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THE RESPONSE OF A 38m HORIZONTAL AXIS TEETERED ROTOR TO YAW

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ABSTRACT

Recent tests on the 38m Mod-0 100 kW horizontal axis experimental wind turbine have yielded quantative data on the teeter response of a rotor to yaw. The test results indicate that yaw rates as high as 5 deg/s could be used in emergency situations to unload and slow a rotor for intermediate sized (500 kW) wind turbines. The results also show that teeter response is sensitive to the direction of yaw, and that teeter response to yaw is reduced as either the rotor speed or the blade Lock number is increased.

INTRODUCTION

A primary concern of designers from the beginning of the use of wind power has been the problem of unloading the rotor and preventing an overspeed in the event of a failure in the drive train or, in recent times, the loss of electrical load on the generator. There are three methods of handling this situation: (1) the blades can be unloaded either by feathering or by use of devices to spoil blade lift and/or increase drag, (2) a brake can be installed to dissipate the energy of the rotor, and (3) the rotor can be yawed or pitched out of the wind to remove the driving force. Until the present, only the first of these methods has been given serious consideration for large wind turbines with a rated power of 100 kW or more. However, with the use of a teetered rotor higher yaw rates can be used and the potential of yaw as a safety procedure has become more attractive. This paper presents results of tests designed to evaluate the effect of yaw on teetered rotor response with a view toward using this maneuver as an emergency safety procedure.

Operating experience indicated the teetered rotor had considerably more tolerance to yaw than did the rigid hub rotor and tests were conducted to determine the maximum yaw rate that could be safely used with a teetered rotor to assess the potential of the yawing maneuver as a safety device. In addition to this primary objective, the test results were considered to be valuable in that they would provide baseline test data for future analytical studies.

The results presented were obtained from tests conducted on the Mod-0 100 kW experimental wind turbine located at Sandusky, Ohio. Two rotors were tested, one with twisted aluminum blades and the other with untwisted tip-controlled blades having a steel spar as the primary structural member. Both rotors used the same teetered hub and tests were run at rotor speeds of 20 and 31 rpm on the steel spar blades and of 26 rpm on the twisted aluminum blades. Yaw rates were varied from 0.8 to 4.7 deg/s.

TEST CONFIGURATION AND PROCEDURE

The teetered rotor yaw tests were conducted on the Mod-0 100 kW experimental wind turbine shown schematically in Figure 1. The essential features of the machine have been described previously [1 and 2]. All tests were conducted in the downwind rotor configuration, i.e., with the rotor downwind of the supporting tower and the rotor axis was tilted 8-1/2 deg to provide tower clearance for the blades. Two rotor configurations were tested; a tip-controlled rotor with untwisted blades and, a fixed pitch rotor with highly twisted aluminum blades. Both rotors were unconed and used the same teetered hub. The blades are described in Table 1 and Figures 2 through 5.

Tests of the tip-controlled rotor were conducted at 20 rpm and at 31 rpm and of the fixed pitch rotor at 26 rpm. Unfortunately the fixed pitch rotor could not be safely tested at 31 rpm due to the danger of exceeding the 100 kW power limit. Also, testing at 20 rpm was inconclusive because of the tendency of the rotor to lose teeter stability in higher wind speeds as the blade began to stall near the tip, and the difficulty in starting the fixed pitch rotor in low wind speeds. The yaw rate was varied by making use of the yaw brake hydraulic power unit which is installed in the nacelle. This unit and the hydraulic yaw drive motor provided capability for yaw rates up to approximately 5 deg/s. A manual flow control valve was used to control yaw rate.

The tests were conducted by first setting a yaw rate, aligning the wind turbine with the wind and yawing the machine 100 deg out of the wind in first the positive and then the negative yaw directions. During the test the generator was synchronized with the utility grid and the overrunning clutch was in the drive train. The overrunning clutch permitted the rotor speed to drop below synchronous speed when the wind load was removed but would not permit the rotor to exceed synchronous speed.

Test data were taken on a strip chart recorder and on magnetic tape. The response of the teetered rotor to yaw of the nacelle was determined by analysis of the teeter angle trace. From this time history, the amplitude and phase of the teeter motion was obtained. Teeter angle amplitude was determined by taking a mean of the one-half amplitude of the teeter angles which occurred during a yaw maneuver of 100 deg. Teeter motion is limited by the teeter stops at approximately ± 5.8 deg; therefore, a mean value of teeter amplitude slightly in excess of 5 deg can involve some teeter stop impacts and a teeter amplitude above 5.5 deg involved teeter stop impacts throughout most of the maneuver.

Phase angle, , was determined by noting the rotor position at the instant when teeter angle was a maximum for each rotor revolution during the yaw maneuver. Typically, phase angle achieved a steady value during the first five rotor revolutions after the yaw maneuver commenced and maintained a relatively constant value during the remainder of the operation. This relatively constant value is reported as the phase angle for a given yaw rate.

Each data point presented represents an average value obtained from five yaw maneuvers unless the data indicated that excessive teeter stop impacts occurred, in which case the test was not repeated.

Sign Convention and Definition of Terms

Figure 6 presents the sign conventions used at the Mod-0 test facility. Nacelle and wind azimuths, ψ_N and ψ_W, are measured in degrees from north. Yaw rate, $\dot{\psi}_N$, is considered to be positive if the nacelle azimuth is increased. Nacelle yaw angle, ψ_{NW}, is measured relative to the wind. A positive yaw angle results if the nacelle azimuth is larger than the wind azimuth. A positive yaw angle, ψ_{NW}, is shown in Figure 6.

$$\psi_{NW} = \psi_N - \psi_W$$

Rotor position, ϕ, describes the angle of blade #1 relative to the vertical and down location and is measured in degrees from zero to 360. The rotor direction of rotation is indicated in Figure 1 and by the vector, Ω, in Figure 6.

The elements essential in describing the motion of a teetered rotor are shown in Figure 7 and are described below. When a rotor is turning in uniform flow without teetering, the blade tips define a circular track in a plane which is perpendicular to the axis of rotation. This plane is called the rotor reference plane. Teeter motion is described by two quantities, maximum teeter angle, β_{max}, and phase angle, ζ. Positive teeter angle is defined as that teeter angle which causes blade #1 to move upwind of the rotor reference plane and, of course, maximum teeter angle is the largest positive teeter angle during a given rotor revolution. The point of maximum teeter angle is located by a phase angle, ζ, which describes the angular position of β_{max} relative to the lowest point of the rotor disc. In steady wind conditions, the rotor teeters at a frequency approximately equal to the rotor speed or, once per revolution. This produces a tilt in the plane described by the blade tip path relative to the rotor reference plane. Teeter amplitude, β_{max}, defines the angle the rotor plane makes with the rotor reference plane while the phase angle, ψ, defines the orientation of the tilted plane relative to the rotor zero position.

Blade Lock number, γ, is a non-dimensional term used to describe the ratio of air forces to inertia forces for a rotor blade. The term is defined as

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

where:

ρ - air density

a_0 - slope of airfoil lift curve

c - average blade chord

R - blade radius at tip

I_B - blade mass moment of inertia about the rotor center of rotation

Lock number is a measure of the damping of a rotor blade and the term $\gamma/16$ for a rotor blade has a meaning similar to C/C_c in damped harmonic motion in that it indicates the nature of the blade's transient response.

RESULTS AND DISCUSSION

The results of the yaw rate tests are presented in Figures 8 , 9 and 10. Figures 8 and 9 present a mean value for the maximum teeter angles, β_{max}, recorded during the yaw maneuver of 100 deg for each of the yaw rates shown. The teeter angle value is the average of five maneuvers for most of the points. Teeter angle versus yaw rate is shown for two rotors. Figure 10 presents phase angle versus yaw rate for the tip-controlled rotor only.

The tip-controlled rotor at 20 rpm produced higher teeter angles than it did at 31 rpm. This is to be expected because aerodynamic forces, which stabilize the rotor and reduce teeter angle, increase as the square of the tip speed or rotor speed while gyroscopic forces which increase teeter angle with yaw rate increase with the first power of rotor speed. Therefore, increasing rotor speed will increase the permissible yaw rate for a given rotor. Also, rotors with higher Lock numbers should permit higher yaw rates at the same rotor speed.

This conclusion is indicated in Figure 9 which shows a yaw rate of +4.3 deg/s was required to cause teeter stop impacts on the rotor with aluminum blades, with a Lock number of 11.95, while a yaw rate of only 3 deg/s produced the same result on the rotor with the steel spar blades having a Lock number of 6.56, shown in Figure 8. Also, for negative yaw rates, the mean teeter angle for a given yaw rate was approximately the same for the aluminum blades at 26 rpm and the steel spar blades at 31 rpm. This indicates that lower Lock numbers produce higher teeter angles for the same yaw rate if rotor speed is held constant. Unfortunately, the fixed pitch rotor could not be operated safely at 31 rpm and a direct comparison of the rotors at the same rotor speed was not possible.

There was a definite difference in the teeter response to positive and negative yaw rates, with positive yaw rates producing a higher teeter angle response than negative yaw rates. This is shown clearly in Figures 8 and 9. The reason for this behavior can be understood by examining the phase angle of the rotor during normal operation and during yaw maneuvers of the nacelle.

During normal operation of a downwind teetered rotor aligned with the wind, the phase angle will be at or near 90 deg. This is due to the variation in flow over the rotor disc caused by wind shear and tower interference and the fact that the response of a teetered rotor lags the disturbance by 90 deg. Thus a disturbance occurring when the blades are vertical will be seen when the blades are horizontal. Tower interference and wind shear are most pronounced when the blades are vertical and the response measured by teeter angle is maximum at or near the 90 deg position (which produces a phase angle, ψ , of 90 deg) and further, since wind speed is higher at the top of the rotor disc, (a blade position of 180 deg) and lower at the lowest point on the rotor disc, the lower, ascending, blade being lightly loaded relative to the upper, decending, blade will cause a teeter motion which brings the tip of the ascending blade into the wind or upwind of the rotor reference plane when the blade is horizontal (see Figure 7).

A second concept is necessary to the understanding of teeter response to yawing motion. When a teetered rotor is yawed, gyroscopic forces resist the motion. These gyroscopic forces on the rotor in a uniform flow would tend to make the rotor have a phase angle and teeter angle of zero if no yaw motion were taking place, a phase angle of +90 deg for yaw in a positive direction and a phase angle of -90 deg for yaw in a negative direction. In this instance, the phase angle and the teeter angle would be created by the tendency of the rotor to remain in its initial plane of rotation.

When the effect of non-uniform flow over the rotor disc is added to the effect of yaw motion, we have a situation which is additive for positive yaw and is cancelling for negative yaw. These effects are indicated by the phase angle versus yaw rate results shown in Figure 10 for the tip-controlled rotor operating at 31 rpm. When the rotor operates normally without yawing, a phase angle of 92 deg was measured. For positive yaw rates, the phase angle for operation without yawing is nearly the same as that produced by yawing the machine and the two effects, tower interference and wind shear plus yaw rate, tend to add creating a higher teeter angle and very little change in phase angle.

When the wind turbine is yawed in the negative direction, the two effects tend to counteract one another which results in smaller teeter angles and more tolerance for higher negative yaw rates. In effect, the initial yaw rates are used in changing the phase angle from +90 deg to -90 deg rather than in merely increasing the maximum teeter angle as was the case in yawing the machine in the positive direction. As indicted in Figure 10, the rotor phase angle is changed from +90 deg to -60 deg by increasing the yaw rate to approximately 4 deg/s and the data indicates that negative rates near 5 deg/sec could be tolerated without teeter stop impacts. Thus, a negative yaw rate of approximately 5 deg/s is required for the rotor gyroscopic forces to overcome the effects of non-uniform airflow and create a situation where impacts with the teeter stops could occur.

The test results also indicate the connection between phase angle and rotor response to yaw rates. This implies that the addition of δ_3 to the teetered rotor would have an effect on the allowable yaw rate. δ_3 is a term taken from helicopter terminology and refers to a method of coupling blade pitch with the teetering of a teetered rotor as indicated in Figure 11. δ_3 has an effect on the phase angle, ψ , of a teetered rotor and should therefore affect teeter response to yaw. Results have been reported in this area [3], and work is currently underway to extend this effort. These test results and work done previously indicate that yaw could be used as an effective method for removing the load from a rotor under emergency conditions.

CONCLUSIONS

The results of yaw tests on a 38m horizontal axis teetered rotor indicate the following conclusions:

- Teeter response to yaw was lower when the wind turbine was yawed in a negative direction.
- Teeter response to yaw is decreased as
    - (a) Rotor speed is increased
    - (b) Blade Lock Number is increased
- Yaw rates of 5 deg/s appear to be possible for intermediate size wind turbines with teetered rotors.

NONENCLATURE

a_o - slope of airfoil lift curve

c - average blade chord

C/C_c - ratio of damping to critical damping for a damped spring mass system

I_B - blade mass moment of inertia about center of rotation

R - blade radius at tip

V_{wind} or V_W - wind vector

β - teeter angle

γ - Lock number, defined in text

δ_3 - pitch--teeter angle coupling
= sin 3

θ - blade pitch angle

ξ - phase angle, defined in text

ρ - air density

ϕ - rotor position, angular position of blade #1 relative to vertical, down line

Ψ_N - wind turbine nacelle azimuth

Ψ_W - wind azimuth

Ψ_{NW} - nacelle yaw angle i.e. angle made by nacelle axis and wind vector

Ω - rotor speed

REFERENCES

1. Glasgow, J.C. and Miller, D.R.: Teetered, Tip-Controlled Rotor: Preliminary Test Results from Mod-0 100kW Experimental Wind Turbine
DOE/NASA/1028-80/26, NASA TM-801445, 1980.

2. Glasgow, J.C., Miller, D.R. and Corrigan, R.D.: Comparison of Upwind and Downwind Rotor Operations of the DOE/NASA 100 kW Wind Turbine
DOE/NASA/1028-31, NASA TM-81744, 1981.

3. Hohenemser, K.H. and Swift, A.H.P.: Dynamics of an Experimental Two Bladed Horizontal Axis Wind Turbine with Blade Cyclic Pitch Variation. Paper presented at Second DOE/NASA Wind Turbine Dynamics Workshop, Cleveland, Ohio. Feb. 1981.

Table 1 - ROTOR CHARACTERISTICS

Steel Spar, Tip Control Blade		Twisted Aluminum Blade	
Rotor dia., m (ft).	38.39 (126.0)	Rotor dia., m (ft).	38.5 (126.37)
Root cutout, % span	23	Root Cutout, % Span	5
Tip control, % span	30	Fixed Pitch	--
Blade pitch, inb'd sec., deg.	Zero	Blade Pitch 75% Span, deg.	2.8
Airfoil (inb'd sect.)	NACA 23024	Airfoil	NACA 230 series
(outb'd 30%).	NACA 64_3-618	(root to tip)	
Taper.	Linear	Taper	Linear
Twist, deg.	Zero	Twist, deg.	34
Solidity.	0.033	Solidity.	0.030
Precone, deg.	Zero	Precone, deg.	Zero
Max. teeter motion, deg.	±6	Max teeter motion, deg.	±6
Blade mass, kg (lb)	1815 (4000)	Blade mass, kg (lb)	1043 (2300)
Blade Lock number	6.56	Blade Lock number	11.95

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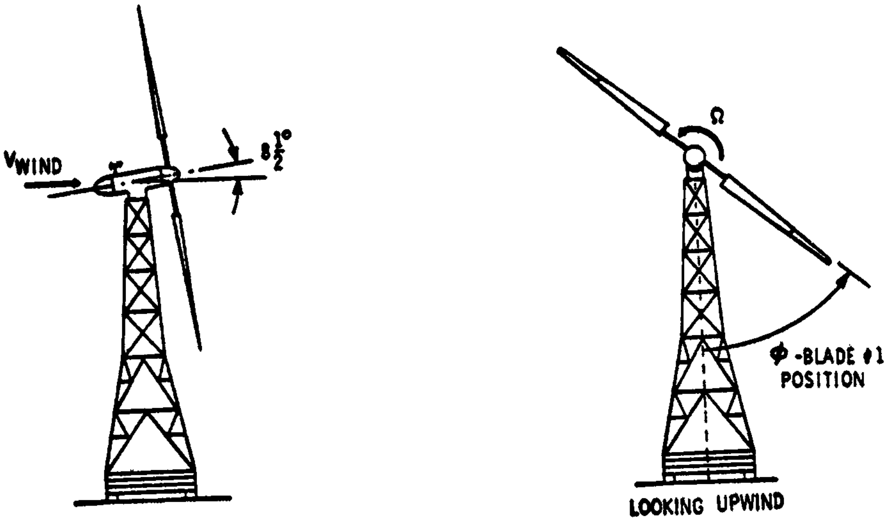
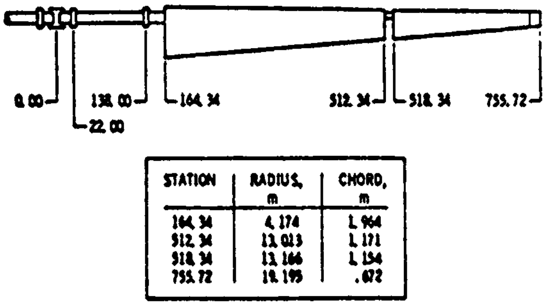
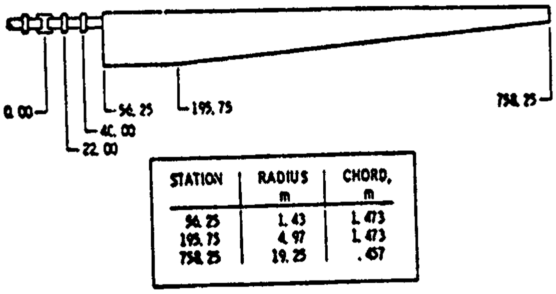


Figure 1. - Mod-0 100 kW Experimental Wind Turbine with Teetered, Tip-Controlled Rotor.



STATION	RADIUS, m	CHORD, m
164.34	4.174	1.964
512.34	13.013	1.171
518.34	13.166	1.154
755.72	19.195	.672

Figure 2. Steel Spar, Tip Control Blade Planform



STATION	RADIUS m	CHORD, m
56.25	1.43	1.473
195.75	4.97	1.473
758.25	19.25	.457

Figure 3. Twisted Aluminum Blade Planform

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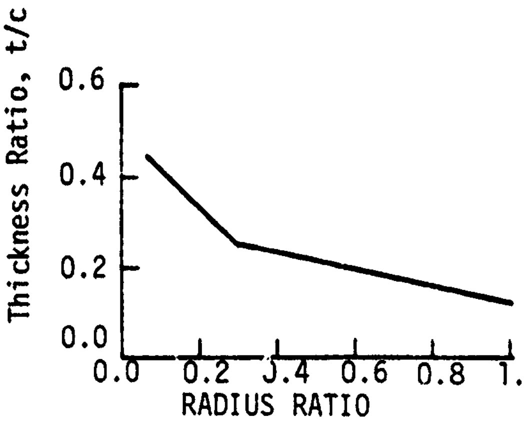

Figure 4. Thickness to Chord Ratio for Twisted Aluminum Blade

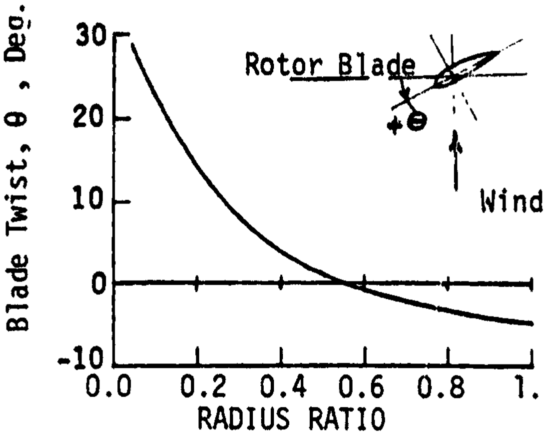

Figure 5. Twist Distribution for Twisted Aluminum Blades

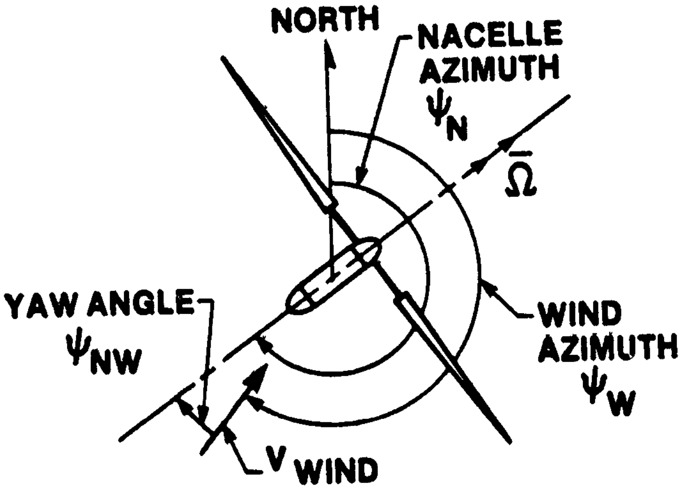

Figure 6. Mod-0 Wind Turbine Sign Convention

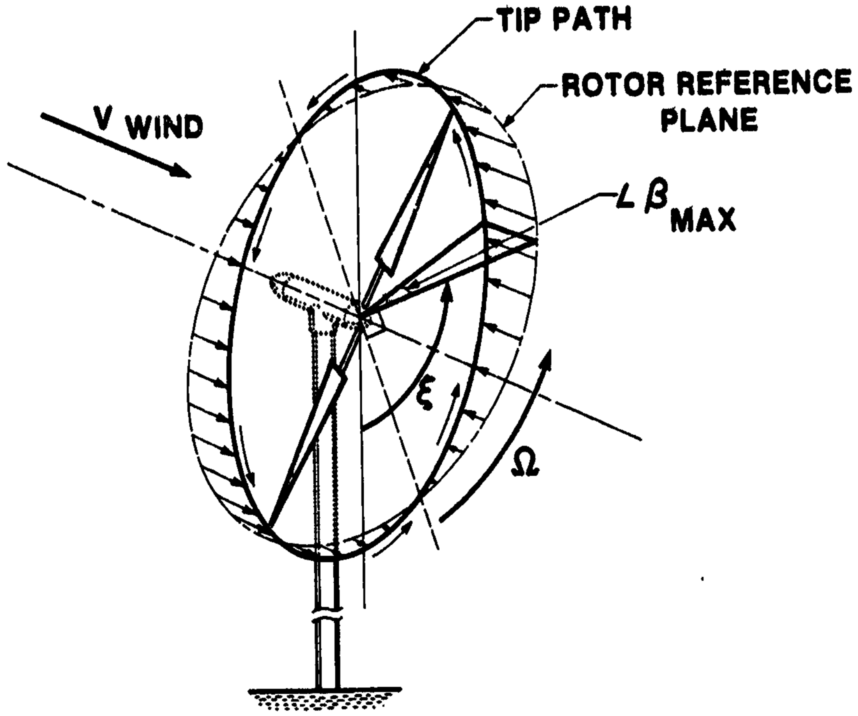

Figure 7. Teetered Rotor Coordinates Showing Maximum Teeter Angle, β_{max}, and Phase Angle, ξ .

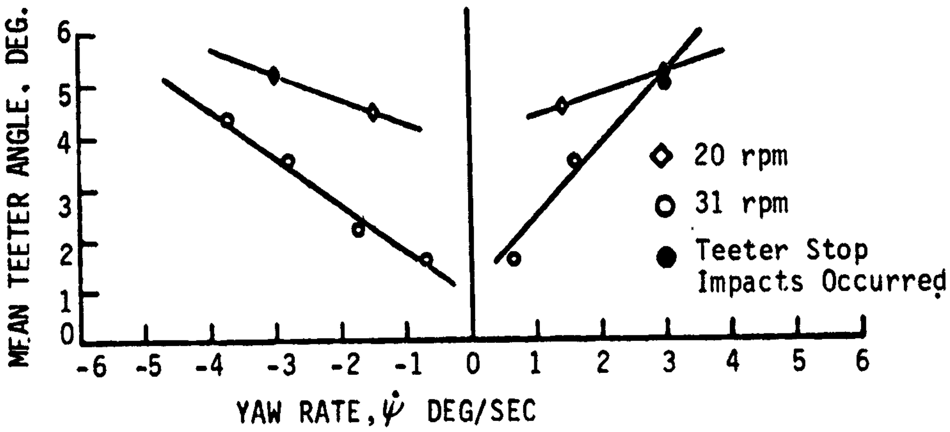

Figure 8. Teeter Angle Versus Yaw Rate for Tip-Controlled Rotor at 20 and 31 rpm.

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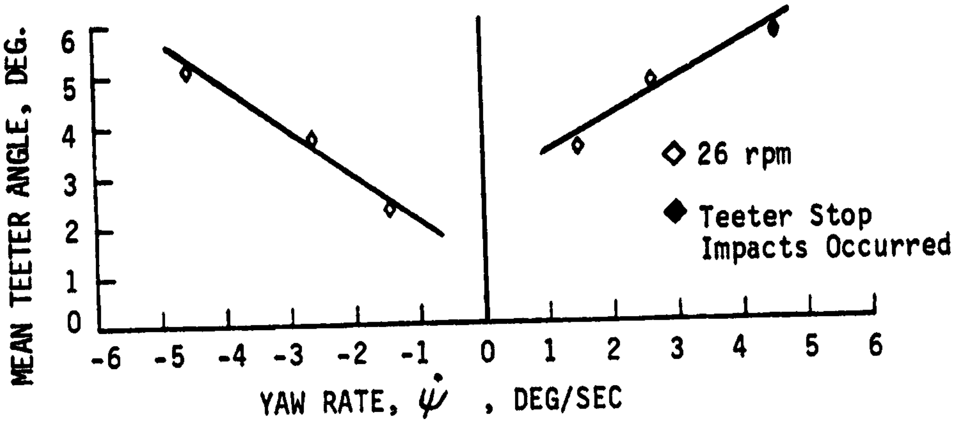

Figure 9. Teeter Angle Versus Yaw Rate for Fixed Pitch Rotor with Twisted Aluminum Blades at 26 rpm

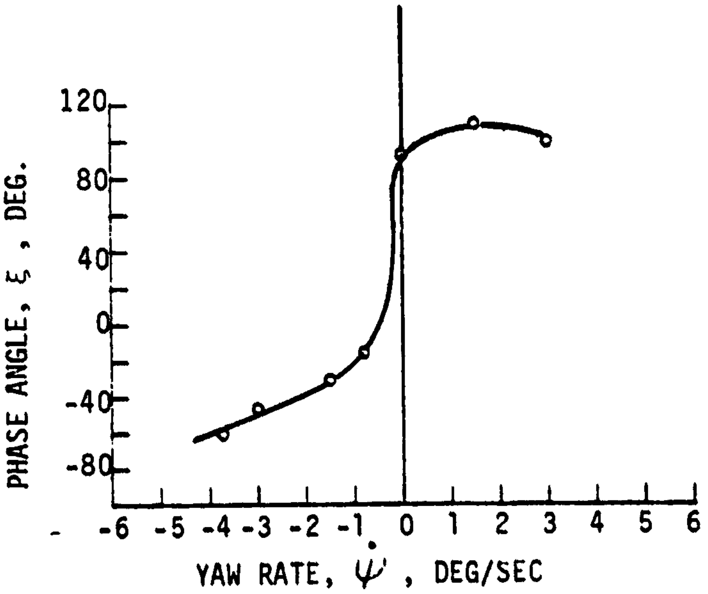

Figure 10. Rotor Phase Angle, ξ, Versus Yaw Rate for Tip-Controlled Rotor at 31 rpm.

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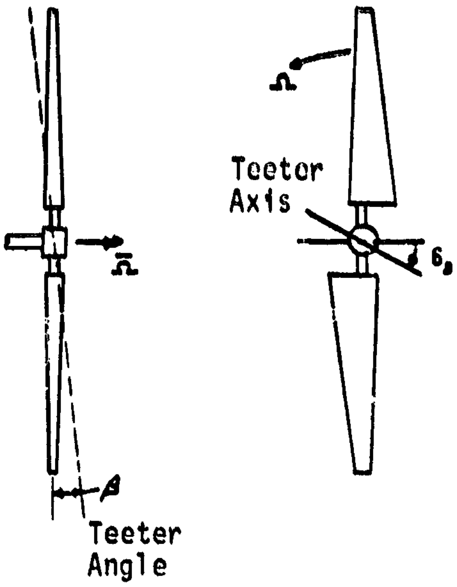

Figure 11. Schematic of Teetered Rotor with δ_3. By canting the teeter axis relative to a line perpendicular to the blade axis, blade pitch, Θ, is coupled with rotor teeter angle, β, by the relation:
$\Theta = \beta \sin \delta_3$, for small values of β.

QUESTIONS AND ANSWERS

J. C. Glasgow

From: G. R. Kotley

Q: Can you explain the action of Delta-3 hinge geometry in suppressing teeter amplitude?

A: *Delta-3 makes the teetered rotor stiffer in that it reduces the teeter response to a disturbance. Delta-3 will also change the phase, which should have an effect on teeter amplitude during yawing maneuvers.*

From: R. Barton

Q: Have you or do you plan to run a transient free yaw from an upwind-loss of load condition (i.e. MOD-2)?

A: *No, we have not run this case but measurements of yaw moment for a teetered upwind rotor indicate the machine is unstable in this mode. However, teetered rotors in free yaw appear to respond very slowly in yawing to a desired zero load condition and the test would probably be very well behaved.*

From: A. Swift, Jr.

Q: Have you considered yaw control for power or torque control above the rated wind speed or only for emergency shutdown? Is 5° per second sufficient for power control (for fixed pitch-aluminum twisted blades)?

A: *We have considered this but the test results to date indicate that the response would be poor for "up gusts" while operating at the rated wind speed and aligned with the wind. In this condition about 30° of yaw would be required before significant power could be shed.*

From: S. Oye

Q: What was the actual Delta-3 angle during your experiments?

A: *The Delta-3 angle was zero degrees.*

From: C. Rybak

Q: What is the teeter angle sensitivity to yaw error or yaw rate?

A: *This data is presented in a report "Teetered, Tip Controlled Rotor: Preliminary Test Results," reference 1 above. These data indicated higher teeter angles for positive yaw angles, but no trend, i.e. flat for zero and negative yaw angles.*

J. C. Glasgow (continued)

From: A. Swift, Jr.

Q: Why do the teeter angle response lines not extrapolate to zero at zero yaw rate and why do the lines of response extrapolate to difference values for different yaw rate directions?

A: *The lines should extrapolate to the same value at zero yaw rate. The data shown should not include the +4.5° per second point with teeter stop impacts, see Figure 9. The teeter stop reduced the teeter amplitude for this point. Using only the first two positive yaw rate points will produce the correct result, approximately equal teeter amplitude at zero yaw rate.*