Two persons were needed for the operation. The machine was furled during tower tilting operation. As soon as the tower was tilted somewhat from vertical, the tail boom swung under the effect of gravity into its lowest possible position. When approaching the working platform the tail boom, then in near vertical position, was manually lifted up to the near horizontal position and the tower was lowered onto its cradle. It had been the policy to lower the tower to its cradle whenever the site was unattended. The tach generator, used as a starting motor and as a brake, was used to position the blades properly before the tower contacted its cradle. The rotor had the tendency to start when raising or lowering the tower when the wind was from the West or from the East. Using the tach generator as a brake, starting could be prevented. Raising and lowering the tower has been performed in wind speeds up to 15 miles per hour.

1.4.4 Instrumentation

Three kinds of instruments were used for recording the test data:

- A multi-channel oscillographic recorder.
- A microprocessor data acquisition system including analog to digital converters, internal clock, 12 in screen monitor, and printer-plotter.
- Display instruments for monitoring and manual recording.

Auxiliary recording equipment included a twenty channel "Vishay" model 2100 strain gage conditioner and amplifier system, a twelve ring slipring unit to transmit signals from the rotating system, and various signal conditioning filters and output buffers.

Both slow-varying and fast-varying quantities were measured. Slow-varying quantities included wind speed, rotor speed, furl position, yaw post position, load voltage, alternator temperature and ambient temperature. The fast-varying quantities were: blade flap-bending, blade in-plane bending, shaft torque, blade cyclic pitch variation, vertical and sidewise tail boom bending, and fore-aft and sidewise linear accelerations of the rotor bearing block.

1.4.5 Data Acquisition

Two kinds of data acquisition methods were used: Analog data acquisition with an oscillograph, and digital data acquisition with a microcomputer. Approximations to steady state data were obtained from oscillograph records and from meter readings. Data on transients were extracted from oscillograph records. Steady state data were difficult to obtain during atmospheric testing since wind speed and rotor speed were continuously changing. All oscillograph records contained traces of wind speed and rotor speed so that it was possible to judge when a more or less steady state occurred over several seconds.

In addition to steady state evaluations vs. rotor speed and vs. wind speed, some time histories were extracted from the oscillograph records. They showed starting and furling processes and responses to gusts. Digital data acquisition and processing were used to obtain statistics on performance parameters.

Five computer programs were developed for statistical data sampling using the "method of bins". The five programs sampled data as follows:

1. Two performance variables vs. wind speed, using BASIC computer language;

2. One dynamic variable, (usually cyclic pitch amplitude) vs. yaw rate;

3 & 4. Two or six performance variables vs. wind speed using a high speed sampling machine language routine; and

5. Six dynamic load variables vs. rotor speed.

The first program collected the mean value, standard deviation, the global maximum and the global minimum of rotor speed and cyclic pitch amplitude for each wind speed bin. The second program collected the mean and standard deviation of the cyclic pitch amplitude for each yaw rate bin. From the oscillograph records, a clear dependence of cyclic pitch amplitude on yaw rate was observed. It was decided to collect statistical data on this dependence. The third and fourth programs collected statistical data required for performance evaluation vs. wind speed bins. The fifth program collected statistical data for dynamic loads vs. rotor speed bins.

In addition to the five sampling programs, two analysis programs were developed. The first program converted the digital voltage data sorted in each bin array to a graphical plot. The second program performed statistical data evaluation of the rotor power vs. wind speed data and calculated and plotted the rotor coefficient of performance as a function of average wind speed and for each wind speed bin.

A more detailed description of these programs is presented in the Final Report SERI/TR-8085-15. The documentation for these programs is presented in Appendix D of that report.

1.5 SUMMARY AND CONCLUSIONS

The machine was operated between May 23 and October 25, 1980 during 41 days for 96 hours. The operational envelope extended to 16 m/s wind velocity, 360 rotor rpm, 45° yaw angle power-on and 80° yaw angle power-off. For most tests the nacelle was automatically furled when 228 rpm at 10 kW rotor power was exceeded. Unfurling was performed manually. When dividing the total rotor energy output by the total wind energy flow through the rotor disk during a test run, power coefficients C_p of over 0.4 were obtained. This was based on data from an anemometer located 13.4 m above ground and 5.5 m below the rotor center. Winds were never sufficiently high to obtain full power or full rotor speed at 45° yaw angle. Thus, the power cut-off wind speed limit above which loads would become excessive could not be determined. It also was not possible, for lack of steady wind speeds above 13 m/s, to obtain high yaw angle power-off operation at rated rotor speed. Within the operational envelope, dynamic loads and vibrations were low. The highest loads were recorded at the overspeed power-on condition with 16 m/s wind velocity and 360 rpm. This condition was far outside the normal operational envelope.

The following summarizes the performance of the atmospheric test equipment used during this study:

- o Due to the moment free rotor hub with passive cyclic pitch variation, the test machine adapted rapidly to wind direction changes and developed yaw rates up to about 15°/sec. No reduction in power from rapid yawing was observed despite yaw rate-produced cyclic pitch amplitudes up to $\pm 5^{\circ}$. When relating total rotor energy output to total wind energy flow through the disk, average power coefficients C_p of over 0.4 were measured during a test run of 30 to 60 minutes in duration. Total wind energy flow was based on data from an anemometer located 13.4 m above the ground and 5.5 m below the rotor center. Performance of the test rotor was good and may be superior to conventional rotors of equal size.

- Yaw rates producted by wind direction changes or from the operation of the furl actuator produce cyclic pitch amplitudes in proportion to the yaw rate, thereby preventing gyroscopic moments from being transferred to the hub. When operating the machine power-on with 45^o furl angle (causing about 45^o yaw angle), the average C_p value during a 110 minute test run was reduced from 0.46 to 0.18. Thus, at 45^o yaw angle the wind speed can be increased by a factor of $(0.46/0.18)^{1/3}$ = 1.35 over rated wind speed without exceeding rated power. Rated rotor power of 10 kW is reached at about 21 mph wind speed. Operating with 45^o yaw angle allows 10 kW to be produced at 28 mph. Higher yaw angles could not be tested power-on because of the absence of average winds over 28 mph. Thus, the maximum cut-off yaw angle and wind speed has not been determined. Yaw angles up to 80^o were tested power-off and resulted in a tip speed ratio of about 5.0. This corresponds to power-off operation at rated rotor speed of 230 rpm at 40 mph wind speed. For higher wind speeds, yaw angles greater than 80^o are required. One can conclude that the yaw characteristics explored so far insure rated power operation up to at least 28 mph (12.5 m/sec) and power-off operation to at least 40 mph (18 m/sec).

- Loads have been measured power-on at 15^o, 30^o, 45^o yaw angle and power-off up to 80^o yaw angle. It is expected that an expansion of the operational envelope beyond these values would be possible if wind speeds above 28 mph were available. Dynamic bending moments in the vertical direction of the tail boom and in the yaw post were found to be approximately equal and caused by vertical tail boom oscillations peaking at the tail boom resonance of 160 rpm. Blade dynamic in-plane bending moments are gravity produced and are almost independent of rpm and yaw angle. Blade dynamic flap-bending moments peak at 160 rpm and increase with yaw angle. Dynamic rotor shaft torque is normally insignificant except during furl operation. Linear acceleration at the rotor main bearing block is below $\pm$ 0.15 g. All dynamic stresses are well within fatigue limits. One can conclude that the dynamic loads and vibrations in the test machine are far below the allowable level despite the two-bladed rotor which often caused unacceptable loads and vibrations in conventional designs.

- The test machine can be started at 5 mph (2.2 m/sec) wind speed with the help of the tach generator/starter motor. The rotor keeps turning at this wind speed with the generator load resistance of 6 ohm connected after the starter motor is turned off. The rotor self-starts at an average wind speed of 9 mph if an occasional gust to 14 mph is available to overcome the minimum driving torque at about 20 rpm. A gust of 14 mph for self-starting is required because the inner third of the rotor radius has no airfoil section. It is a box with a 6 in square cross section. This design was selected in order to use the Astral Wilcon Model 10B blades. According to the analysis in a prototype design with a blade airfoil extended close to the rotor hub, the starting torque should be doubled. Self-starting should then require only a 10 mph (4.5 m/sec) gust. With a new blade design, starting characteristics of the prototype rotor will be good and motored starting will not be required.

In summary, the measurements have shown that the two-bladed wind rotor with passive cyclic pitch variation performs as well as expected. The cyclic pitch variation does not degrade the performance and may actually enhance it due to the rapid adaptation of the machine to changes in wind direction.

A full evaluation of the concept requires the development and testing of a completely automatic rotor speed control system to replace the overspeed furling system presently installed. In a prototype, a number of modifications are necessary. The blades with their long retention box should be replaced by slightly longer blades and air foil sections extended closer to the hub. This will gain, according to analysis, about 10% in performance and about 50% in starting torque. The generator in its present configuration has good efficiencies only at high power and poor efficiency at the more frequently used lower power outputs. For electric grid connections, either a synchronous inverter must be added or an induction or synchronous generator must be used. A preliminary study has shown that the concept should be readily applicable to larger machine sizes. The simplicity, ruggedness and reliability of a two-bladed, tail vane stabilized, furl angle controlled machine with passive cyclic pitch variation may make this concept attractive for quite large horizontal axis wind turbines. Tail vane stabilization is used for the largest airplanes. There is no compelling reason not to consider tail vanes for large wind turbines. The usual objection against tail vane stabilization - the high gyroscopic loads on the rapidly yawing wind direction following rotor - is not valid for the yawing of wind turbines with blade cyclic pitch variation, no matter how large the machine.

The analytical and test work to date has shown the concept under study to be viable. It has the potential for cost effective wind energy conversion. Continuation of the work was recommended to SERI. Recommendations stressed the importance of and need for design and evaluation of automatic yaw control systems used in conjunction with the blade cyclic pitch variation innovative concept prior to the development of a commercial prototype machine design.

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