

MOD-0 WIND TURBINE DYNAMICS TEST CORRELATIONS*

by

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ABSTRACT

The behavior of the teetered, downwind, free yaw, MOD-0 wind turbine, as represented by NASA dynamic test data, was used to support confidence in the Hamilton Standard computer code simulations. Trim position, performance at trim, and teeter response as predicted by the computer codes were compared to test results. Using the computer codes, other possible configurations for MOD-0 were investigated. Several new test configurations are recommended for exploring free yaw behavior. It is shown that eliminating rotor tilt and optimizing coning and blade twist can contribute to good free yaw behavior and stability. The effects of rotor teeter, teeter gravity balance, inflow and other physical and operating parameters were also investigated.

INTRODUCTION

The 100 kW experimental MOD-0 wind turbine located near Sandusky, Ohio, (Plumbrook installation) has served as the test bed for the U.S. Large Horizontal Axis Wind Energy Program since its initial operation in 1975 (Reference 1). The MOD-0 installation is shown in Figure 1. In 1980, NASA conducted tests on the machine in downwind operation mode, with a teetered hub, and tip controlled blades. The tests covered the range of start-up, shut-down, and normal operation and focused on power control characteristics, and aerodynamic performance. Information in the strip chart data included such operating parameters as wind speed, yaw direction, generator power output, teeter angle, blade bending moments and bearing loads.

Since early 1979, Hamilton Standard has supported these aspects of the NASA MOD-0 SR and T Program with analytical studies using the F762 computer code simulation. The F762 program has been under development at Hamilton Standard for several years. This analysis is a teetering rotor computer program characterized by a rigorous modeling of the blade, and accounting for the nonlinear and time varying structural twist using modal response methods.

The tower response including yaw motions are described in the six degree of freedom equations of motion of the hub. The complete nonlinear response of the tower and rotor time history solutions are printed and/or

plotted for harmonic analysis and transient aeroelastic response calculation purposes. The co-ordinate system for the wind turbine as defined in F762 is described schematically in Figure 2. Note, from the top-left drawing in Figure 1, that the difference between the nacelle yaw and the wind yaw is the angle that the nacelle makes with respect to the wind. This is known as yaw alignment.

This study of the MOD-0 test data had the following three objectives:

1. Confirm the behavior of the MOD-0 machine as represented by the NASA data using the F762 time history program.
2. Recommend to NASA a new test configuration for MOD-0.
3. Study yaw trim behavior as a function of blade twist, rotor cone, $\Delta 3$, inflow character, teeter, and other physical and operating parameters.

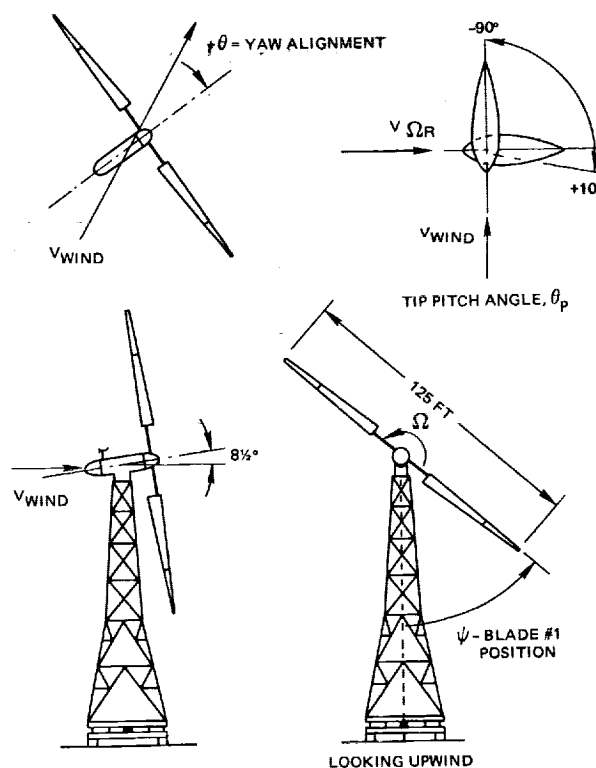


Figure 1 - MOD-0 kw wind turbine with teetered, tip control rotor

*Presented at the Second DOE/NASA Wind Turbine Dynamics Workshop, February 24-26, 1981 in Cleveland, Ohio.

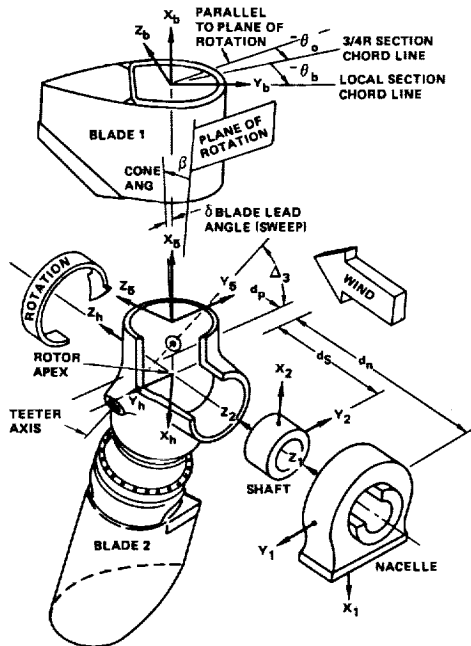


Figure 2 - Wind turbine load coordinate systems

The results of this study are summarized in this paper in two parts: one dealing with the correlation of test and calculations and the other dealing with optimized MOD-0 configurations.

Test/Analysis Correlation

Test data for the MOD-0 machine were compared with calculations for a model simulation using the F762 computer code time history results. A comparison of calculated and measured yaw behavior for the MOD-0 machine is shown in Figure 3. Both the test and calculations were for the MOD-0 operating at 33 RPM with no tip control. The calculations were made for a constant wind speed of 18 mph, whereas the test was conducted at varying wind conditions. The test was conducted at zero blade angle. The blade angle used for calculations was set at -4.5 degrees in order to produce the rated power at rated wind speed.

The MOD-0 machine was tested first in the fixed yaw mode with the yaw brake on. During subsequent test runs, the brake pressure was gradually bled off to zero so that the machine was allowed to yaw freely. The bottom curve in Figure 3 shows the tested yaw alignment vs. time. The yaw alignment for this run starts near zero but, as the yaw brake is released, the yaw alignment increases until it stabilizes at about -50 degrees. The variation from -50 degrees is due to the many changes in wind speed and direction which occurred during the test run. The results from the calculation are shown in the top curve. The model used in the calculation was started at a zero yaw position and allowed to yaw freely. The final yaw alignment settled at -65 degrees, approximately matching the test result. Note that the time for the calculation to reach trim is much less than the time observed dur-

ing the test. The reason for this is unclear, but it is believed to be due to friction in the real system caused by drag on the yaw brake and in the yaw bearing.

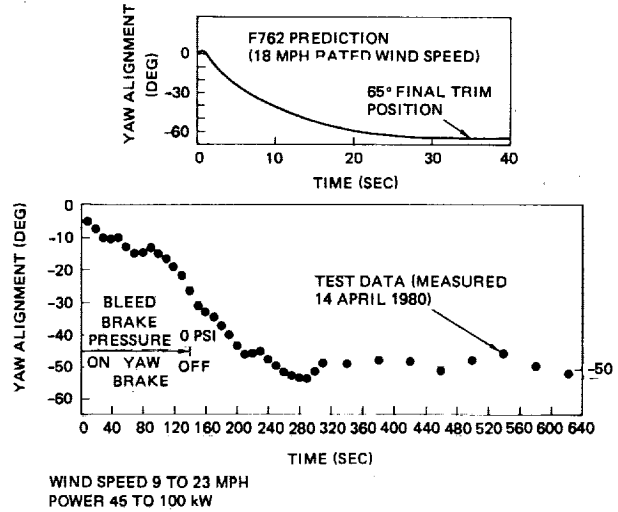


Figure 3 - Yaw behavior MOD-0 Plumbrook

A comparison of measured and calculated teeter angle time histories is shown in Figure 4. The measured teeter angle time history is shown in the top curve for a portion of the test run when the wind speed was steady at $18 \text{ mph} \pm 1 \text{ mph}$ for about 10 seconds. The yaw alignment was -50 degrees varying little for this period and the teeter angle had reached steady-state. The corresponding F762 prediction is shown in the bottom curve. The time history calculations used in Figures 3 and 4 were started with no initial displacement at constant RPM. The rotor was therefore instantaneously immersed in the flow field. Thus, there was an initial transient response for an instantaneous 18 mph gust. The results are qualitatively equivalent to teeter gust responses observed in the measured data. In the calculation, this initial transient quickly decays, to the steady-state teeter response shown. The predicted teeter angle is of similar magnitude as that shown for the test data.

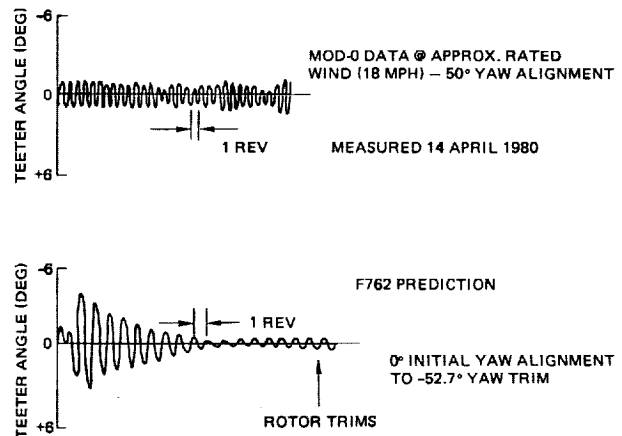


Figure 4 - MOD-0 teeter angle F762 vs. measured data

A comparison of the MOD-0 measured and calculated performance vs. wind speed is shown in Figure 5. The measured data represent the actual power output of the MOD-0 machine alternator, with the machine operating in free yaw at the approximate yaw trim position. This is within a few degrees of the -50 degree position as shown in Figure 3. The predicted performance was, for convenience, calculated using a computer code, which assumes a fixed yaw, rigid rotor. This computer code has basically the same aerodynamic formulation as in F762 and has been shown to give very similar performance results. The calculation assumed a fixed yaw position of -50 degrees and an alternator system efficiency of 80 percent (Reference 2). The sensitivity in the measured data of power output to wind speed at this extreme yaw position is well predicted by the calculation. The calculation is somewhat conservative for output power level at a given wind speed, which is possibly caused by the extreme yaw angle or by error in the assumed alternator efficiency, wind shear or other factors.

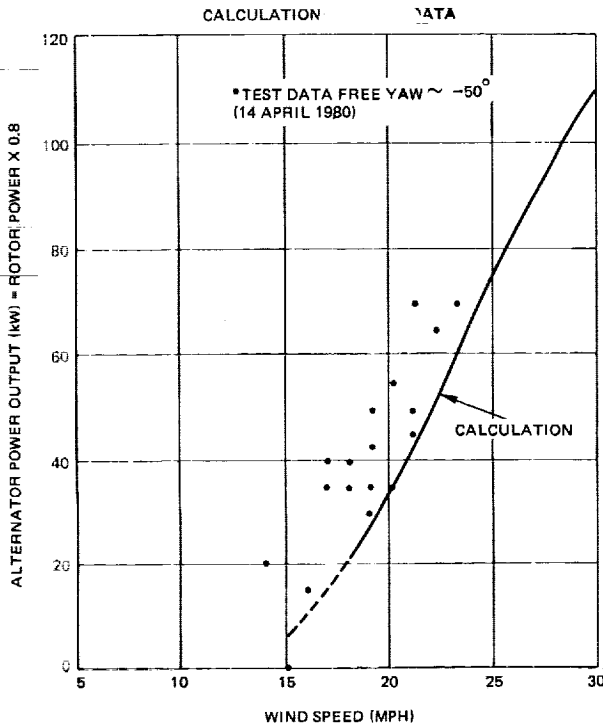


Figure 5 - MOD-0 performance at -50° yaw alignment 0° blade angle - calculations vs. test data

MOD-0 Configuration Studies

It was desired to design a new test configuration for the MOD-0 machine, one that was practical to build and that would provide better yaw behavior than the current design to achieve consistently full rated power. Using the F762 computer code, studies of various MOD-0 configurations were performed to accomplish this by investigating yaw trim behavior as a function of blade twist, coning, Δ_3 , teeter, and other basic parameters.

The effect of introducing aerodynamic blade twist to the MOD-0 base configuration is shown using the yaw trim diagram in Figure 6. The base configuration is the computer code model for the current MOD-0 machine described above at rated wind conditions. The investigated twist distributions are based on the Hamilton Standard twist distribution. The amount of twist at each radial station relative to the reference station (3/4 radius) is multiplied by a constant factor. Multiplying by 1.0 gives the Hamilton Standard twist, see

Table 1, while a zero multiplier gives an untwisted blade. The base configuration has untwisted blades. The yaw behavior for the base case is shown at the far left of Figure 6. The zero twist case will yaw to the -65 degree position and trim (see Figure 3). The MOD-0 with Hamilton Standard aerodynamic twist will trim at -54 degrees yaw. Increasing the twist will cause the MOD-0 to trim closer to the wind.

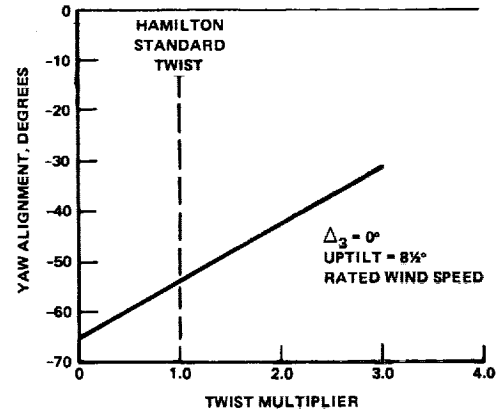


Figure 6 - Effect of twist on MOD-0 yaw trim calculated results, Plumbrook test configuration

Table 1

Hamilton Standard Wind Turbine - Blade Twist

Radial Station	Twist (Degrees)	
0.0203	-12.5	
0.0751	-12.1	
0.146	-11.7	
0.217	-10.2	
0.289	- 7.80	
0.360	- 5.63	
0.431	- 4.14	
0.502	- 2.91	
0.573	- 1.94	
0.644	- 1.02	
0.715	- 0.31	
Reference Station	0.750	0.00
	0.787	0.10
	0.858	0.53
	0.929	0.96
	0.982	1.22

Several configuration changes to the base model, without blade twist, were studied. The effect of coning the blades 6 degrees downwind on yaw trim behavior was examined. Coning the rotor without providing static balance causes the rotor to yaw further from the wind than the base case. Statically balancing the coned rotor, by placing the teeter pin at the rotor center of gravity, decreases the yaw rate somewhat. However, the trend is still to yaw further off wind. Finally, the addition of a 20 degree $\Delta 3$ angle to the teeter pin produces insignificant changes to the yaw behavior. Thus, none of these coning modifications to the base model produced satisfactory yaw behavior.

Since the base model has 8 1/2 degrees of uptilt, there is a significant component of the rotor torque in the yaw moment direction. Therefore, the effect of removing uptilt was examined. The results are shown in Figure 7, where the base case with 8 1/2 degrees of uptilt is shown at the right. The base case without uptilt is shown at the left. By removing the uptilt, the yaw rate is greatly decreased, although a trim position is not found. It was therefore, decided to investigate further modifications with the uptilt removed.

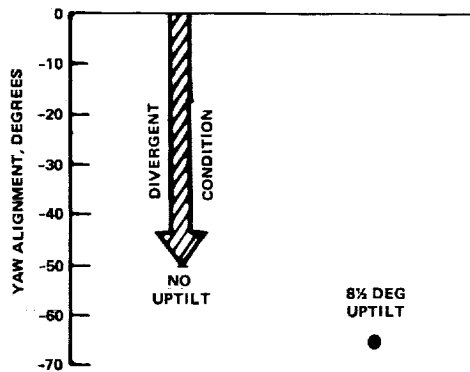


Figure 7 - Effect of uptilt on MOD-0 yaw trim untwisted rotor $\Delta_3 = 0^\circ$ rated wind speed

The effect of tilt removal and rotor static balance on the MOD-0 machine are shown in Figure 8. The configuration is identical to the base case except that the rotor is untilted and coned 6 degrees. The degree of rotor static balance can be varied by moving the teeter pin from the rotor apex to some fraction of the distance to the rotor center of gravity. The distance between the rotor apex and the teeter pin is called hub undersling. For the MOD-0 rotor coned 6 degrees, static balance is achieved with a hub undersling of 27.85 inches. The rotor is called half-balanced if the hub undersling is 13.925 inches.

As shown in Figure 8, there is no improvement in the yaw trim position for the fully statically balanced configuration over the base model. However, the half-balanced configuration shows some promise, trimming at about -45 degrees. The configuration with only 40

percent static balance shows further improvement, trimming at about -28 degrees. With less than 40 percent static balance the trim diverged. For these cases, if the time history is initialized with the rotor in the positive yaw position region, the rotor tends to move further off the wind, not toward the trim position. If the degree of static unbalance is increased, this behavior becomes worse.

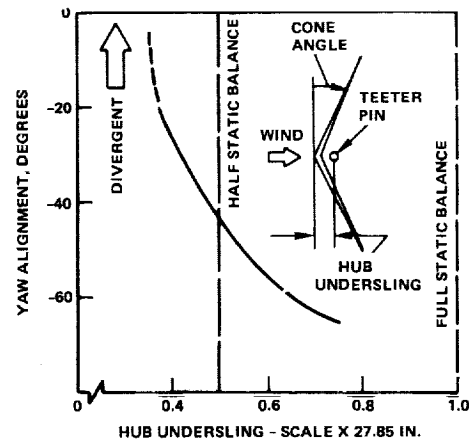


Figure 8 - Effect of rotor static balance on MOD-0 yaw trim, calculated results, untilted, untwisted rotor, $\Delta_3 = 0^\circ$ cone = 6° rated windspeed

It was apparent that a cause of this poor yaw behavior could be improper coning of the rotor blades. Since static balancing of the rotor affects yaw behavior, it seemed reasonable that the unbalancing effect of deflection in the loaded rotor, that is out-of-plane blade root bending, could also effect yaw behavior. Thus, a study was made to determine the cone angle that relieves out-of-plane (flatwise) blade bending moments. Since removing rotor uptilt and introducing blade twist improved the yaw behavior of MOD-0, these features were also included in the next study configuration. The results of the study are shown in Figure 9. The averaged out-of-plane blade root bending moments are plotted vs. rotor cone angle. These cases were statically unbalanced. The flatwise root moment is relieved for a cone angle of about 3.7 degrees, for the rated wind speed and power condition studied. The optimum cone angle would change for another wind speed since the balance of aerodynamic, structural dynamic and gravity forces would be different.

The free yaw behavior of the MOD-0 with optimum coning for rated wind speed was studied for several blade twist distributions. The results are shown in Figure 10. The configuration studied is untilted, with 3.7 degree coning, zero hub undersling and zero $\Delta 3$ angle. The blade twist distributions are multiples of the Hamilton Standard twist distribution. All of the models trim in yaw closer to the wind than the unconed, untilted base configuration. The case with Hamilton Standard twist trims very near the wind. The cases with more twist trim more rapidly. Thus, it seems

that one way to insure rapid yaw trim behavior for the MOD-0 wind turbine is to provide highly twisted blades.

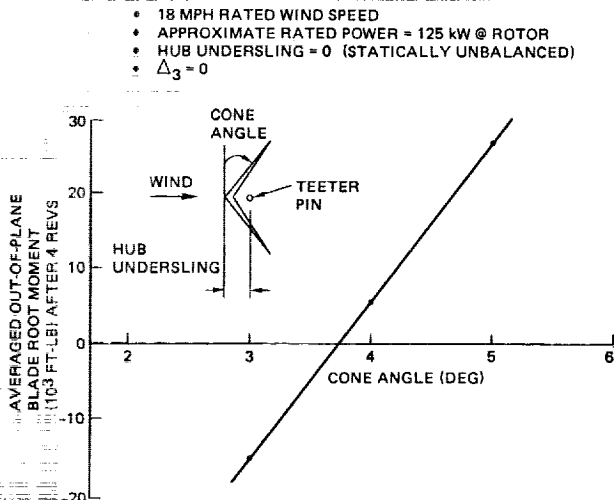


Figure 9 - MOD-0 optimum cone angle downwind untilted rotor with Hamilton Standard blade twist

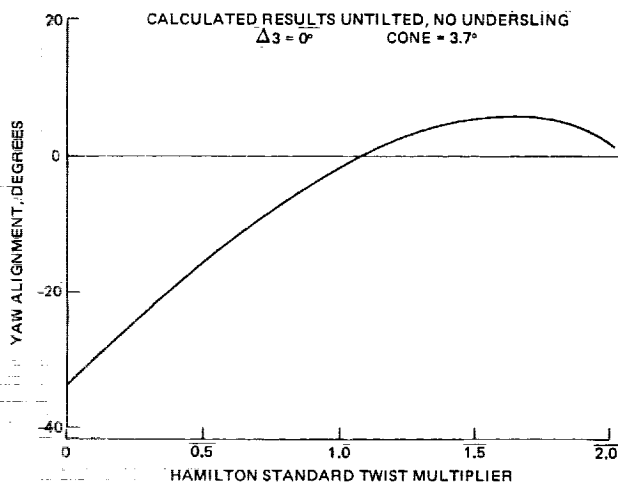


Figure 10 - Effect of twist on optimum MOD-0 yaw trim

Another way to modify yaw behavior is to include a Δ_3 angle at the teeter pin. The effects of varying Δ_3 for the MOD-0 configuration with optimum coning and Hamilton Standard twist are shown in Figure 11. The convention for positive Δ_3 is shown in the diagram. It is also defined as teeter upwind, leading edge downwind. The case with zero Δ_3 is repeated from Figure 10 so that the effects of twist and Δ_3 can be compared. The models with large positive Δ_3 trim in the positive yaw region at about +40 degrees. For negative values of Δ_3 , the trim position moves slightly off the wind.

The effect of wind speed on yaw behavior was examined for the MOD-0 configuration with no tilt, zero hub undersling, optimum coning, zero Δ_3 , and Hamilton Standard twist. Wind velocities higher than rated but less than cut-out were studied. For these conditions, blade angle was set to maintain rated power. The wind velocities were input to the calculation as gust factors, so the wind shear and tower shadow did not change. The higher velocities shift the yaw trim position somewhat, but do not seriously disturb the trim behavior. In addition, studies of yaw behavior using several different wind shear and tower shadow descriptions were made. The effect of these factors on yaw trim behavior is insignificant. Any configuration which is chosen for testing should be investigated for yaw behavior and stability at cut-in and cut-out wind velocities.

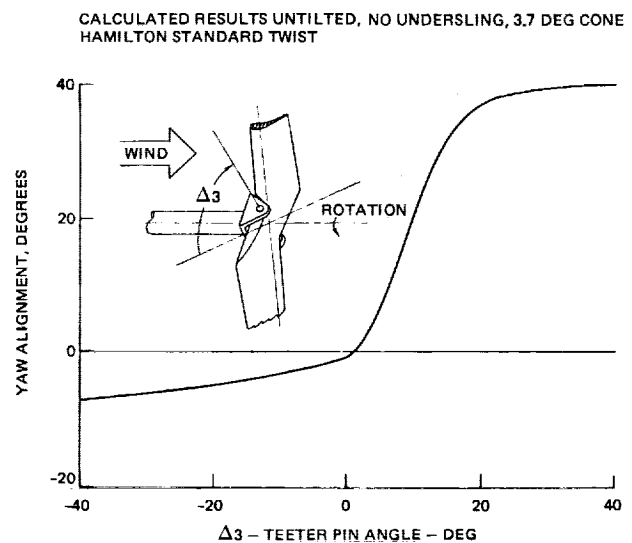


Figure 11 - Effect of Δ_3 on optimum MOD-0 yaw trim

So far, the configurations presented which display satisfactory yaw behavior had blade twist, optimum coning, and static unbalance. The effect of introducing hub undersling at the teeter pin (see Figure 8) was studied next. For a cone angle of 3.7 degrees, the MOD-0 rotor is statically balanced with a hub undersling of 17.2 inches. When this was introduced to the model, it was seen that the yaw trim position shifts significantly off the wind.

The effect of Δ_3 angle on this statically balanced configuration with optimum coning is shown in Figure 12. A positive value for Δ_3 of 30 degrees provides excellent yaw behavior. The yaw trim position is within a few degrees of the wind and the configuration is quite stable. These results show that this type of configuration is successful in providing good yaw trim behavior for free yaw wind turbines.

Finally, the necessity of blade twist for good yaw behavior was confirmed using a MOD-0 configuration identical to that just discussed, but without blade twist. Without twist, yaw trim behavior for this configuration is unstable.

UNTILTED, 3.7 DEG CONE,
UNDERSLING = 17.2 IN.
HAMILTON STANDARD TWIST

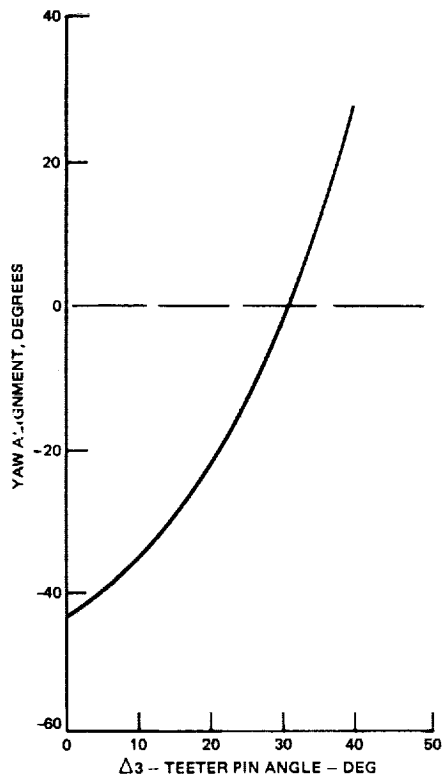


Figure 12 - Effect of $\Delta 3$ on the yaw trim of the MOD-0 balanced rotor

These studies demonstrate that it is possible to modify the MOD-0 to a configuration that balances the forces tending to yaw the rotor off the wind, and so achieve good yaw trim behavior. Essential elements of the design are an untilted rotor, optimum coning and blade twist. The value of $\Delta 3$ needed to insure good trim position with stability varies with the degree of static balance of the rotor.

CONCLUSIONS

The conclusions reached from this study are:

- The F762 computer code model provides a good representation for the behavior of the MOD-0 machine. Specifically, yaw trim behavior, performance at trim position and teeter angle are reasonably well predicted.

- Assuming that undersling is not possible, the modified free yaw MOD-0 configuration should include the following:

- No uptilt, as this will reduce the yawing moment.
- Optimum coning in order to relieve blade root moments and improve trim behavior.
- Blade twist in order to improve trim stability and performance.

Calculations show that this configuration would exhibit a final trim position within a few degrees of the wind direction. It is stable for yaw gusts to at least ± 60 degrees to the rotor shaft. The configuration is also stable for higher than rated wind speed and several different wind shear and tower shadow descriptions.

- In addition to the above factors, the effects of hub undersling (rotor static balance) and $\Delta 3$, and their interrelation were investigated. A stable rotor either with or without hub undersling can be designed. However, the values of $\Delta 3$ needed for each case are different in order to insure good yaw behavior.

Acknowledgement

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REFERENCES

1. Glasgow, J. C. and Miller, D. R., "Teetered, Tip-Controlled Rotor: Preliminary Test Results from MOD-0 100 kW Experimental Wind Turbine"; DOE/NASA/1028-80/26, also NASA TM-81445, 1980.
2. Glasgow, J. C. and Pawlas, G., "Drive Train Efficiency for MOD-0 in Teetered-Hub Tip-Control Rotor Configuration"; NASA-Lewis Research Center - Wind Energy Project Office, Project Information Release No. 137, 1980.

QUESTIONS AND ANSWERS

B. Brooks

From: Anonymous

Q: What is the "Hamilton-Standard" twist?

A: *This is the performance optimized nonlinear twist for the SVU configuration.*

From: W.C. Walton

Q: 1) Please explain the term "six-degree of freedom hub."

2) How is the tower represented in the analysis (1) by modes? (2) directly by finite element model?

A: 1) *Six-degree of freedom is coupling between the rotor and the tower, 3 translations, 3 rotations.*

2) *Indirectly by finite element coupled with the six-degree of freedom hub.*

From: Anonymous

Q: How sensitive is yaw behavior to gust characteristics?

A: *The sensitivity of tested yaw behavior to variations in wind speed are shown in Figure 3. Large changes in wind speed produce small effects. Of course, a good machine will have yaw damping.*

From: Y.Y. Yu

Q: Is F762 code proprietary?

A: *Yes.*

