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Design and Initial Testing of a One-Bladed 30-Meter-Diameter Rotor on the NASA/DOE Mod-0 Wind Turbine

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Wind/Ocean Technology Division

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DESIGN AND INITIAL TESTING OF A ONE-BLADED 30-METER-DIAMETER ROTOR ON THE NASA/DOE MOD-0 WIND TURBINE

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SUMMARY

The concept of a one-bladed horizontal-axis wind turbine has been of interest to wind turbine designers for many years. Many designs and economic analyses of one-bladed wind turbines have been undertaken by both United States and European wind energy groups. The analyses indicate significant economic advantages but at the same time, significant dynamic response concerns.

In an effort to develop a broad data base on wind turbine design and operations, the NASA Wind Energy Project Office has tested a one-bladed rotor at the NASA/DOE Mod-0 Wind Turbine Facility. This is the only known test on an intermediate-sized one-bladed rotor in the United States. The 15.2-meter-radius rotor consists of a tip-controlled blade and a counterweight assembly. A rigorous test series was conducted in the Fall of 1985 to collect data on rotor performance, drive train/generator dynamics, structural dynamics, and structural loads.

This report includes background information on one-bladed rotor concepts, the Mod-0 one-bladed rotor test configuration, supporting design analysis, the Mod-0 one-bladed rotor test plan, and preliminary test results.

INTRODUCTION

The concept of a one-bladed wind turbine rotor has existed for some time. As early as 1931, E.N. Fales built a prototype and reported test results to the American Society of Mechanical Engineers (ref. 1). In 1934, Ulrich Hutter tested a 6-meter-diameter, one-bladed wind turbine rotor in Germany (ref. 2). He concluded that the single blade, wind turbine rotor concept attributed significant economic advantages to the one-bladed but "... the eccentric position of the in-rotor-plane component of the aerodynamic forces on the rotor caused an imbalance which resulted in a tendency to vibrations -- quite difficult to overcome. Therefore these solutions have been so far abandoned in spite of their fascinating economic advantages" (ref. 2, pp. 2 to 5). As in Europe, interest in the United States in a one-bladed wind turbine rotor continued. R. Pruyn, W. Weisner, and P. Sulzer of the Boeing Vertol Company reported on the potential construction and consequent economic advantages of a one-bladed rotor (refs. 3 and 4) while predicting that vibratory loads would probably be significant. "The rotor is subjected to a high one-per-rotor-revolution Coriolis torque caused by blade flapping and the shear component of the rotor in the plane of rotation" (ref. 3, pp. 2 to 101). Prototype single-bladed wind turbines continued to be built primarily by European wind energy groups. Under the guidance of J.R.C. Armstrong, a 10-meter prototype single-bladed wind turbine was built in Britain in 1978 (ref. 5). In 1981, the West German company Messerschmidt-Bolkow-Blohm built a 400 kW, single-bladed wind turbine demonstrator (Monoptoris) as part of the development of a 5 mW, single-bladed wind turbine (GROWIAN II) (refs. 6 and 7). The results of the research and development efforts for the GROWIAN II program are detailed in reference 8. The most recent development in one-bladed wind turbines was the construction of a 200 kW, 22-meter-diameter, one-bladed wind turbine by the Italian firm RIVA CALFONI S.P.A. in 1984.

The significant advantage of a one-bladed wind turbine appears to be the economic savings over a multiple-bladed wind turbine. These savings result from structural requirements and operating conditions possible with the one-bladed rotor design. Most obvious is that it requires only one blade per rotor. This results in a blade with less stringent aerodynamic shape tolerances. In some cases, the blade and counterweight assembly can be made as one continuous assembly, thereby simplifying rotor hub design and construction. The one-bladed rotor has inherently lower rotor solidity than a multiple-bladed rotor with similar structure and power requirements. The lower solidity allows higher tip speed ratios causing a lighter, lower cost rotor and reducing drive train torque requirements with consequent reductions in drive-train costs (refs. 3 and 4).

In the brief one-bladed rotor wind turbine survey, it appears that most investigators believe that the economic advantages of the system outweigh the technical difficulties. However, no direct comparisons between one-bladed and multi-bladed rotors on the same turbine have been reported in the literature. Comparative tests of this type, in which only the number of blades is changed, are needed to quantify differences in performance and vibratory loads. Therefore, it was decided to test the NASA/DOE Mod-0 experimental horizontal-axis wind turbine, which normally has two blades, configured with a one-bladed rotor. Researchers felt that by using the existing NASA/DOE Mod-0 wind turbine, with its well-defined two-bladed data base, this one-bladed test configuration would minimize hardware changes and maximize performance, dynamics, and load comparisons needed to resolve technical issues. The specific purpose of these tests is to collect data on performance, loads, and dynamic behavior of an intermediate-sized one-bladed wind turbine. This initial report presents a description of the Mod-0 one-bladed rotor wind turbine configuration and the predicted and measured performance, dynamics, and loads associated with the new configuration. Where appropriate, the results for the one-bladed wind turbine will be compared to predicted and measured data for a two-bladed rotor on the Mod-0 wind turbine.

TEST CONFIGURATION AND CONDITIONS

Hardware

The one-bladed rotor testing was conducted on the Mod-0 100 kW experimental horizontal-axis wind turbine. The wind turbine (fig. 1) consists of the rotor and nacelle mounted atop a tubular tower with the rotor axis 38 meter above the ground.

The rotor (fig. 2) is a tip-controlled, teetered rotor consisting of two components: a blade assembly and a counterweight assembly.

The rotor utilizes a teetered hub concept that allows ±6° of teeter motion. Also incorporated with the hub section are rubber stops that provide damping for the teeter motion.

The blade assembly is 15.2 meter long, tapered, untwisted, and mounted with a pitch angle of 0° relative to the plane of rotation. It consists of three sections: a hub section, an inboard section, and a transition/tip-control section. The hub section is 1 meter long and incorporates 3° of coning for the blade. The inboard section of the blade is 11.2 meters long and is constructed of laminated wood. The inboard section utilizes the NACA 23024 airfoil and has a truncated trailing edge over the inner 4 meters. The transition/tip-control section is 3.0 meters long and is constructed of sheel metal over ribs. It also utilizes the NACA 23024 airfoil. The pitchable tip section spans 12.5 percent of the rotor radius and can be deflected from 0° to -90° with -90° being feathered. The entire blade assembly has a mass of 2201 kg.

The counterweight assembly is 4.6 meters long. It consists of three sections: the hub section, the spar, and the counterweight. The hub section is 1 meter long and incorporates 0° of coning for the counterweight assembly. The spar is a 2.9-meter-long steel tube. The counterweight is a solid steel ellipsoid with a minor axis of 0.74 meter and a major axis of 0.98 meter. It is mounted on the rotor so that the major axis is in the plane of rotation. The counterweight assembly mass is 3690 kg.

The drive train consists of a low-speed shaft with two bearings, a three-stage, parallel-shaft gearbox, a high-speed shaft with two bearings, and an induction generator driven by a multiple V-belts. The induction generator was set for 5 percent slip at 100 kW. The V-belt pulley ratios can be altered to allow the rotor to operate at selected speeds between 33 and 49 rpm.

The wind turbine yawning system has a yaw controller that regulates the yaw drive assembly. The yaw controller compares the nacelle yaw angle (difference between the nacelle azimuth and the wind azimuth) taken from the nacelle-mounted wind vane, 2.37 meters above the nacelle and 4.88 meters upwind of the rotor, with a desired yaw angle. The controller allows a yaw angle error band of ±5° about the desired yaw angle. When the mean yaw angle over a 128-sec interval falls outside this band, the controller will actuate the system and yaw the nacelle in 2-1/2° increments towards the desired yaw angle. This continues until the mean measured yaw angle is within ±5° of the desired yaw angle. A yaw brake is set to dampen yaw motion due to backlash in the yaw drive assembly.

Operating Conditions

The one-bladed rotor tests were conducted on the Mod-0 horizontal-axis wind turbine with the rotor operating downwind of the tower and under controlled yaw. The rotor is operated at two nominal rotor speeds: 33 and 49 rpm. Yaw alignment of the wind turbine is maintained at 0°, +15°, or -15°, depending upon the particular test requirements. Testing is conducted over a wide range of wind speeds. Generator power for the Mod-0 wind turbine as configured for these tests is limited to 200 kW because of the induction generator specifications. With drive train losses, this corresponded to approximately 240 kW at the rotor. At generator power levels less than

200 kW, the tip pitch angle was maintained at 0°. Once at 200 kW, the tip pitch controller positioned the tip section to limit the power to that level.

Test Measurements

Data were collected and recorded from various sensors in and around the wind turbine. Rotor loads data were measured by strain gauges mounted at station 0.8 and in the blade transition section at Station 11.5. Accelerometers mounted in the nacelle measured nacelle and tower motions. Sensors also recorded generator power output, blade-tip pitch angle, yaw torque, rotor speed, rotor teeter angle, low-speed shaft torque and bending moments, and nacelle yaw angle. Wind data were taken from instruments mounted at the rotor hub height on an array of five measuring station towers, each located 59.4 meters (1.5 rotor diameters) from the wind turbine and spaced 45° apart. For a given test run, the tower most nearly upwind of the wind turbine was selected as the reference wind station. Both wind speed and wind direction are measured at this point. Atmospheric temperature and barometric pressure data were taken from instruments located at the control room.

ANALYSIS

Performance Predictions

Performance was predicted for the one-bladed rotor, and for comparison, a two-bladed rotor using the Wind II Rotor Performance Prediction Code (9). This code is based on the blade element/momentum theory (ref. 10) that divides the blade into radial elements. These radial elements are treated as two-dimensional airfoil segments. Then, by using the blade geometry, operating conditions, and "induced" flow conditions, the local angle of attack is calculated. The force acting on the element is determined by using two-dimensional airfoil aerodynamic data. The "induced" flow is calculated in an iterative process with the thrust coefficient as the prime link between the blade element and momentum theories. The airfoil data used in the code was based on measured NACA 23024 airfoil data taken at a Reynolds Number of 3 million (ref. 11), with post-stall empirical corrections made to model constant rotor torque after stall (ref. 12).

The rotor performance predictions for the one-bladed rotor are shown in figure 3 for rotor speeds of 33 and 49 rpm.

In predicting the performance of the one-bladed rotor, researchers estimated the power lost due to the drag of the counterweight assembly to be 3 kW at 33 rpm and 9 kW at 49 rpm. Included in figure 3 for comparison purposes are measured and predicted rotor power for a two-bladed rotor operating at 33 rpm with blades identical to that on the one-bladed rotor. For the two-bladed rotor, the predicted and measured performance agree well in the windspeed range for which there was data and provide some validity to the use of the WIND II code.

Comparison of the performance between the one-bladed rotor and the two-bladed rotor shows that rotor speed plays a critical part in making a one-bladed rotor produce as much energy as a two-bladed rotor of the same diameter but with twice the blade area. This fact can be seen more clearly in figure 4, which shows predicted power coefficients as a function of the tip speed ratio (rotor tip speed to wind speed) for both rotors. Counterweight losses are not included in this figure.

This figure indicates that the one-bladed rotor can achieve a power coefficient above 0.4 at tip speed ratios between 10 and 13 and that the two-bladed rotor can achieve a comparable power coefficient at tip speed ratios between 6.5 and 9. This indicates that in the same wind speed, the one-bladed rotor will produce nearly the same power as the two-bladed rotor when operating at 1.5 times the two-bladed rotor's optimum power coefficient rotor speed.

Natural Frequency Predictions

A real eigenvalue analysis of the Mod-0 wind turbine configured with a one-bladed rotor was performed to determine the natural frequencies of the system. The analysis was done using the MSC/NASTRAN Finite Element Method computer code (ref. 13).

The Mod-0 wind turbine consists of three structural sections: tower, nacelle, and rotor. The pole tower is made of two twelve-sided tubes fitted together with an overlapping joint. Twelve pinned struts attach the tower body to a spring base. These consist of eight horizontal struts at the tower base and four diagonal struts attached part way up to the tower. An upper "cage" portion of the tower is constructed mainly of angle sections and structural tubes. The nacelle, which rests on the case, consists of a beam bedplate and the drivetrain components. The rotor, described earlier, is attached to the low speed shaft component of the drive train.

A drawing of the wind turbine model used in the MSC/NASTRAN code is shown in figure 5.

The pole tower was modeled using four types of structural elements. The tower tube was modeled using seven beam elements, arranged end to end. The supporting struts were each represented by a rod element. The lower eight struts were combined into four struts for modeling simplicity. The supporting base was rigidly restricted from translation in the X, Y, and Z directions. Concentrated masses were used to account for strut-to-tower connection hardware and accompanying gussets. The "cage" at the tower top was modeled using beam and plate elements. The top of the cage was connected to the nacelle via plate elements. The nacelle and drive train models used were from a previous NASTRAN analysis of the Mod-0 wind turbine (ref. 14). The one-bladed, teetered hub rotor was modeled with bar elements and concentrated masses. The drive train was modeled with a bar element for the low-speed shaft and a lumped inertia for the gearbox, brake disks, and generator. The rotor shaft was unrestrained in the rotational direction.

The results of the natural frequency analysis for the Mod-0 wind turbine configured with the one-bladed rotor are summarized in the Campbell diagram (fig. 6) for the rotor horizontal.

The first elastic blade flapwise bending frequency was corrected for rotational effects in accordance with reference 15. The lower vibration frequencies predicted for the tower were first fore/aft bending at 0.95 Hz, first lateral bending at 0.97 Hz, and first torsional bending at 4.0 Hz. The lower vibration frequencies predicted for the rotor were first elastic blade flapwise bending at 2.8 Hz and first elastic blade chordwise bending at 3.4 Hz. For operation at 33 rpm, the Campbell diagram indicates the possibility of a five-per-rev, first elastic blade flapwise bending resonance; a six-per-rev, first elastic blade chordwise bending resonance; and a seven-per-rev, first tower torsional resonance. For operation at 49 rpm, the Campbell diagram indicates the possibility of a four-per-rev, first elastic blade chordwise bending resonance and a five-per-rev, firs tower torsional resonance. Because of high-per-rev excitation and damping and because the operating speeds are not exactly at the per-rev and natural frequency crossing values, no serious resonance problems were indicated by this analysis.

ONE-BLADED ROTOR MOSTAB ANALYSIS

The one-bladed rotor was modeled for use in the MOSTAB-HFW computer program (ref. 16) to provide a preliminary indication of rotor loads and dynamic behavior. MOSTAB-HFW calculates steady-state dynamic loads for an aeroelastic rotor. Input to the program includes rotor geometry, mass distribution, blade natural frequency and modal data, and operating conditions. The operating conditions that were varied for this analysis include rotor speed, yaw angle, and wind speed. The output of MOSTAB-HFW contains rotor loads and deflections in both the time and the frequency domains. Along with the domain output, the program includes mean and cyclic values. Mean and cyclic values are based on the maximum and minimum values that occur during one rotor revolution. The mean is calculated as (max + min)/2 and cyclic as (max - min)/2.

The most important results of the MOSTAB analysis are the teeter angle deflections, the cyclic blade loads, and the cyclic torque values. The teeter angle and cyclic load values are largely dependent on the nature of the wind input. Cyclic loads are also affected by the aerodynamic behavior of the blade (sharpness of stall and possible dynamic stall) as well as the blade, hub, drive train, tower and yaw stiffnesses, and control system activity.

In this analysis of the one-bladed rotor, the wind input included a tower wake model and a wind turbulence model that included wind shear. The wind turbulence model was based on the NASA Interim Turbulence Model (ref. 17) that provided the relative wind harmonic amplitudes and allowed the phase angles of the harmonics to be selected. The overall magnitude of the wind harmonics was an input parameter in the program. The magnitude of the harmonic components was selected by matching the flatwise cyclic bending moments from MOSTAB-HFW with measured results for a two-bladed rotor having blades identical to the blade of the one-bladed rotor.

MOSTAB-HFW allows modeling of the teeter hinge of the one-bladed rotor hub; however, the support of the low-speed shaft is assumed to be rigid and the rotor speed is assumed to be constant. The teeter hinge was modeled with a linear teeter spring to simulate the rubber teeter stops on the rotor hub.

Modeling of a nonaxisymmetric rotor on MOSTAB-HFW was possible because researchers define the blade and counterweight assembly as a single-rotor element with the radial stations on the counterweight assembly having negative values.

Figures 7 and 8 show teeter angle as a function of wind speed for rotor speeds of 33 and 49 rpm.

Both mean and cyclic teeter angles are shown for a yaw angle of 0°. Several MOSTAB runs were made with yaw angles of 0° and ±15°. In all cases, the mean teeter angles were only slightly affected by yaw angle, so only the 0° yaw angle cases are shown. For both the 33 and 49 rpm cases, the mean teeter angles become more negative with increasing wind speed, with values near zero for wind speeds less than 8 m/s. The mean teeter angle can be varied by changing the values of coning angles for the blades and counterweight. Cyclic teeter angles generally increase with wind speed. Positive yaw angles tend to increase cyclic teeter angles, and negative yaw angles tend to decrease cyclic teeter angles. Cyclic teeter angles are smaller for the 49 rpm case because of the stronger effective teeter spring caused by centrifugal force. Cyclic teeter angles are influenced by the teeter spring stiffness, and the hub delta-3 angle (the one-bladed rotor has a 0° delta-3).

Mean and cyclic flatwise loads for both 33 and 49 rpm are shown in figure 9.

At low wind speeds, the mean moments are positive due to centrifugal effects on the coned rotor. As the thrust loading increases with wind speed, the mean flatwise moments become negative. The points at which the bending moments change sign are dependent on the coning angles of the blade and the counterweight and the rotor speed. Cyclic flatwise moments increase moderately with wind speed for winds up to 12 m/s and then tend to level off.

Cyclic chordwise bending moments are almost entirely due to the gravity load, with the maximum cyclic chordwise load equal to 105 percent of the gravity load. The rotor model did include a blade edgewise degree of freedom; however, there was little edgewise harmonic activity of the blade, possibly due to the rigid low speed shaft assumption (ref. 18).

The cyclic torques predicted by MOSTAB are very large for the one-bladed rotor, with values that are 100 percent of the mean torques. The large cyclic torques are partly due to the large variations of axial wind seen by the single-blade because of the tower wake and the turbulent wind model. Another contributor to cyclic torque is Coriolis acceleration of the teetering rotor, although it is only significant for the cases with large teeter angles. The actual cyclic torques on the low speed shaft will be significantly less than the MOSTAB predictions because of torsional flexibility and damping in the drive train.

Figure 10 shows predicted yaw torques versus wind speed for the one-bladed rotor at rotor speeds of 33 and 49 rpm. Included on the figure is measured yaw torque for the two-bladed rotor. Although the yaw torques for a one-bladed rotor are expected to be larger than those of a two-bladed rotor, they are not expected to be a problem. Teetered rotors reduced yaw torques by an order of magnitude compared to rotors with rigid hubs (ref. 19), and the one-bladed, teetered rotor should have yaw torques significantly less than those for a rigid rotor.

TEST PLANS

A rigorous test plan was followed for the Mod-0 wind turbine configured with the one-bladed rotor. The tests can be grouped into three categories: (a) checkout, (b) performance and loads, and (c) dynamics and vibrations. The checkout tests were conducted at rotor speeds up to 49 rpm. They verified the system operation, including mechanical components, instrumentation, and safety items such as shutdown capability and significant rotor/tower resonances. The performance and loads tests were conducted at rotor speeds of 31 and 49 rpm to gather a broad data base on rotor performance, rotor loads, and yaw loads. Included in these tests were yawed operation and tip control shutdowns. The dynamic and vibration tests were conducted at rotor speeds of 33 and 49 rpm to evaluate motions of the rotor, drivetrain, yaw system, and tower structure. During all these tests, data were collected from instrumentation on the wind turbine, in the block house, and on the meteorological towers. This information was recorded on brush charts, FM analog, and digital tapes.

MEASURED WIND TURBINE PERFORMANCE: PRELIMINARY DATA

During the initial operation of the rotor at 49 rpm, researchers observed a strong one-per-rev and first tower bending resonance. To enable operations to continue at a rotor speed of 49 rpm, researchers adjusted the leaf-spring system at the tower base to "soften the tower" and reduce the first tower bending frequency to 0.6 Hz. Wind turbine operation at a rotor speed of 49 rpm was then continued without further problems. No other significant resonances were observed.

Some preliminary rotor performance data were obtained for the one-bladed rotor at a rotor speed of 49 rpm; and they are shown in figure 11. To obtain the rotor performance, researchers recorded measured generator power as a minimum and maximum value for each rotor revolution, from which they obtained mean and cyclic values. The mean values were then averaged for 2.5 min intervals and corrected for drive train losses, yaw angle, and density variations to obtain rotor power values. This data was then processed with a bins analysis to condense the data. The data collection/reduction process described above is covered in detail in reference 20. The equation used in this paper to account for drive train losses at a rotor speed of 49 rpm is:

$$P_{rotor} = (0.00134\ P_{gen} + 1.09)\ P_{gen} + 9.3 \tag{1}$$

in which

P_{rotor} rotor power in kW

P_{gen} generator power in kW

Figure 11 also shows measure rotor performance of the two-bladed rotor with identical blade characteristics at a rotor speed of 33 rpm. To make a rotor performance comparison between the two rotor configurations, the researchers should use the data between 5 and 7 m/s because both rotors are operating near optimum efficiency. Then the one-bladed rotor performance is about 10 kW less than the two-bladed rotor performance. This difference is due primarily to counterweight drag and secondarily to higher tip losses. Design changes should reduce both these losses. However, it must be conceded that these losses are inherent to the one-bladed rotor. The final comparison between one- and two-bladed rotors should be made not only on the basis of rotor performance but as an overall economic issue that takes into account rotor performance, machine complexity, and cost.

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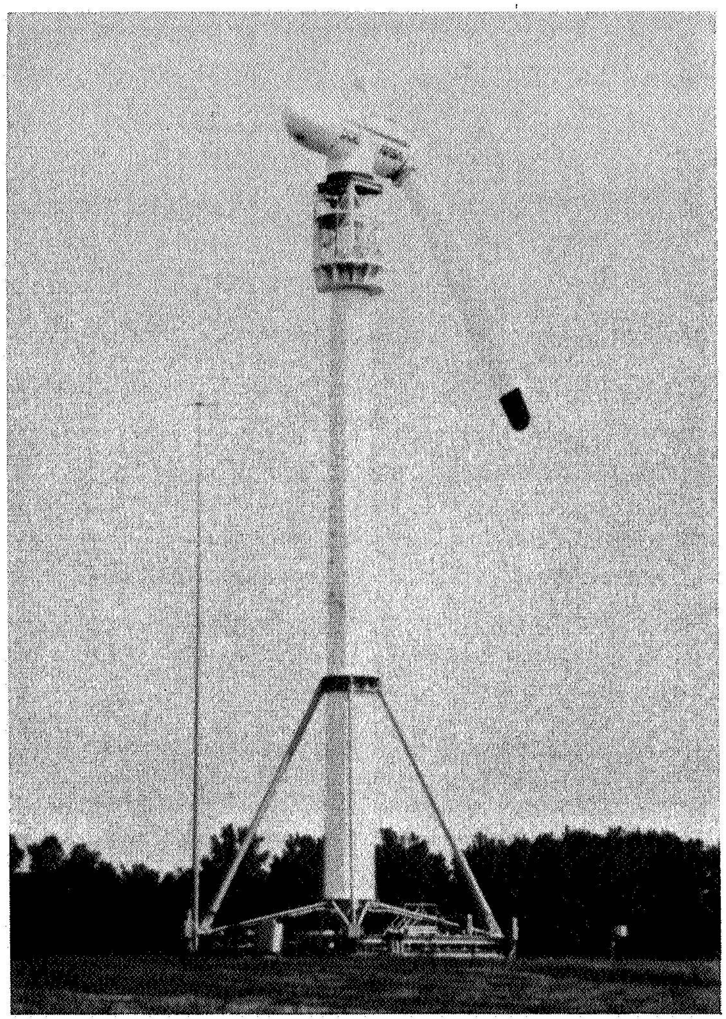
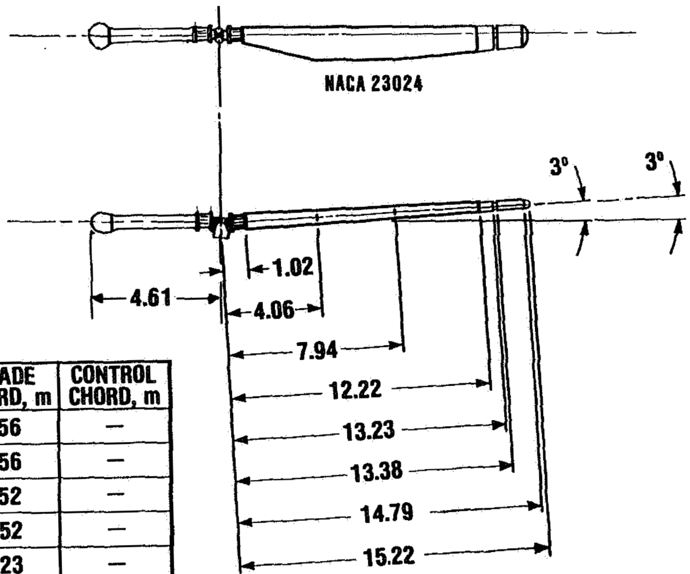


FIGURE 1. - MOD-0 WIND TURBINE WITH A ONE-BLADED ROTOR.



STATION, m	BLADE CHORD, m	CONTROL CHORD, m
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7.94	1.52	—
12.22	1.23	—
13.23	1.15	—
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FIGURE 2.- PLANFORM OF THE ONE-BLADED ROTOR.

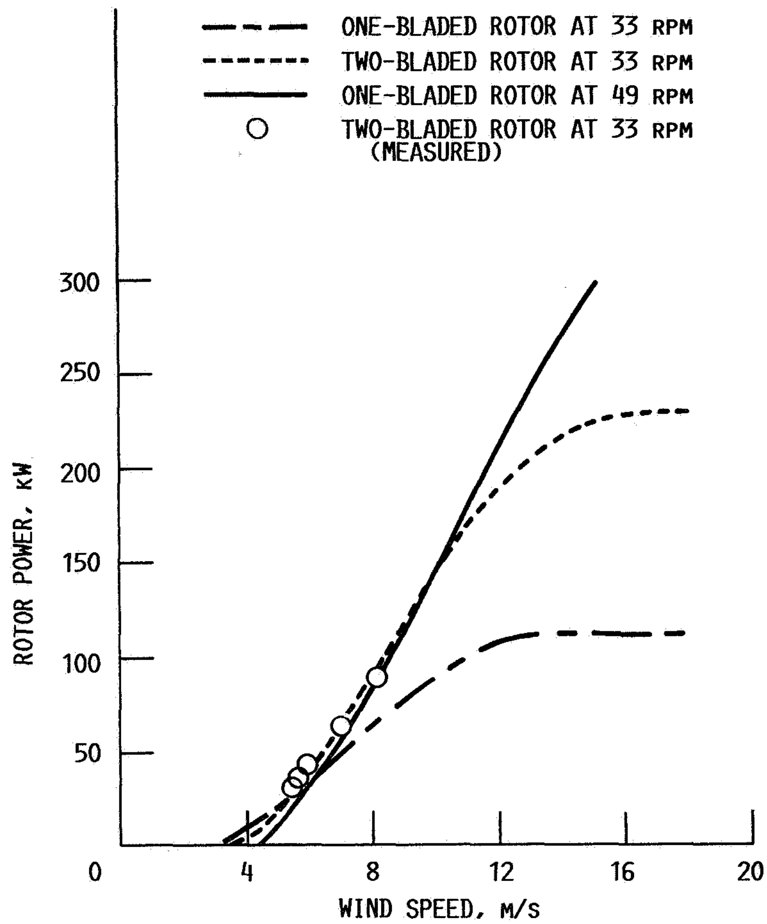

FIGURE 3.- PREDICTED ROTOR PERFORMANCE.

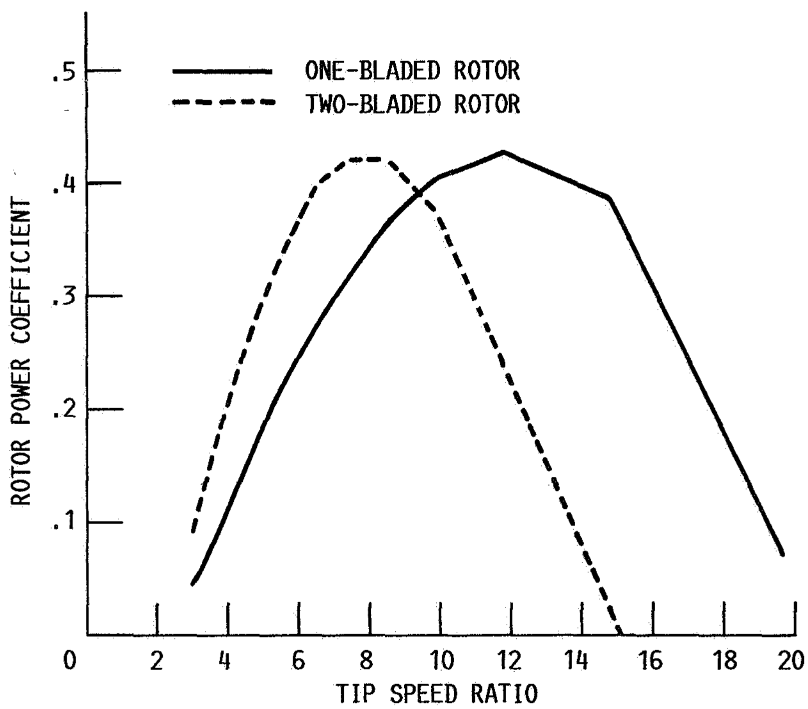

FIGURE 4.- PREDICTED ROTOR POWER COEFFICIENT.

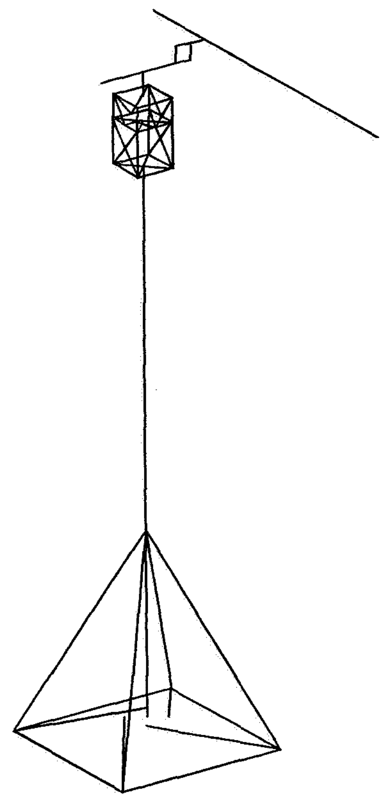

FIGURE 5.- MODEL OF THE MOD-0 WIND TURBINE WITH A ONE-BLADED ROTOR USED FOR MCS/NASTRAN MODEL ANALYSIS.

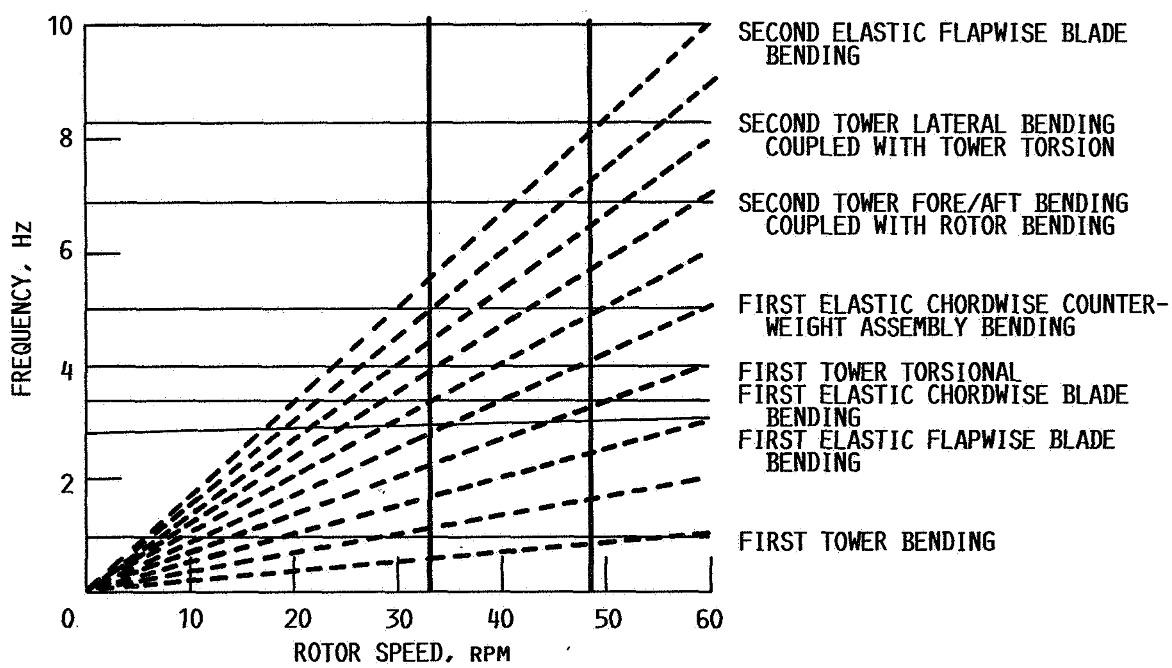

FIGURE 6.- CAMPBELL DIAGRAM FOR THE MOD-0 HAWT WITH A ONE-BLADED ROTOR.

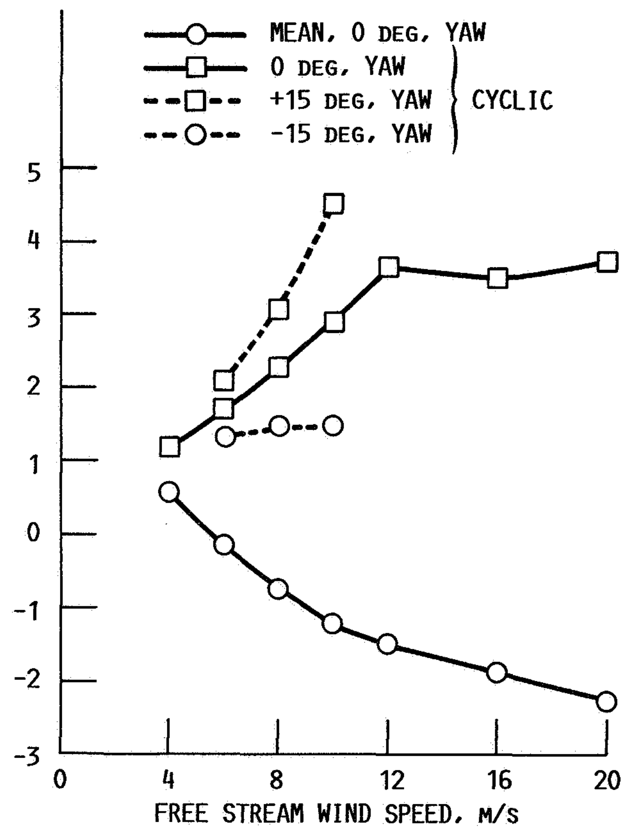

FIGURE 7.- MOSTAB TEETER ANGLE PREDICTIONS FOR THE ONE-BLADED ROTOR AT 33 RPM.

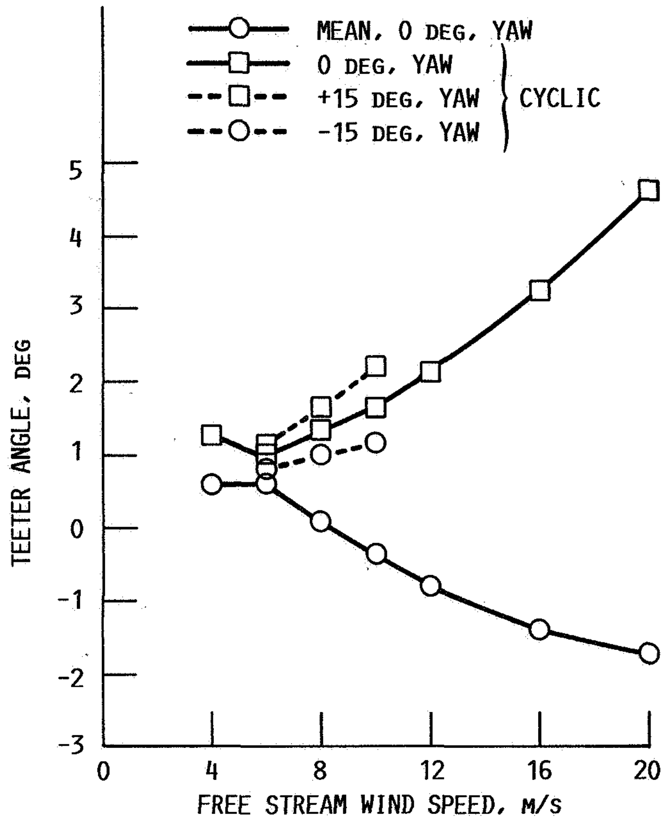

FIGURE 8.- MOSTAB TEETER ANGLE PREDICTIONS FOR THE ONE-BLADED ROTOR AT 49 RPM.

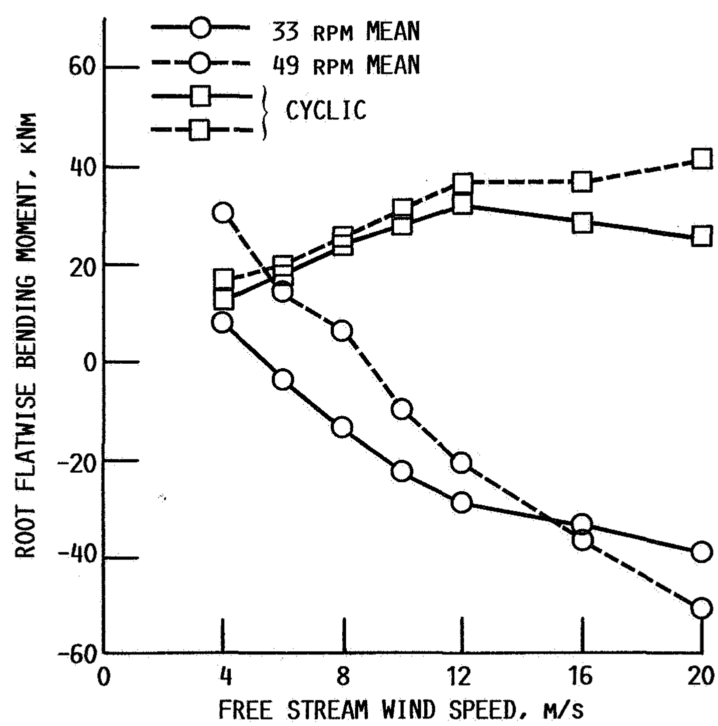

FIGURE 9.- MOSTAB FLAPWISE BENDING MOMENT PREDICTIONS FOR THE ONE-BLADED ROTOR.

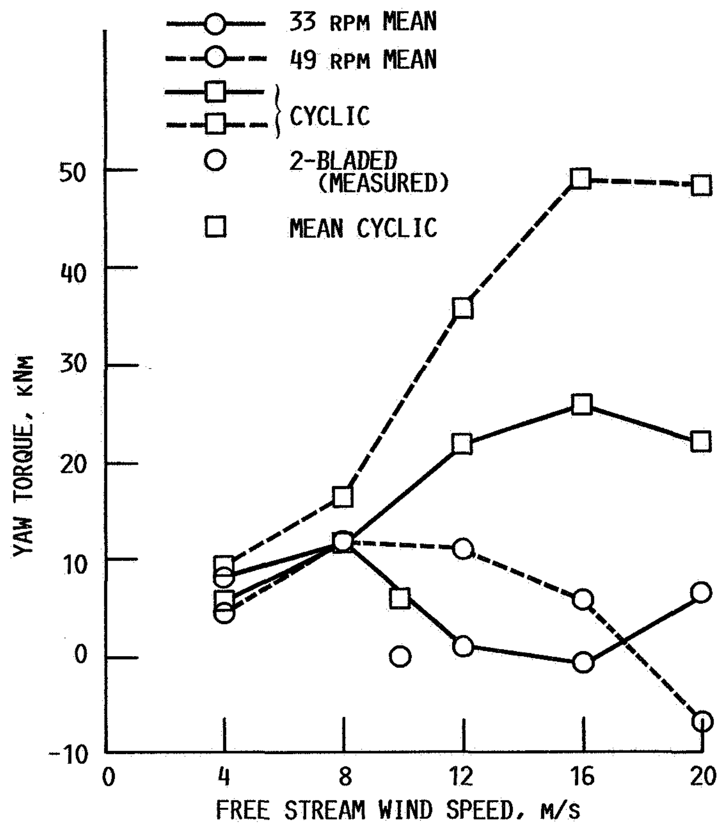

FIGURE 10.- MOSTAB YAW TOR2QUE PREDICTIONS FOR THE ONE-BLADED ROTOR.

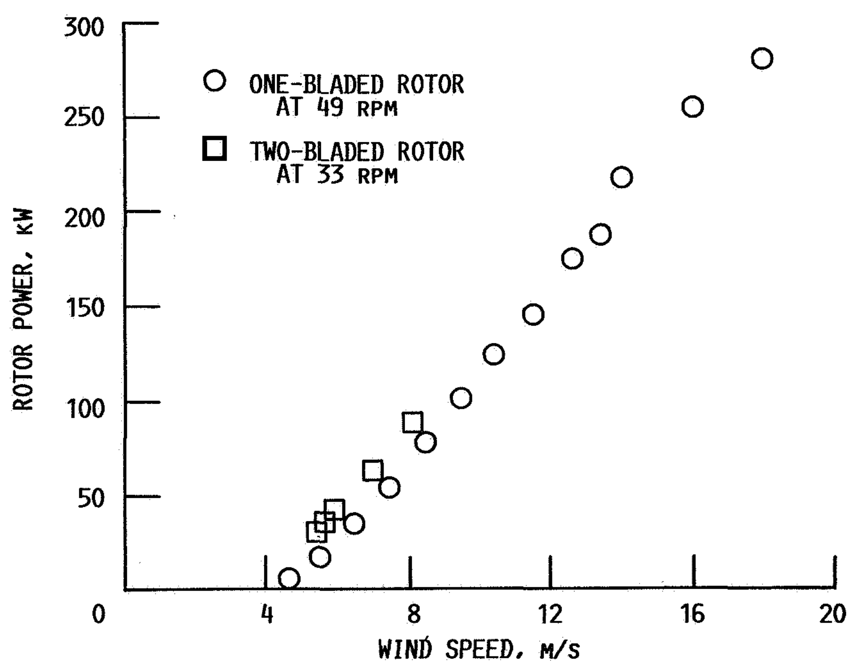

FIGURE 11.- MEASURED ROTOR POWER FOR ONE-AND TWO-BLADED ROTORS.

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15. Supplementary Notes

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16. Abstract

@DBS The concept of a one-bladed horizontal-axis wind turbine has been of interest to wind turbine designers for many years. Many designs and economic analyses of one-bladed wind turbines have been undertaken by both United States and European wind energy groups. The analyses indicate significant economic advantages but at the same time, significant dynamic response concerns. In an effort to develop a broad data base on wind turbine design and operations, the NASA Wind Energy Project Office has tested a one-bladed rotor at the NASA/DOE Mod-0 Wind Turbine Facility. This is the only known test on an intermediate-sized one-bladed rotor in the United States. The 15.2-meter-radius rotor consists of a tip-controlled blade and a counterweight assembly. A rigorous test series was conducted in the Fall of 1985 to collect data on rotor performance, drive train/generator dynamics, structural dynamics, and structural loads. This report includes background information on one-bladed rotor concepts, the Mod-0 one-bladed rotor test configuration, supporting design analysis, the Mod-0 one-bladed rotor test plan, and preliminary test results.

@ABA Author

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