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Work performed for
U.S. DEPARTMENT OF ENERGY
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E-1724

ABSTRACT

Tests were conducted on the Mod-0 100 kW experimental wind turbine to provide data on yaw alignment characteristics of a large horizontal axis wind turbine with its yaw restraint removed (i.e., in free yaw). The wind turbine consisted of a downwind horizontal axis rotor mounted on a tubular tower. Three rotor configurations were tested. Each rotor was teetered, coned 3° and tip-controlled. Two of the rotors had pitch-flap coupling or Delta-3, and one rotor had none. The two rotors with Delta-3 differed in the airfoil used in the tip sections.

Test results indicate the rotor without pitch-flap coupling did not align closer than 25° with the wind, and pitch-flap coupling improved the wind turbine's alignment with the wind. Yaw damping was shown to have a favorable effect on free yaw characteristics. The change in the tip airfoil section was shown to affect the free yaw alignment also. The rotors with Delta-3 were shown to be capable of responding to wind shifts and exhibited stable operating properties.

INTRODUCTION

The concept of "free yaw" in a horizontal axis wind turbine with a downwind rotor is quite attractive to the wind turbine designer. It permits one to eliminate the active yaw drive and its control system and allows the wind turbine the freedom of responding to changes in wind direction immediately, without a command from a control system thereby achieving a more precise alignment with the wind. If the concept could be successfully employed, it would conceptually result in a net increase in energy capture, the elimination of the components necessary for an active yaw drive, and reduced tower loads in hurricane force winds.

Tests were conducted on the Mod-0 100 kW experimental wind turbine to provide baseline data for future wind turbine development. The data are also compared with trends predicted in analysis conducted earlier and reported in references 1 and 2. The tests were planned in support of the WTS-4, Systems Verification Unit (SVU), a 4 MW wind turbine which was being procured by the National Aeronautics and Space Administration for the U. S. Department of the Interior for evaluation at Medicine Bow, Wyoming.

The WTS-4 wind turbine (ref. 3) was designed as a free yaw machine, and incorporated the following features which were considered to be important in producing its free yaw characteristics: (a) rotor coned 6° and (b) teetering rotor with 30° of Delta-3, i.e., teeter axis 30° off a perpendicular to the blade longitudinal axis, (c) blade twist of approximately 14°, and (d) under slung rotor, i.e., teeter axis not located at the intersection of the blade axis and the rotor axis of rotation but located inside the cone formed by the coned blades (this moves the teeter axis closer to the rotor center of gravity). These properties were not simulated in a single rotor on the Mod-0 wind turbine, but selected properties were simulated on different rotors and tested.

The test results reported herein were obtained from tests of three rotor configurations. All of the rotors were tip controlled, teetered and coned 3°. One of the rotors had no Delta-3, (i.e., 0° of Delta-3) while the other two had 20° of Delta-3. This provided information on the effect of Delta-3 on free yaw alignment. Also, one of the rotors with 20° of Delta-3 had a NACA 64_3-618 airfoil on its outboard, moveable tip, while the second rotor with 20° of Delta-3 had a NACA 23024 airfoil on its moveable tip. This provided information on the effect of airfoil selection on free yaw alignment.

Each of the three configurations was tested to determine its free yaw characteristics and the resulting data were processed to emphasize two aspects of the wind turbines response. First, the alignment of the wind turbine with the wind was determined during synchronous operation in winds covering the wind turbines operating range from cut-in wind speed to winds above rated wind speed. Second, yaw response was determined as an indication of the machine's ability to maintain alignment with the wind after a sudden wind shift.

The test results from the three configurations are compared to each other and with the trends predicted in the previously reported analysis, and conclusions are presented.

TEST CONFIGURATION

Tests were conducted on the Mod-0 100 kW experimental wind turbine shown in figure 1. The machine was mounted on a tubular steel tower with the rotor axis 37 m above the ground. The rotor diameter was 38 m. The rotor was teetered and tip-controlled, the blade had a 22 percent root cutout and the moveable tip extended over the outboard 31 percent of the blade. The blade had a linear taper, no twist, and was mounted with its chord plane coincident with the plane of rotation. The rotor was coned 3° and the rotor axis was horizontal. Rubber teeter stops were used in the teetered hub. These stops provided approximately 2034 Nm deg^{-1} (1500 ft-lb deg^{-1}) of restraint to teeter motion. Metal stops limited the teeter motion to $\pm 6°$.

Three rotor configurations were tested using variations of a single rotor. The baseline rotor, Configuration 1, had a NACA 64_3-618 airfoil section on the moveable tip and a NACA 23024 airfoil on the fixed inboard section. The rotor also had 20° of Delta-3. The second rotor, Configuration 2, was identical to the baseline configurtion except that the 20° of Delta-3 was removed. The third rotor, Configuration 3, was identical to the baseline configuration except that its outboard moveable tip had a NACA 23024 airfoil rather than the NACA 64_3-618 airfoil on the baseline configuration. The unique characteristics of each rotor are listed below as an aid to the reader.

<u>Rotor configuration 1</u>

(Baseline configuration)
Delta-3 = 20°
Moveable Tip Airfoil - NACA 64_3-618

<u>Rotor configuration 2</u>

Delta-3 = 0°
Moveable Tip Airfoil - NACA 64_3-618

Rotor configuration 3

Delta-3 = 20°
Moveable Tip Airfoil - NACA 23024

Sketches of the rotor showing the configuration with 20° of Delta-3 and with the Delta-3 removed are shown in figure 2. Rotor properties are shown in table I.

The rotor drove a two-speed induction generator and an overrunning clutch was used on the high speed shaft. The overrunning clutch prevented the generator from driving the rotor when the wind speed fell below that required to maintain synchronous rotor speed. The tests were conducted at a nominal rotor speed of 31 rpm. Yaw restraint was removed from the nacelle by means of a clutch located between the hydraulic yaw drive motor and gearbox which drives the yaw shaft. The yaw shaft turns a pinion which drives the nacelle in yaw. A sketch of the nacelle interior is shown in figure 3.

Wind data were taken from an anemometer 1.56 rotor diameters upwind of the wind turbine and yaw angle was measured on the nacelle-mounted anemometer/wind vane 2.37 m above the nacelle and 4.6 m upwind of the rotor. Figure 4 defines the terms used to describe wind and nacelle direction and the sign convention for yaw angle.

TEST PROCEDURE

Two types of tests were run, operational and yaw response tests. The operational tests demonstrated the characteristics of the machine under normal operating conditions, i.e., during power production. The yaw response tests demonstrated the ability of the machine to realign itself with the wind after an initial displacement off the wind.

In the operational tests, the wind turbine was aligned with the wind, the rotor brought up to a 31 rpm, the generator synchronized with the grid, and then the yaw drive clutch was disengaged releasing the nacelle for free yaw. The wind turbine was then allowed to operate in free yaw under power control. Each rotor configuration was run in this condition during the test periods for a total time of at least 6 hours in winds ranging from 4 to 12 ms^{-1}. Data were recorded during this period.

For the yaw response tests, the wind turbine was started as described for the operational tests and the nacelle was yawed out of the wind by the yaw drive. At this point the yaw drive was disengaged and the nacelle was allowed to yaw freely. The subsequent motion of the nacelle was recorded on strip charts and a microcomputer. These tests were repeated for various initial yaw angles up to 90° (rotor plane perpendicular to the wind).

Data from all tests were recorded on magnetic tape and the tests were monitored on strip charts. The taped data from the operational tests were reduced by a computer program to provide averaged data over 5 minute intervals and were plotted to show the free yaw alignment and aerodynamic performance of the wind turbine. The yaw response characteristics shown were obtained from two sources: strip chart recordings of test data and microcomputer plots of data processed in real time during the tests.

TEST RESULTS

The results from the free yaw tests conducted are presented in three general categories. First, free yaw alignment with the wind is presented in the form of plots that show wind turbine yaw angle as a function of wind speed. Here the data for each of the three rotor configurations are presented and compared. Second, the character of the nacelle yaw motion is presented in time history format to indicate the response to changes in wind direction and speed. Third, data on the recovery of yaw alignment after initial yaw displacement out of the wind is presented.

Wind Turbine Alignment with the Wind

The primary concern in free yaw operation of a wind turbine is alignment with the wind while power is being generated. In these tests, five parameters were monitored: wind speed, wind direction, nacelle azimuth, yaw angle and alternator power. Wind speed and direction were measured 1.5 rotor diameters upwind of the wind turbine. Yaw angle was measured on the nacelle-mounted wind vane which measures wind direction relative to the wind turbine axis. These parameters are depicted in figure 4, which also defines the coordinates used to describe yaw for the wind turbine.

To show free yaw alignment, yaw angle versus wind speed for each rotor configuration is presented. Figure 5 shows the results of the operational tests for each configuration. Rated wind speed indicated on the figure was determined for each rotor configuration and represents the lowest wind speed at which rated power was attained.

The results from the baseline configuration are shown in figure 5(a). The yaw angle remained within $\pm 10^\circ$ for wind speeds below rated wind speed and tended to increase as wind speed increased above rated wind speed, achieving a mean yaw angle of approximately 20° at wind speeds of 12 ms^{-1}.

The results from Configuration 2 with no Delta-3 is shown in figure 5(b). It indicates that alignment with the wind varied between -60° and -23° in winds ranging between 4 and 12 ms^{-1}. The rotor never aligned itself with the wind although alignment did improve as wind speed increased, achieving a mean yaw angle of -30° in winds near 8 ms^{-1}. Yaw alignment was worse in wind speeds above and below this point, however. These results indicate that 20° of Delta-3 improved rotor alignment by about 30° at a wind speed of 8 ms^{-1}; and in general, provided more improvement at other wind speeds.

The Configuration 2 rotor experienced particular alignment difficulty in winds below 4 ms^{-1} and on one occasion the rotor turned past a -90° yaw angle into an upwind position. This tendency to turn upwind in low winds has been experienced on numerous small wind turbines.

The results from Configuration 3 are shown in figure 5(c). This rotor configuration is an exact duplicate of the baseline rotor, with 20° of Delta-3, with only the tip airfoil changed. For this configuration, yaw is relatively unaffected by wind speed for winds above 7 ms^{-1}. Yaw angle varied mostly in a band of $\pm 5^\circ$ about a -5° mean value. The reason for the marked change in behavior compared to the rotor configured with the 64 series blade tips is not known.

Nacelle Motion in Free Yaw

Nacelle yaw motion during free yaw operation is shown in figures 6 and 7. Figure 6 shows the variation of nacelle azimuth with time which was typical of that observed in the test. As indicated in the figure, the character of the motion changed with wind speed, with the frequency and amplitude of the yaw excursions increasing at wind speeds above rated. The data shown in this figure are typical of that observed. It was generated by a microcomputer which averaged nacelle azimuth over successive 30 second intervals. A review of strip chart data indicates that nacelle yaw rates as high as $2^\circ.s^{-1}$ could be expected in gusty wind conditions similar to the ones experienced here.

A short test was conducted to assess the effect of damping on the yaw motion of the nacelle. Damping was obtained by applying pressure to the yaw brake which produces a frictional force resisting yaw motion. The yaw brake was pressurized at 734, 1475, and 2214 Nm^{-2} (20, 40, and 60 psi), which produced constant resisting torques of appoximately 1695, 3390, and 5084 Nm (1250, 2500, and 3750 ft-lb) on the nacelle. The results of this test are shown in figure 7 which presents a time history of nacelle yaw motion for four levels of friction damping.

As indicated, damping reduces the nacelle yaw motion while allowing it freedom to adjust to varying wind directions. The test was conducted only to demonstrate the effect of damping on the yaw motion; however, and no attempt was made to optimize the amount of damping for the Mod-0 wind turbine. The results indicate that the addition of yaw damping would be beneficial to the free yaw performance of the wind turbine.

The results reported in this section were obtained on the baseline configuration. However, all configurations were tested and there was no observable difference between the three configurations in nacelle motion. Since the results were the same, only one configuration was reported.

Recovery of Yaw Alignment after Initial Displacement in Yaw

A wind turbine operating as a free yaw machine must be capable of maintaining alignment with the wind if the wind direction shifts radically as occurs in the case of the passage of a frontal system or thunderstorm. Under such conditions, wind shifts approaching 180° can occur in a few minutes. In view of such conditions, the ability of the wind turbine to respond to large yaw displacements should be assessed. To do this the wind turbine was yawed out of the wind with the yaw drive and then placed in free yaw. Subsequent motion of the nacelle was then observed on strip chart recorders and a microcomputer. The tests were conducted at yaw displacements up to 90° (+ and -) and on each occasion the wind turbine returned to an equilibrium position in a very stable and direct manner with no particular tendency to overshoot or undershoot. These tests were conducted on Configurations 1 and 3 only. These rotors had 20° of Delta-3 and achieved reasonably good alignment with the wind. These tests were not conducted on the rotor configuration without Delta-3 because the information was of little interest due to its poor alignment with the wind under normal operating conditions.

The data presented for the time history of nacelle response is based on tests of the baseline Configuration 1. The tests were performed on Configuration 3 also, but the responses were similar so only one is presented. Figure 8 shows a time history of typical tests at positive and negative yaw angles. The data shown in this figure was obtained from successive 10 second averages of nacelle azimuth and yaw angle. The test runs shown depict yaw angles in excess of 90° at the point of yaw drive release for free yaw. The machine exhibited no tendency to turn upwind at yaw angles up to 90°. The tendency to turn upwind was experienced at positive yaw angles in the neighborhood of 100°. This was not experienced at yaw angles near -100°, indicating that there is a stable restoring moment that is more reliable at high negative yaw angles. Tests at yaw angles in excess of 100° were not conducted. The yaw alignment recovery tests showed that the wind turbine in normal free yaw operation would realign itself with the wind from initial yaw angles of up to 90° (positive or negative yaw angle).

The stable nature of the nacelle motion is illustrated in figure 9 which shows an expanded trace of the instantaneous nacelle yaw angle and nacelle azimuth as a function of time after the yaw drive was released. Data are shown for two mean wind speeds, 10 and 6 ms^{-1}. As indicated by the plot of nacelle azimuth, the wind turbine moved quite smoothly to its equilibrium alignment position without overshooting. The trace of nacelle yaw shows some scatter reflecting change in the wind direction as the nacelle motion is taking place. Also, the nacelle yaw angle at equilibrium was approximately 10° for the case with a 10 ms^{-1} mean wind speed and near zero deg for the 6 ms^{-1} case. These equilibrium yaw angles are consistent with the results obtained in normal free yaw operation. In the figure, the nacelle azimuth has been shifted such that the azimuth at equilibrium conditions was zero deg.

Yaw rate varied with wind speed; as indicated by the slope of the nacelle azimuth versus time plot in figure 9. In the two cases shown, a maximum rate of 2.5°.s^{-1} was achieved when the mean wind speed was 10 ms^{-1} and a yaw rate of 1.0 deg.s^{-1} occurred in the 6 ms^{-1} wind. This indicates that the restoring torque increases with wind speed and that the wind turbine in free yaw is more capable of responding to large changes in wind direction and maintaining wind alignment in high winds than in low winds. No difficulty in maintaining alignment with the wind was experienced during tests in low winds at or just below cut-in wind speed when rotor speed was maintained at near operating rotor speed. These tests indicate that Configurations 1 and 3, with 20° of Delta-3, should have no difficulty in responding to wind shifts and maintaining alignment with the wind.

DISCUSSION

The free yaw tests were designed to provide data for evaluating the validity of analyses which had been conducted previously and reported in references 1 and 2. The baseline rotor configuration incorporated some features considered to be essential in achieving good alignment with the wind. These included a horizontal axis of rotation, rotor coning, and a teetering rotor with Delta-3. In the tests, the baseline demonstrated the best alignment characteristics of the three configurations. The wind turbine operation was stable and would respond to large changes in wind direction and regain normal alignment with the wind. The machine maintained a yaw angle between +10° and -10° below rated wind speed and tended to yaw out of the wind slightly at wind speeds above rated.

Tests of the Configuration 2 rotor with no Delta-3 show that this rotor did not align well with the wind and indicated that 20° of Delta-3 improved the alignment by approximately 30° near rated wind speed. This agrees quite well with the analysis in reference 2 which predicted a change in yaw alignment of about 35° for 20° of Delta-3 on a teetered rotor.

The test of Configuration 3 rotor indicated that a change in airfoil on the rotor can have an effect on alignment with the wind. While the yaw angle was not markedly larger for this rotor, having the NACA 23024 airfoil tips relative to the baseline configuration having the NACA 64_3-618 tips, the yaw alignment was less desirable. This was because yaw angles at wind speeds below rated wind speed ranged between -20° and +5° while the yaw angles for the baseline rotor ranged between $\pm$10°. Yaw alignment is more critical at wind speeds below rated where it is desirable to utilize all of the power available from the wind. In higher wind speeds, precise yaw alignment is not as critical. Also, this change in the alignment characteristics is an indication of the sensitivity of yaw alignment to altered rotor aerodynamics. The

NACA 64_3-618 airfoil has a center of pressure which is farther aft than the NACA 23024 and this characteristic could be a contributing factor in the different alignment for this rotor.

Results obtained previously from tests conducted on an unconed teetered rotor which had the rotor axis tilted 8-1/2°, were reported in reference 1. That configuration operated at a yaw angle of approximately -45° in winds of 8 ms^{-1}. Comparing those results with the results from this test series indicates that the addition of 3° of coning and removing the 8-1/2° of rotor tilt improved the wind alignment of the rotor by approximately 15°. The results of analysis presented in Reference 1 have indicated that the effect of each of these changes, i.e., rotor coning and a horizontal rotor axis would improve yaw alignment. The size of the improvement could not be determined, however.

Both of the rotors with 20° of Delta-3 responded to wind direction changes and achieved relatively good alignment with the wind, but both operated in a wide yaw angle band of appoximately 20°. This indicates that the system is delicately balanced and the restoring moment is too weak to bring the nacelle into precise alignment around its mean alignment angle. This results in a rather broad deadband. For wind turbine operation it would be desirable to reduce this range to ±5° about a zero deg yaw angle. This level of alignment can be routinely maintained with an active yaw controller and is necessary if maximum energy capture in winds below rated wind speed is to be achieved.

The baseline rotor with Delta-3 tended to yaw out of the wind in winds above rated wind speed. While this is not a problem with respect to energy capture, increased yaw angles produce higher teeter angles as wind speed increases (ref. 4), and this effect should be accounted for in a free yaw machine designed to operate at high yaw angles in winds above rated wind speed. High teeter angles could result in tower clearance problems or teeter motion larger than that allowed for in the design.

The free yaw tests conducted to date have answered some of the questions about the factors affecting free yaw. Delta-3, axis inclination, and coning have been shown to affect yaw alignment. Analysis indicates that blade twist has a significant effect. The tests have shown that the choice of the airfoil shape can have an effect also. Other things which must be considered include the degree of rotor gravity balance about the teeter pin, or underslinging, rotor dynamics and overall machine structural dynamics. These items combine to make the design of a free yaw machine a very complex problem. The data indicate that system balance at the yaw equilibrium point is delicate and the analysis indicates that a number of items can affect this balance. It is felt that the effect of each of these parameters, individually and of various combinations, must be demonstrated in more comprehensive testing before analytical techniques can be used with confidence in the design of a free yaw machine. Without additional testing and verification of analytical methods, achieving a viable free yaw wind turbine will probably require some degree of adjustment or trimming after the prototype wind turbine has been installed and initial operation has been evaluated. This could involve minor adjustment such as providing more yaw damping, or could require major changes such as Delta-3 adjustment or blade redesign.

CONCLUSIONS

The free yaw tests conducted on the Mod-0 100 kW Wind Turbine indicated the conclusions given below:

(1) Delta-3 has a pronounced effect on the free yaw alignment of a horizontal axis wind turbine.

(2) A change in blade aerodynamics can have an effect on free yaw alignment.

(3) A wind turbine in free yaw should have no difficulty in responding to sudden wind shifts and regaining alignment with the wind.

(4) Yaw damping can improve free yaw performance of a wind turbine.

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TABLE I. - ROTOR CHARACTERISTICS

STEEL SPAR, TIP CONTROL BLADE

Rotor diam., (ft)	39.2 (128.6)
Root cutout, Δ span	23
Tip control, Δ span	31
Blade pitch, (inb'd sec.), deg	Zero
Airfoil (inb'd sect.)	NASA 23024
(outb'd 31)	NACA 64_3-618 or NACA 23024
Taper	Linear
Twist, deg	Zero
Solidity	0.033
Precone, deg	3
Delta-3, deg	0 or 20
Max. teeter motion, deg.	±6
Blade mass, kg (lb)	2000 (4400)
Rotor Moment of Inertia about Teeter Axis kg-m^2 (in-lb-sec^2)	
(Delta-3 = 0°)	290,000 (2,600,000)
(Delta-3 = 20°)	260,000 (2,300,000)
Blade Lock Number*, γ	
(Delta-3 = 0°)	7.11
(Delta-3 = 20°)	7.97

* Blade Lock Number, γ is the ratio of aerodynamic force to inertia force on a rotor blade and is defined as:

$$\gamma = \frac{\rho a_0 c R^4}{I}$$

ρ = air density
a_0 = slope of airfoil lift curve
c = average blade chord
R = blade radius at tip
I = blade mass moment of inertia

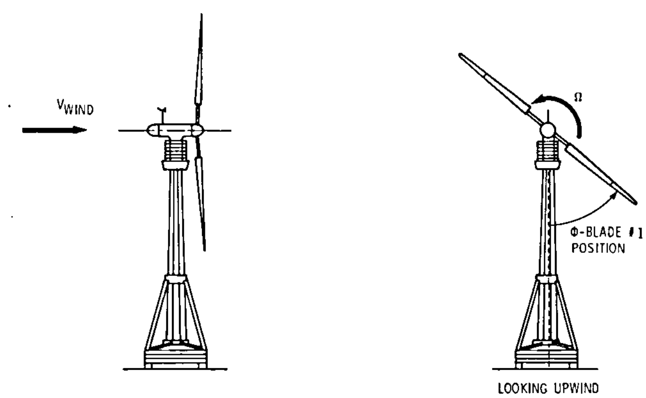
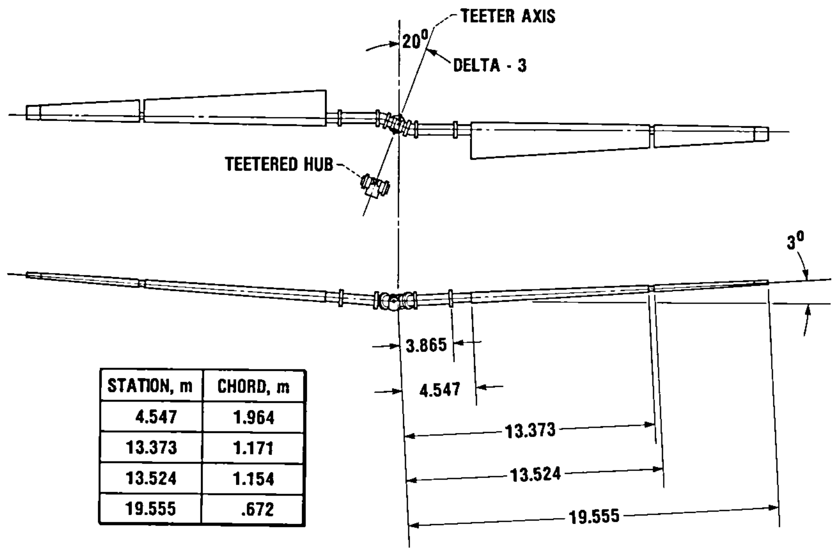


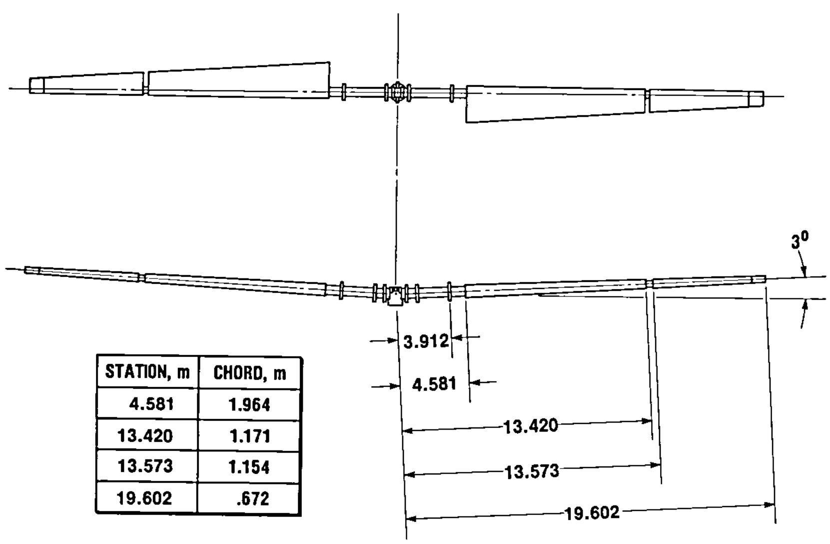
Figure 1. - Mod-0 wind turbine free yaw test configuration.

TEETERED ROTOR WITH 20^0 DELTA-3 AND 3^0 CONING



STATION, m	CHORD, m
4.547	1.964
13.373	1.171
13.524	1.154
19.555	.672

TEETERED ROTOR WITH 0^0 DELTA-3 AND 3^0 CONING



STATION, m	CHORD, m
4.581	1.964
13.420	1.171
13.573	1.154
19.602	.672

Figure 2. - Test rotors with 20^0 of delta-3 and with delta-3 removed.

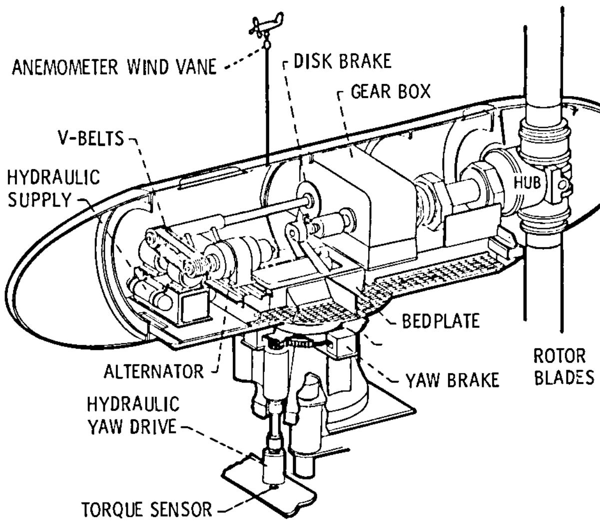


Figure 3. - Interior of nacelle.

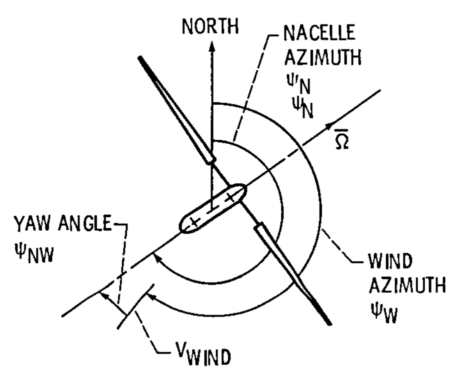
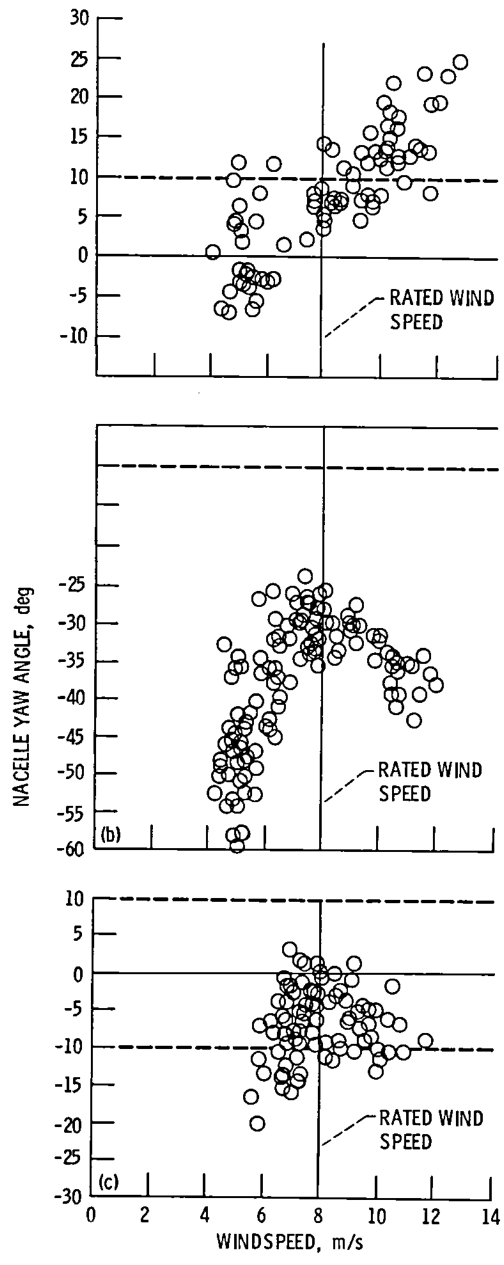


Figure 4. - Sign convention and definition of terms. Positive yaw angle shown.

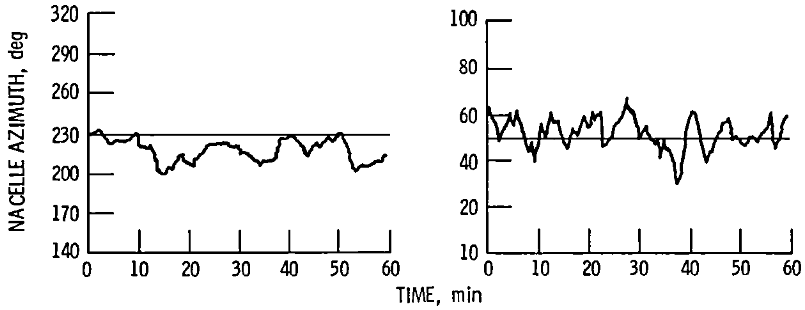


(a) Configurations 1, 20 deg delta-3, NACA 64_3-618 tip.

(b) Configuration 2, 0 deg delta-3, NACA 64_3-618 tip.

(c) Configuration 3, 20 deg delta-3, NACA

Figure 5. - Free yaw wind alignment for three rotor configurations (5 minute averages).



(a) Mean wind speed 5 m/s.
(b) Mean wind speed 10 m/s.

Figure 6. - Nacelle azimuth versus time - typical nacelle yaw motion during free yaw operation of two mean wind speeds. Configuration 1 (30 second averages.)

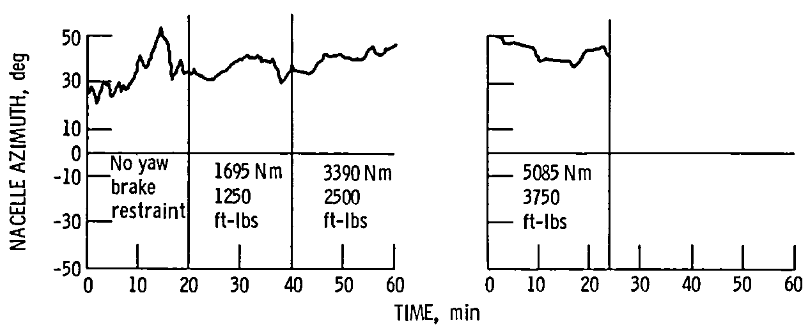
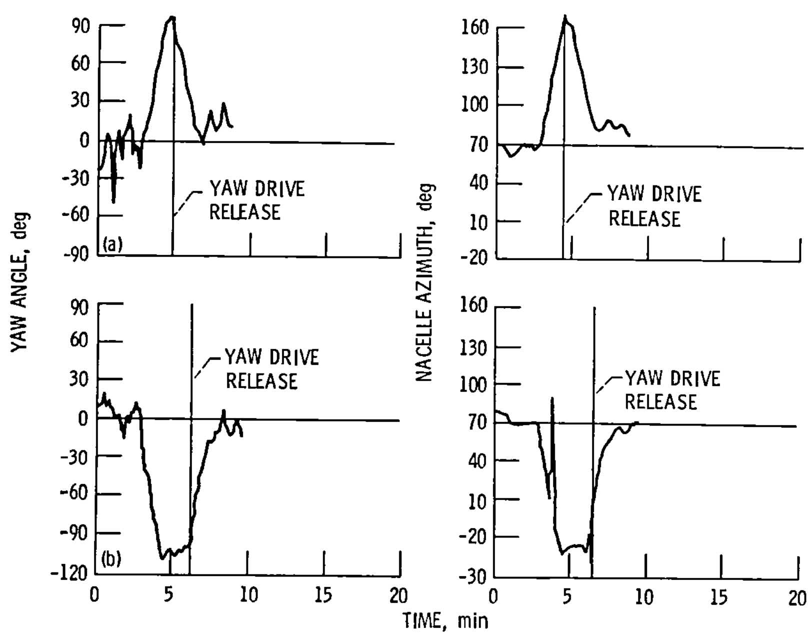
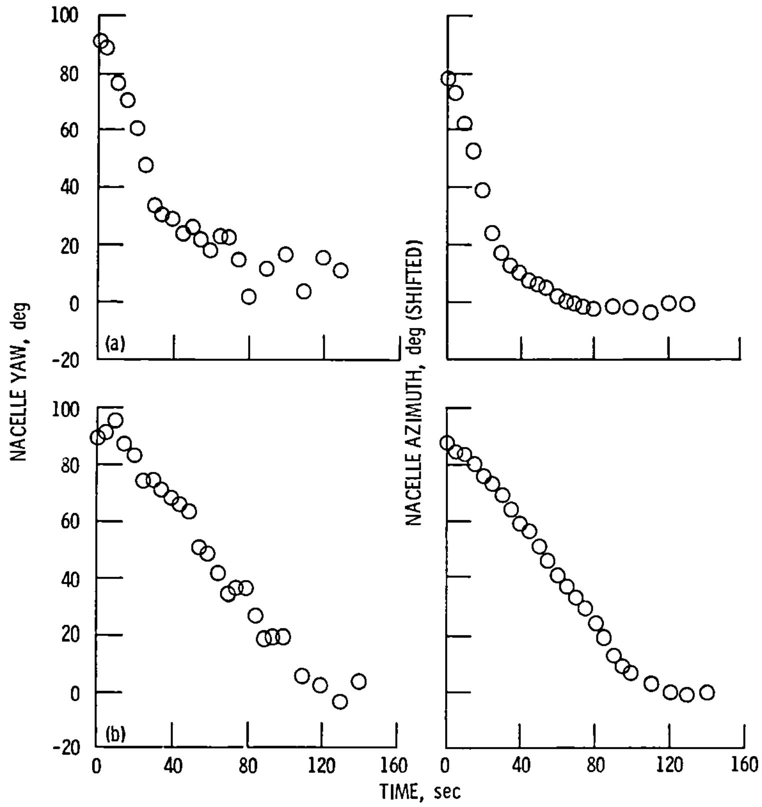


Figure 7. - Effect of yaw brake restraint on nacelle angular motion. Three levels of nacelle yaw torque are shown. (30 second averages).



(a) Positive yaw displacements.
(b) Negatiave yaw displacements.

Figure 8. - Yaw alignment recovery after initial yaw displacement in excess of 90 deg. (10 second averages).



(a) Mean wind speed 10 ms^{-1}, maximum yaw rate 2.5 deg. s^{-1}.
(b) Mean wind speed 6 ms^{-1}, maximum yaw rate 1 deg. s^{-1}.

Figure 9. - Wind alignment recovery - yaw and macelle azimuth angle versus time after release of yaw restraint for two mean wind speeds (nacelle azimuth angle shifted to zero at equilibrium point).

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16. Abstract

Tests were conducted on the Mod-0 100 kW experimental wind turbine to provide data on yaw alignment characteristics of a large horizontal axis wind turbine with its yaw restraint removed (i.e., in free yaw). The wind turbine consisted of a downwind horizontal axis rotor mounted on a tublar tower. Three rotor configurations were tested. Each rotor was teetered, coned 3 deg and tip-controlled. Two of the rotors had pitch-flap coupling or Delta-3, and one rotor had none. The two rotors with Delta-3 differed in the airfoil used in the tip sections. Test results indicate the rotor without pitch-flap coupling did not align closer than 25 deg with the wind, and pitch-flap coupling improved the wind turbine's alignment with the wind. Yaw damping was shown to have a favorable effect on free yaw characteristics. The change in the tip airfoil section was shown to affect the free yaw alignment also. The rotors with Delta-3 were shown to be capable of responding to wind shifts and exhibited stable operating properties.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Wind turbine; Horizontal axis; Free yaw; Pitch-flap coupling; Delta-3; Teetered rotor	Unclassified - unlimited STAR Category 44 DOE Category UC-60

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