NORTH WIND 4KW 'PASSIVE' CONTROL SYSTEM DESIGN

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An overview of a mechanical rotor control design is presented. Operation at constant RPM and rapid response are obtained by using blade pitch moments for both sensor and blade pitch actuation. The basic concept, static or equilibrium design, and dynamic analysis are briefly presented.

INTRODUCTION

The control system described here is part of a SWECG design done for North Wind Power Co., under a Rockwell/DOE contract. The machine, as now configured, is a 10 meter, down wind, HAWT rated at 4kW 8 m/s. It is a line interface unit using a direct drive synchronous alternator. The rotor is a two blade, teetering system with delta three and uses solid laminated wood blades. The system is free yawing on a suced wooden pole tower.

The rotor control is an all mechanical system which responds to blade aerodynamic loads and RPM. Power and load control is accomplished through blade pitchings in the direction of Feather with shut down being Full Feather. Starting comes from an inboard blade twist.

CONCEPT

The control system concept is to change blade pitch angle in response to blade pitch moment. The blades are then sensors transmitting control information, and also supplying control actuation forces via blade pitch moment. Pitch moment, through placement of the pitch axis, is made sensitive to aerodynamic and centrifugal forces. This control can thus be used with a rotor operating at constant, synchronous, RPM while still providing protection against overspeed conditions.

Figure 1 shows the pitch axis placement at one radial station. Aerodynamic Lift, the Predominant blade force, will create a pitching moment through offset Xa. Equilibrium is obtained by applying the control moment Mc. For a given wind speed there is one equilibrium pitch angle C. For example, assume B is increased from an equilibrium position, then the airfoil angle of attack will decrease, reducing the coefficient of Lift and thus Lift Force. The aerodynamic moment is now less than the control moment which actuates a blade pitch, decreasing B, until equilibrium is again reached. This aerodynamic restoring force maintains equilibrium.

For constant RPM operation a change in wind speed will move the system to a new equilibrium pitch angle. The predominant effect of an increase in wind speed is an increase in angle of attack which increases the lift coefficient and Lift Force. This difference between aerodynamic and control moments will tend to increase the pitch angle until a new equilibrium point is reached.

The control moment Mc is a function of pitch angle and will determine the equilibrium pitch angle at each wind speed. The rotor power output, being dependant on wind speed and pitch angle, is determined by this Mc Function.

Figure 1 also shows the blade center of gravity offset from the rotor axis. This gives a positive (+B) pitching moment due to rotor angular velocity which results in sensitivity to rotor overspeed.

STATIC DESIGN

Static Design of this control system involves a trade-off between rotor geometry, control moment characteristics, desired power curve, and results of unloaded equilibrium overspeed. Figure 2 represents the final geometric layout of the rotor.

To evaluate this analytically a Blade Element Theory for aerodynamic forces (ref 1) is combined with a simple rigid body model for rotational effects. A plot for constant rotor RPM is given in Figure 3. Here the pitch moment, or equilibrium control moment, is given as a function of pitch angle for constant wind speeds and rotor power outputs. Figure 4 presents the same type of plot for zero power output, representing the unloaded control response.

Equilibrium performance is determined by these plots. With control moment given as a function of pitch angle the resulting power, unloaded RPM, and blade pitch are defined as functions of wind speed. Assumed control moment curves are presented in Figures 3 and 4 as dotted lines.

Trade-offs to obtain desirable static performance characteristics involve adjusting rotor geometry, control moment function, and associated structure. Since these involve constraints such as manufacturability and conceptual design they don't lead to explicit evaluation.

AEROSTATIC

The torsional stiffness of this blade-hub system is inherently very low being predominantly from the aerodynamic restoring force mentioned earlier. Because of this the rotor is susceptible to aerostatic instabilities.

Modes which involve in-plane motions shouldn't be excited due to the high natural frequencies in this degree of Freedom. Following this reasoning, problems of ground resonance and whirl modes aren't anticipated. A teetering system with free yaw is not prone to these problems (ref 2).
This leaves pitch/flap instabilities which are of concern. These involve the rotor mode shapes and noting pitch deflections are concentrated at the pitch axis a single blade analysis can be justified.

Out-of-plane vibration modes can be classified into two groups as either involving or not involving teeter. Figure 5 shows the first four out-of-plane mode shapes for a teetering rotor. The first and third (5a, 5c) involve a teetering motion with the flap deflections of each blade opposite. Conversely, the second and third (5b, 5d) involve no teetering deflection and have identical flap deflections. Control pitch deflections, due to mechanical requirements of the pitch linkages, change the pitch angles of each blade by the same amount.

Pitch/Flap instabilities involve an aerodynamic coupling of the above control pitch and out-of-plane deflections. The above then would require instabilities involving teeter motion to have a different mode shape for each blade. A 180 degree phase shift in pitch/flap deflections would have to occur. For this reason instabilities which involve a teetering motion are not anticipated. Other pitch/flap instabilities which involve cantilever deflections are however possible.

Note that pitch deflections due to a delta 3 angle, being directly coupled to teeter motions, are not independant degrees of freedom. This delta 3 effect will further stabilize modes which involve teeter motions (ref 3,4).

Three simple analytic models have been used to investigate pitch/flap aeroelastic stability. All involve rigid body, equivalent hinge representations. The first being a "classic" form derived from the helicopter industry. It incorporates Quasi-Steady, Theodorsen, aerodynamics with constant chord and twist (ref 5a). The second uses the same formulation but assumes steady state aerodynamics. Figure 6 shows a representation of the first two models. The third model uses steady state aerodynamics but includes several geometric improvements over the first two. It includes twist and taper along with hinge offsets to better approximate geometric control characteristics. This model was derived for time domain investigations of control response. Figure 7 represents this model.

Each of these analytic models can be presented in matrix form as:

\[
\begin{bmatrix}
\frac{M'_0}{M_0} & 1 \\
\frac{M'_1}{M_1} & \frac{M'_2}{M_2}
\end{bmatrix}
\begin{bmatrix}
M_0 & M_1 & M_2 \\
M_1 & M_2 & 0
\end{bmatrix}
\begin{bmatrix}
ym_0 \\
y_1 \\
y_2
\end{bmatrix}
\begin{bmatrix}
\dot{\theta} \\
\dot{\theta}_1 \\
\dot{\theta}_2
\end{bmatrix}
\]

The stability derivatives, here the matrix elements, are given in Table 1 for each of the theoretical models. A numerical eigen value approach was used to solve the unformed equations for stability information.

A pitch/flap instability was predicted in each case. An attempt has been made to understand the parameters involved with this instability and eliminate it. In doing so some understanding of the system and the models used has been gained.

Various parameters were changed to determine which have a significant effect on this instability. This resulted in three parameters being flap natural frequency, RPM, and pitch damping. RPM is determined by the static design and was kept as small as reasonable. This leaves flap natural frequency and pitch damper for adjustment. Figure 8 shows stability plots for each of the three analytical models. These are calculated for running RPM and show flap natural frequency versus pitch damper. The three agree in general, predicting the instability, but differ quantitatively.

The flap natural frequency can be adjusted but, without a change in blade structure, this parameter can not be varied enough to stabilize the system. Since pitch deflections are concentrated at the pitch axis damps can be added. This solution was adopted although a damper, being mechanical, can fail and allow the system to become unstable. A vibration shut down is required. For reliability, dampers are placed at the pitch shaft to avoid linkages and fatigue. Although having a minimal impact, pitch dampers slow system response.

Some insight can be gained about the three analytical models from the stability plots in Figure 8. Note that the first two models compare well with the only difference due to aerodynamics. The similarity of these plots may be misleading due to the very low torsional stiffness which tends to slow the motions and minimize the differences between steady and Quasi-steady aerodynamics. The steady state assumption is the more conservative. The third model is considerably less stable than the first two. The modeling differences between these are the control offsets, taper, twist, and sweep but it is not known how much effect each has.

DYNAMIC RESPONSE

To assess dynamic control response the third model with its forcing function was solved in the time domain. A numerical solution was used to analytically model several wind mast cases.

Figure 9 shows pitch and flap response for a wind gust of 8 to 24 m/s in one second. This is felt to be an extreme gust which would be rarely encountered. The control system is responding within 1/4 second and the greatest out-of-plane load, corresponding to the greatest flap deflection, occurs at 1/2 second. This response is fast enough to relieve major blade loads. The largest out-of-plane load encountered is near one fourth the worst case load coming from high wind shut down conditions.

The rapid response is inherent with this control system. Translating blade loads into a control pitch involves only the pitch inertia.
Most control systems sense a condition, such as an RPM change, which involves a much lower inertia. Pitch damming, added for aerelastic stability, slows response time but is a minor effect. The plot presented in Figure 9 includes this damming.

CONCLUSIONS

Analysis of the control system is complex but results in a relatively simple mechanical system with control response rapid enough to relieve gusts. This complexity is due to the interdependence of rotor geometry, system loads, dynamic response and aerelastic stability.

The simple aerelastic models used are not in close agreement. These simple models are important in SWECS design where large computer codes are usually not cost effective. Investigations to determine the critical parameters in these models, and correlate results with test data, or the large computer codes (ref 7), would be useful.

ACKNOWLEDGEMENT

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REFERENCES


** "Development of a 4NH SWECS", North Wind Power Company, Rockwell/DDE contract #PF88501C. (Forthcoming Design Reports for further information).

NOMENCLATURE

\(a\) - lift curve slope  
\(c\) - chord  
\(C_l\) - coeff. of lift  
\(d\) - offset (fig 2)  
\(q\) - offset (fig 2)  
\(I\) - \(I_{\alpha}\)  
\(I_{\alpha}\) - flap moment of inertia  
\(I_{\alpha}\) - pitch moment of inertia  
\(I_\alpha\) - cross product of inertia  
\(r\) - blade mass  
\(R\) - local radius  
\(R_{\alpha}\) - inner blade radius  
\(q\) - OS radius  
\(V\) - wind wind velocity  
\(\bar{V}\) - equilibrium wind velocity  
\(\alpha\) - flap angle  
\(\beta\) - equilibrium pitch angle  
\(\gamma\) - air density  
\(\gamma_\alpha\) - quarter chord/plus, axis  
\(\gamma_\beta\) - quarter chord/minus, axis  
\(\Delta\) - rotor angular velocity  
\(\omega_{i}\) - pitch natural frequency  
\(\omega_{\alpha}\) - flap natural frequency

FIGURE 1 - CONTROL CONCEPT

FIGURE 2 - ROTOR LAYOUT

FIGURE 5 - TEETER MODES
QUESTIONS AND ANSWERS

H. Currin

From: T.A. Egolf

Q: How does the nonlinearity of the actual unsteady lift response to rapid high angle of attack variations affect the control system response?

A: Response should be rapid enough to avoid stall with any "real world" gust (an advantage of this control). Dynamic stall, if encountered, initially increasing lift would increase pitch response. Without stall, I'd guess unsteady aero would slow response.