EFFECTS OF ROTOR LOCATION, CONING, AND TILT ON CRITICAL LOADS IN LARGE WIND TURBINES

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ABSTRACT

Three large (1500 kW) horizontal rotor configurations were analyzed to determine the effects on dynamic loads of upwind and downwind rotor locations, coned and radial blade positions, and tilted and horizontal rotor axis positions. Loads were calculated for a range of wind velocities at three locations in the structure: the blade shank, the hub shaft, and the yaw drive. Blade axis coning and rotor axis tilt were found to have minor effects on loads. However, locating the rotor upwind of the tower significantly reduced loads at all locations analyzed. Details of this study are presented in Reference 1.

INTRODUCTION

Many different rotor configurations have been proposed for large, horizontal-axis wind turbines, and several have been tested for varying periods of time. Generally, these configurations can be classified according to the following six factors:

1. Rotor location with respect to the tower -- upwind/downwind
2. Rotor axis inclination -- level/tilted
3. Blade axis inclination -- coned/radial
4. Number of blades -- two/three or more
5. Blade root attachment -- cantilevered/hinged
6. Blade pitch angle -- variable/fixed

No consensus now exists as to the rotor configuration preferred for generating electricity at low cost with high reliability. A systematic evaluation of all rotor configuration factors is required before such a consensus becomes possible.

The purpose of this study is to evaluate the effect on critical wind turbine loads of the first three factors listed above: rotor location, rotor axis inclination, and blade axis inclination. The remaining factors were fixed as follows: two blades, cantilevered root attachments, and variable pitch angles. An earlier study of this type (Ref. 1) investigated the effects which hinged and cantilevered blade root attachments could have on rotor loads. These studies are based on the assumption that factors which reduce critical loads can also reduce plant costs and increase reliability. In this study as in Reference 2, dynamic blade loads were calculated using the MOSTAB-WT computer code. The accuracy of the load analysis methods used in this study has been verified using actual wind turbine test data (Ref. 3).

ROTOR CONFIGURATIONS ANALYZED

Rotor A in Figure 1 is the baseline configuration to which the other rotors are compared. In Rotor B, blade coning is removed, the blade axes are radial, and the rotor axis is tilted 12^{0} to provide the same tower clearance as Rotor A. The downwind location of the rotor is maintained for Rotor B. Rotor C is the same as Rotor B except that its location is upwind of the tower. In this study critical loads were calculated at the following three locations which are shown in Figure 1: The blade shank, the hub shaft, and the yaw drive.

BLADE SHANK LOADS

The effect of rotor configuration on flatwise moments in the blade shank region is shown in Figure 2. In this figure the cyclic component of flatwise moment is plotted versus the steady component, for various wind speeds. Looking first at the results for Rotor A (the baseline configuration), it can be seen that a significant steady bending moment is present at all wind speeds. Large cyclic and large steady load occur simultaneously at cut-out wind speed in Rotor A.

Turning now to Rotor B, the absence of coning causes the steady moment load to change sign. Cyclic moments are almost unchanged compared to Rotor A because the rotor is still downwind of the tower. Small increases in cyclic aerodynamic load caused by tilting the rotor are offset by decreases in cyclic gravity load obtained by removing coning. In Rotor B, large cyclic moments at cut-out occur simultaneously with small steady moments, unlike Rotor A. Thus, while flatwise moments in Rotor A reach a maximum of 1,740,000 lb-ft at cut-out (cyclic plus steady), the maximum moment in Rotor B is only 816,000 lb-ft at the same wind speed.

For Rotor C, steady loads are approximately the same as for Rotor B, because both have radial blades. However, cyclic flatwise moments are significantly lower in Rotor C bacause of the minimal shadow effect upwind of the tower.

To further simplify the load comparison, the steady moment load can be eliminated by assuming a "constant fatigue life" line as shown in Figure 2. The slope of this line is taken as 0.2. At the cut-out wind speed the equivalent cyclic flatwise moments for Rotors A, B, and C are ± 850,000, ± 670,000, and ± 460,000 pound-feet, respectively. Therefore, changes in rotor configuration can significantly lower flatwise cyclic blade loads.

Table I shows estimates of the edgewise bending moments in the blade shanks for the three rotors studied. Most of the load reduction in Rotors B and C results from the assumed reductions in blade weight. In general, Rotor B edgewise moments were not significantly lower than those in Rotor A, whereas Rotor C moments were reduced 20 to 27 percent.

HUB SHAFT AND YAW DRIVE

Hub shaft bending loads are largest about an axis perpendicular to the rotor and blade axes. Moments about this axis are the sum of the flatwise bending moments at the roots of both blades. Figure 3 shows cycles of hub bending moments $M_{y,h}$ calculated for the three rotor configurations at the cut-out wind speed of 52 mph. The moments for downwind rotors, A and B, exhibit sharp peaks at blade aximuths of 40 and 220 degrees. This is a result of the tower shadow response of each blade. These sharp peaks are absent in the upwind rotor, C. Cyclic moments for Rotors A, B, and C are ± 1,420,000, ± 1,297,000, and ± 805,000 lb-ft, respectively. This, removing coning and tilting the downwind rotors has little effect on hub shaft bending. However, location of the rotor upwind reduces the hub shaft bending loads by 40%.

Figure 4 illustrates the variability which can be present in the torque output of rotors in large wind turbines. The shaft torques produced by Rotors A and B show characteristic troughs which occur each time a blade enters the tower's shadow and loses aerodynamic lift. This produces cyclic torques of ± 114,000 and ± 125,000 lb-ft for Rotors A and B, respectively, at a wind speed of 52 mph. Rotor C produces a much smoother torque, verying only ± 28,800 lb-ft, which is less than ± 10% of the shaft working torque.

Yaw drive torques for the three rotor configurations are shown in Figure 5 for a wind speed of 52 mph. Rotors A and B exhibit similar maximum torques, which are 811,000 and 717,000 lb-ft, respectively. The torque for Rotor C is reduced considerably below these values, to a maximum absolute value of 420,000 lb-ft.

SUMMARY OF RESULTS

A summary of the results of this study is given in Table II. Loads for Rotor B do not differ significantly from those for Rotor A except in flatwise bending in the blade shank. The maximum flatwise bending load which occurs in Rotor B at a wind speed of 29 mph is almost 30 percent less than the maximum for Rotor A which occurs at a wind speed of 52 mph. This indicates that the 12^0 cone angle in Rotor A is excessive, since it increases rather than decreases the maximum flatwise moment present in Rotor B with radial (unconed) blades.

The cyclic flatwise moment in Rotor B is approximately 20% less than than for Rotor A. This is primarily the result of adjusting the actual cyclic moments to account for steady moments. The actual cyclic moments are approximately equal for the two rotors.

As shown in Table II, all loads in Rotor C were significantly less than equivalent loads in Rotor A. This can be attributed primarily to the upwind rotor location for Rotor C. Blade shank bending loads were reduced by 25 to almost 50 percent. Hub shaft bending moments were reduced almost 40 percent. Of particular importance is the reduction in cyclic hub torque. Cyclic torques in Rotor C were only one-fourth those in Rotor A at a wind speed of 52 mph. Moreover, at the rated wind speed of 29 mph this ratio was only one-eighth. Yaw drive torques for Rotor C were 30% to 40% less than those for Rotor A.

CONCLUSIONS

1. Coning and tilt have little effect on critical loads in either the blades, the hub, or the yaw drive, provided the angles are not excessive.

2. Coning of blades to reduce loads is unnecessary, though coning might be used to provide tower clearance for a downwind rotor.

3. Rotor location (upwind or downwind of the tower) has a significant effect on blade, hub, and yaw drive loads for rotors with cantilever blade attachments.

4. Locating the rotor upwind of the tower can reduce cyclic shaft torques by 75% to 90% and other critical moment loads by 25% to almost 50%, compared with a downwind rotor location. Thus, an upwind rotor location is potentially very advantageous in terms of both reliability and cost.

REFERENCES

1. Spera, D. A., and Janetzke, D. C.: Effects of Rotor Locating, Coning, and Tilt on Critical Loads in Large Wind Turbines. Wind Technology Journal, Vol. 1, No. 2, 1977, pp. 5-10.

2. Spera, D. A.: Structural Analysis of Wind Turbine Rotors for NSF-NASA Mod-0 Wind Power System. NASA TM X-3198, 1975.

3. Spera, D. A.; Janetzke, D. C.; and Richards, T. R.: Dynamic Blade Loading in the ERDA-NASA 100 kW and 200 kW Wind Turbines. Presented at American Wind Energy Spring Conference, 1977. (To be published.)

DISCUSSION

Q. What confidence do you place in these results, considering the fact that they were obtained with MOSTAB-WT which has only one degree of freedom?

A. We consider MOSTAB-WT and -WTE to be excellent tools for "back-to-back" comparisons in which parameters are varied but the general system remains constant. This is the case here.

Q. Have you looked at blade loads near eight-tenths span?

A. Yes. Loads outboard follow the same trend as the shank loads reported here.

Q. Was a spring constant used in your calculations to represent the drive train?

A. No. MOSTAB-WT enforces a constant shaft speed, which is equivalent to a drive train with infinite impedance.

Q. Was a tower shadow effect used for the upwind rotor?

A. Yes. A truss tower was assumed in which the upwind shadow was 10% of the downwind shadow.

Q. If you could take out the first harmonic of the tower shadow effect, how would the upwind versus downwind comparison look?

A. The load most directly affected would be cyclic flatwise bending of the blades. The difference in this load between the upwind and the downwind configurations would be reduced about 50%.

TABLE I. - ESTIMATES OF EDGEWISE BENDING LOADS IN BLADE SHANKS

[Nominal wind speed, 52 mph; power, 1500 kW.]

Rotor	Blade Weight, lb	Shank edgewise moment, $M_{z,b}$, lb-ft				
		Cyclic, $\delta M_{z,b}$			Steady, $\overline{M}_{z,b}$	Max
		Gravity	Coupled[a]	Total		
A	12,000	260,000	158,000	418,000	175,000	593,000
B	10,700	232,000	156,000	388,000	175,000	563,000
C	9,300	201,000	96,000	297,000	175,000	472,000

(a) 25% of cyclic flatwise moment

TABLE II. - RATIO OF MOMENT LOADS IN ROTORS B AND C TO LOADS IN ROTOR A

[Nominal wind speed, 52 mph; power, 1500 kW.]

Moment Load, M		M_B/M_A		M_C/M_A	
		Max	Cyclic[a]	Max	Cyclic[a]
Blade shank bending	Flatwise	0.73[b]	0.79	0.75[b]	0.54
	Edgewise	0.95	0.93	0.80	0.73
Hub shaft	Bending	0.91	0.91	0.57	0.57
	Torque	1.14	1.10	0.97	0.25[c]
Yaw drive torque		1.13	1.00	0.58	0.71

(a) Adjusted to zero steady load, except hub torque

(b) Max at V_0 = mph for rotors B and C

(c) 0.12 for V_0 = 29 mph

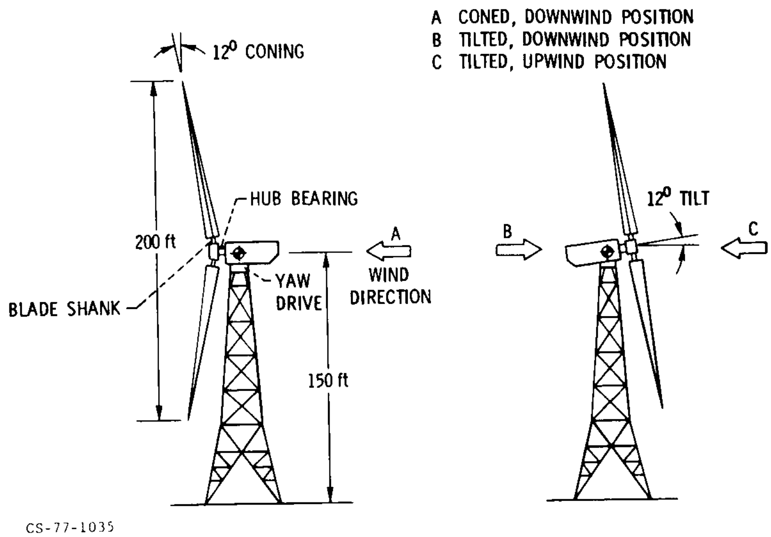

Figure 1. - Rotor configurations analyzed, which are designed to produce 1500 kW at a nominal wind speed of 29 mph.

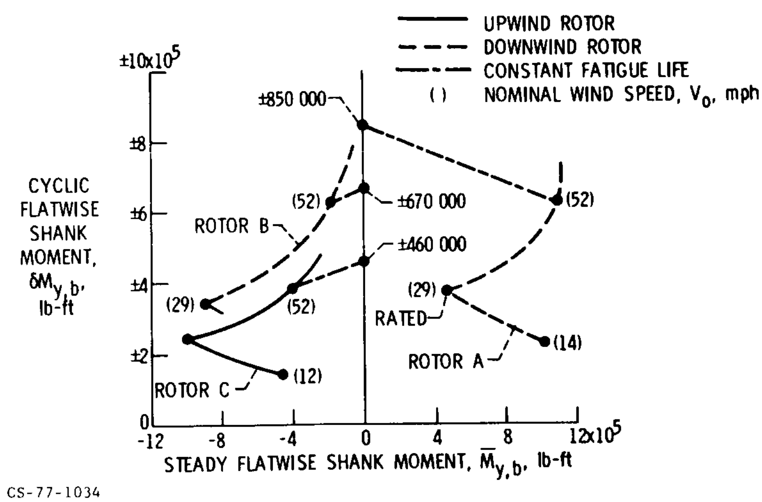

Figure 2. - Calculated variation of flatwise blade shank loads with wind speed and rotor configuration (blades pitched for rated power, V_0 > 29 mph).

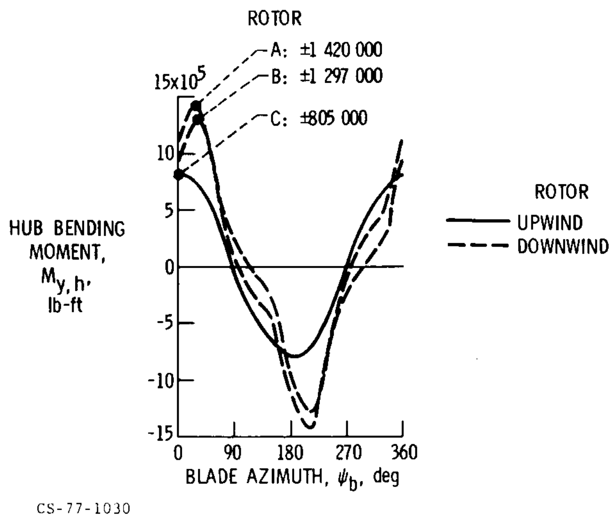

Figure 3. - Calculated variation of hub bending moment with blade azimuth and rotor configuration (wind speed, 52 mph; power, 1500 kW).

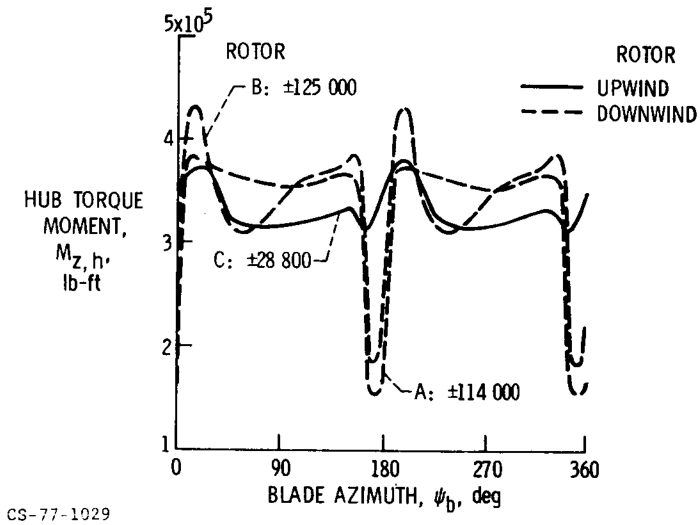

Figure 4. - Calculated variation of hub torque with blade azimuth and rotor configuration (wind speed, 52 mph; power, 1500 kW).

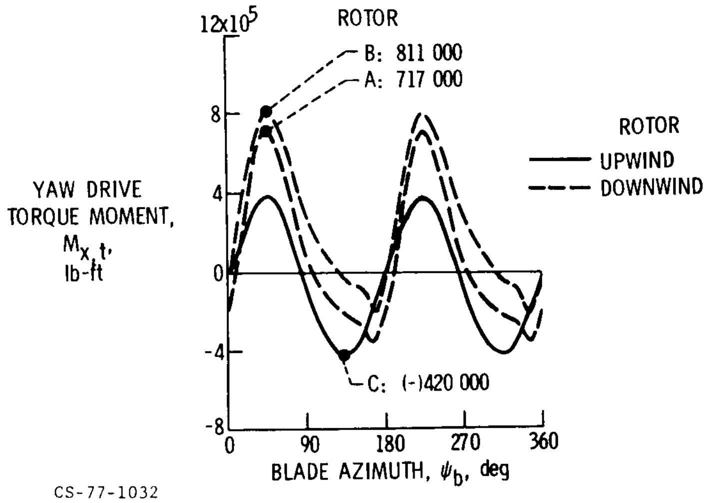

Figure 5. - Calculated variation of yaw drive torque with blade azimuth and rotor configuration (wind speed, 52 mph; power, 1500 kW).