COMPARISON OF BLADE LOADS OF FIXED AND FREE YAWING WIND TURBINES

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ABSTRACT

The UTRC Self Regulating Composite Bearingless Wind Turbine utilizes an automatic pitch control concept and a completely unrestrained yawing degree of freedom. Aerodynamic moments caused by skewed flow provide the control to align the wind turbine with the wind. Model tests have demonstrated the feasibility of the concept and analytical studies have shown the free system to experience lower blade loads compared to the fixed system.

INTRODUCTION

Many of the early windmills were free in yaw and were controlled through an aerodynamic vane or "rudder". These rudders not only directed the rotor into the wind but also served to shut the system down when they were positioned in the same plane as the rotor. The concept was simple and it worked. Modern wind turbines, many times more efficient than their ancestors, have often been designed to be fixed in yaw and mechanically controlled when realignment is required. The purpose of this paper is to make a brief comparison of the blade loads in free and fixed modes of operation for the wind turbine developed by the United Technologies Research Center (UTRC). This wind energy system has been developed under two ERDA contracts, Refs. 1 and 2, and will continue under a recently awarded contract from Rockwell International.

Analytical Results

The moments experienced by a wind turbine, in addition to those related to gravity, are primarily aerodynamic and gyroscopic. Ignoring the effects of wind shear and coning, aerodynamic moments can only originate from nonaxial wind velocities. Under such conditions there exist advancing and retreating blades which produce different lifts resulting in a steady rotor moment. Figure 1 is a schematic of a wind turbine showing the moments experienced when the wind velocity is skewed by an angle, ψ, and the turbine is yawing at a rate, $\dot{\phi}$. Using the right hand rule, the moments are depicted by the vectors M_A and M_G, where the subscripts denote aerodynamic and gyroscopic. When a yaw rate is imposed by an external agent, such as a yaw motor, it produces the following gyroscopic moment:

$$M_G = I\Omega\dot{\phi}$$

where I is the moment of inertia of the rotor and Ω is the rotational speed. The aerodynamic moment can be approximated by the following equation:

$$M_A = KV_w^2 \sin \psi$$

where K is a constant containing blade area, radius, and air density. The total rotor moment is then:

$$M_R = M_G - M_A = I\Omega\dot{\phi} - KV_w^2 \sin \psi$$

Under conditions when V_w is small and the system is being mechanically yawed, the moment reduces to:

$$M_R = I\Omega\dot{\phi}$$

For the free system, the initial rotor moment resulting from the skewed flow is only the aerodynamic moment.

$$M_{RO} = M_A$$

The system responds to this moment and yaws at a rate proportional to this moment,

$$\dot{\phi} = \frac{M_A}{I\Omega} \text{ or } M_A = I\Omega\dot{\phi}$$

however the gyroscopic moment produced by this yaw rate is, as before:

$$M_G = I\Omega\dot{\phi}$$

Thus, $$M_R = M_G - M_A = 0$$

The resulting rotor moment is therefore always eliminated under steady yawing conditions for the free yawing system. The system requiring imposed yaw would always experience moments except at the one time during the maneuver when the gyroscopic moment equals the aerodynamic moment.

The UTRC F762 computer program was used to compare blade stresses under various yaw conditions at a wind speed of 22 mph. The F762 program is a multiblade, movable hub aeroelastic analysis which models general wind turbine configurations and in particular the UTRC wind turbine concept. Three conditions were investigated at a wind speed of 22 mph with an initial wind direction of 30 deg off axis. The cases were: a fixed system without a yaw degree of freedom, a free yaw system, and finally the case where a prescribed yaw rate is imposed externally. The results of these computer runs are presented in Figs. 2 to 4. Figures 2 and 3 show the flatwise and edgewise stresses for the fixed and free yawing systems. The stresses are shown to be generally lower by a factor of 1/2 for the free system. The vibratory stresses in the free yaw case would eventually go to zero as the system aligns with the wind. This would occur in this case in approximately 5 seconds.

The stress characteristics for the condition where a prescribed yaw rate is imposed on the rotor are shown in Fig. 4. The large 1P stress is attributed primarily to the gyroscopic moment which exists as long as the yaw rate is maintained.

Experimental Results

Tests conducted under an ERDA contract, Ref. 1, included conditions where a model wind turbine was allowed to yaw freely under the influence of a skewed wind velocity. The model had blades with relatively low flatwise stiffness in comparison to other blades, such as the Mod 0 blades. Sample results of these experiments are shown in Fig. 5 where the yaw angle and blade stress time histories are presented following the release of a wind tunnel model from a preset angle of -30 deg. Initial vibratory stresses are high due to the aerodynamic moment created by the skewed flow, however the stresses are quickly reduced as the rotor responds. The final yaw angle and resulting stresses are due to the tower shadow.

CONCLUSIONS

1. A free yawing wind turbine does not generate large unbalanced gyroscopic and/or aerodynamic moments as compared to a wind turbine fixed in yaw or having a fixed yaw rate.

2. A free yawing wind turbine having relatively low flatwise stiffness blades inherently adjusts to wind direction changes.

REFERENCES

1. Cheney, M. C. and P. A. M. Spierings: Self Regulating Composite Bearingless Wind Turbine. ERDA Report COO/2614-76/1, Sept. 1976.

2. Spierings, P. A. M. and M. C. Cheney: Design of a Self-Regulating Composite Bearingless Wind Turbine. ERDA Report COO/4150-77/8, August 1977 (to be published).

<u>DISCUSSSION</u>

Q. How would a free-yaw system respond to a wind direction changing $\pm$ 20 degrees, as has been observed at Plum Brook?

A. A free yawing system will continue to try to correct for wind direction changes, however the rate of correction is inversely proportional to the rotor inertia and rotational speed which would result in a lag. If the wind direction is continuously changing from + 20 deg to - 20 deg then the turbine would oscillate at some lower angle however I wouldn't expect the power output to be very much affected.

Q. In the rotor start up mode, when the nacelle was at large yaw angle did you notice any instabilities such as those mentioned by K. Hohenemser - i.e. any tendency to yaw toward the upwind direction?

A. We noticed no such instability when starting from zero rpm at any yaw angle. We did see a tendency for the 4-bladed fixed pitch system to oscillate about a yaw angle of about 45 deg if the turbine was manually positioned at that angle while rotating. However, recent tests with a 2-bladed rotor, using the UTRC pendulum control concept, showed no tendency for the rotor to experience this type of yaw instability.

Q. Since your wind tunnel model was operated at nearly zero torque (i.e. freewheeling) your induced velocity profile may not be representative of a loaded wind generator (i.e. way down into windmill brake). Do you have plans to extract power and to assess the effect of α distribution when loaded?

A. Our model was not operated at zero torque at all conditions. We extracted power for a limited number of runs but the purpose of the test was to explore the dynamic characteristics of the pendulum control system and this could be done most cost effectively by eliminating the power aspect. Also, friction losses were relatively high since the alternator was excessively large for this size model.

Induced velocity is not directly dependent on power extraction. The induced velocity is only a function of the circulation of the bound vorticity on the blade and the shed vorticity in the wake. The vorticity in turn is a function of the blade geometry, tip speed, airfoil characteristics, and wind speed.

We are not planning additional model tests for the purpose of measuring performance, however our performance analysis which we use to predict power characteristics simulates the vorticity and the resulting induced velocity to a high degree of accuracy under all loading conditions.

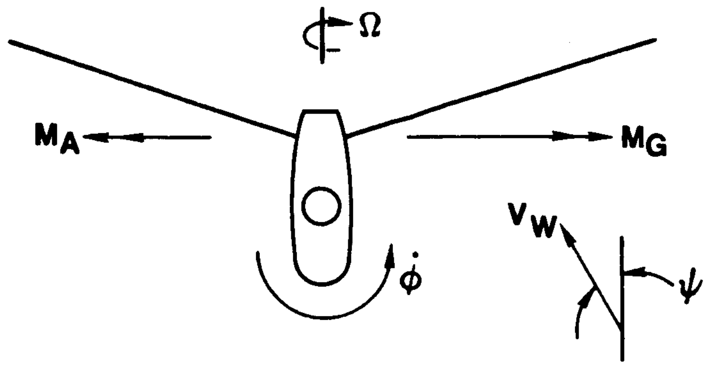

Figure 1. - Schematic of wind turbine yaw moments.

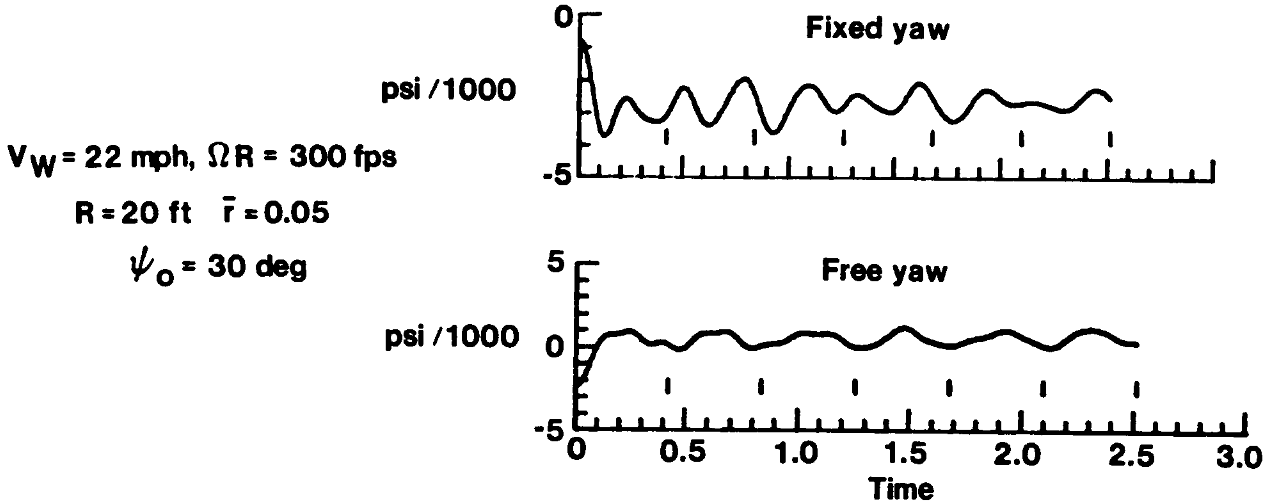

Figure 2. - Blade flatwise stress comparison.

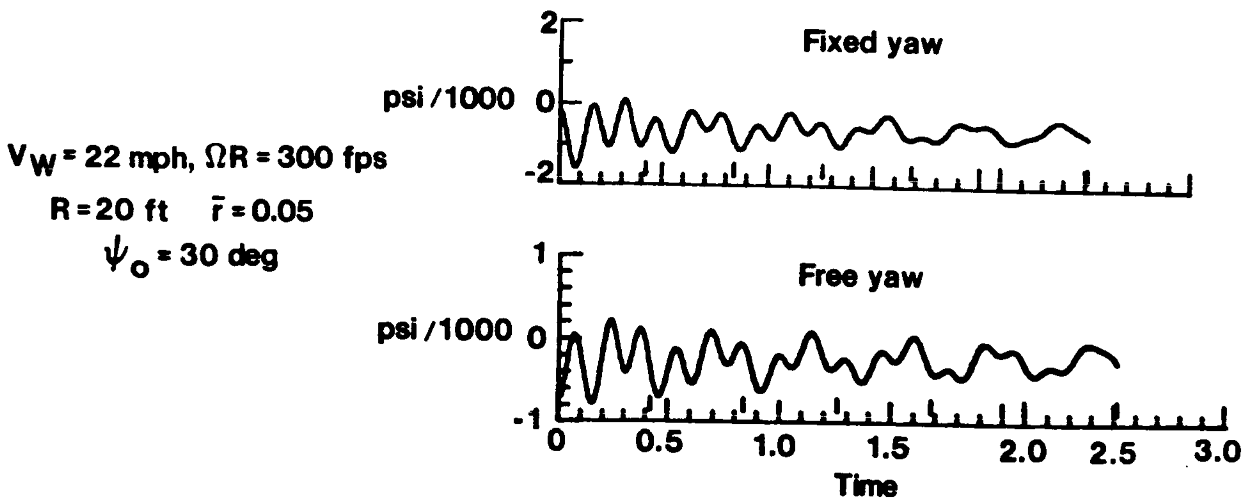

Figure 3. - Blade edgewise stress comparison.

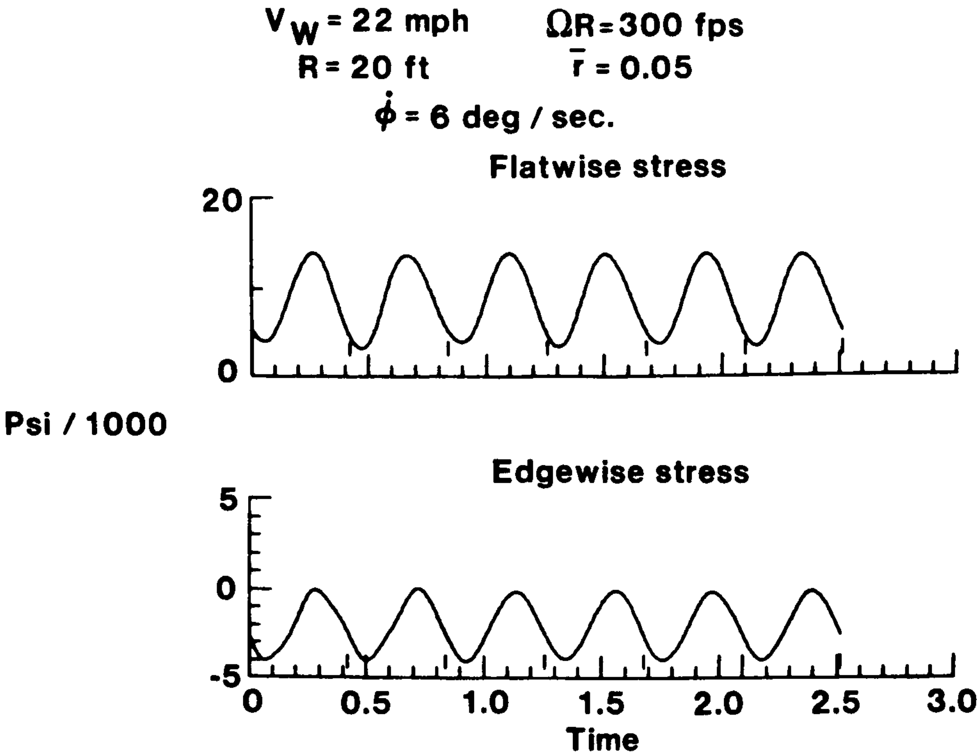

Figure 4. - Stress characteristics for imposed yaw rate.

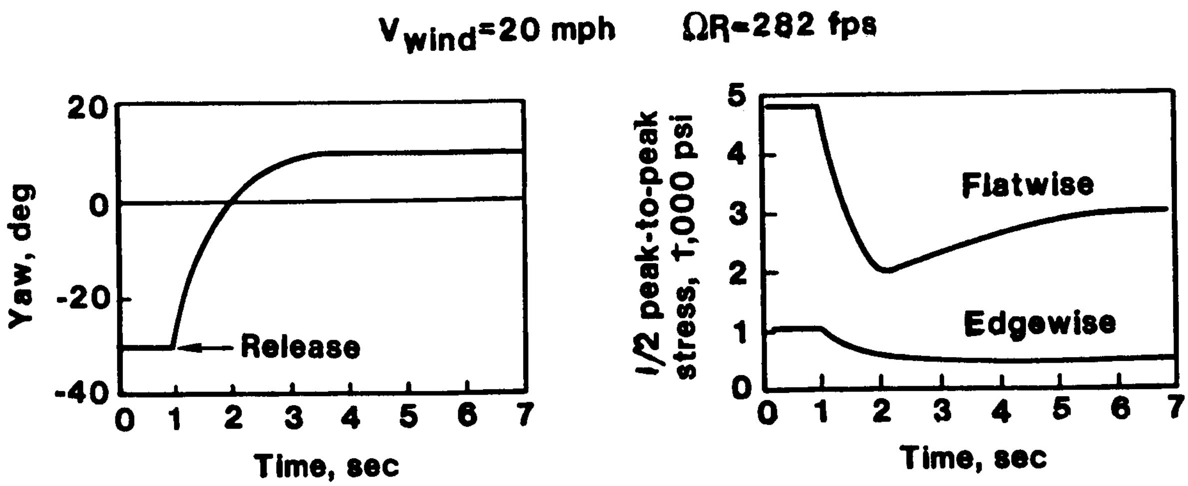

Figure 5. - Model experimental results.