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Literature Survey of Wind Turbine Aeroelastic Stability

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A literature survey of wind turbine aeroelastic stability is presented. The subject received early interest as the emergent wind industry looked to lessons from the helicopter industry. There has not been a utility-scale turbine with flutter problems, but there is a concern over the behavior of larger, more flexible turbines. Blades of innovative design with bend-twist coupling and tip sweep are also a concern. Much of the aerodynamic modeling was formulated in the 1930s by Theodorsen. Modern authors have developed finite element structural models for eigenvalue solutions to the stability models. Calculations for a 1.5 MW turbine blade with bend-twist coupling show flutter speed at twice the rotor rotational speed. Comparisons were made to standard turbine aeroelastic codes showing good agreement, and the possibility of using these codes to check for flutter.

I. Introduction

A former boss of mine once stated that a wind turbine was "…an odd assemblage of parts designed to maximize fatigue." Both of us came from helicopter research and we were well aware of the quirks of rotorcraft. Many from the helicopter research community and industry worked on early analysis of wind turbine problems and the rotor stability problem was a focus due to its importance for helicopters.

A wind turbine is an assembly of flexible elements. Some important ones are the blades, the drivetrain, the tower, and even the foundation. Due to rotation, the blades are acted upon by gravity once per cycle. The aerodynamic loads, which allow the turbine to generate power, can be both unsteady and periodic. In elementary mechanics we learn that a simple harmonic oscillator achieves a resonant condition when the loading frequency coalesces with the system natural frequency. The multiple degree-of-freedom wind turbine has plenty of opportunity to operate in a resonant and potentially unstable condition.

Concerns of aeroelastic stability in the industry are reflected in the literature. Eggleston and Stoddard (1987) devote an entire chapter to the subject in their book on wind turbine design. Review of the ASME Wind Energy conference proceedings show a dearth in the subject from 1988 to 1999. This is probably due to the problem not surfacing in the industry. The comprehensive Wind Energy Handbook (Burton, Sharpe et al. 2001) devotes less than one page to the subject of aeroelastic stability. Its statement on the subject is reproduced here:

> *"During the development of some of the early large machines, the dangers of aeroelastic instability were considered to be a real concern, and much analysis work was directed to demonstrating that individual turbine designs would not be susceptible to it. However, partly no doubt because of the high torsional rigidity of the closed cell hollow structure adopted for most wind turbine blades, aeroelastic instability has not yet been found to be critical in practice, and stability analyses are no longer regarded as an essential part of the design process. This may change, however, if designs become more flexible."*

The problem of stability is difficult to describe and to predict. One problem is that the detailed structural properties required for the analysis are usually not known until the machine is in production. At this point in the development, a serious stability problem would be difficult to remedy. The author is unaware of any serious stability problems, such as flutter, in utility-scale turbines that have resulted in catastrophic failure. There have been edgewise resonant problems in stall-control machines, which in some designs have been solved with the addition of blade dampers.

The author does have experience with a flutter problem on a prototype small-turbine (Larwood 2001). With the generator off and the turbine unloaded, the rotor would achieve a speed where flutter could be heard emanating from the blade tips. The rotor speed would fall dramatically and then the cycle would repeat itself. An interesting study would be to use the methods outlined in the current research to predict this behavior.

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The impetus behind this literature survey was to develop background material for studying the stability of a swept-blade wind turbine design. Background information on the subject can be found in a report by Zuteck (2002). This blade is being developed under a Low Wind Speed Turbine (LWST) contract with Sandia National Labs. The goal of the blade design is to grow the rotor diameter and maintain loads. With tip sweep the blade theoretically will passively unload with increasing wind speed. Torsional stiffness will be reduced to facilitate this action. Due to the uniqueness of the blade, there is a concern that the design could exhibit instabilities.

The current literature survey was limited to the wind energy books in the author's library and to the ASME Wind Energy Conference Proceedings. Some papers on the subject might have been missed if their titles did not include the subject of stability. Some papers were found to deal with a pure structural instability, for instance Pavel (2000). A more complete study should involve reviewing the American, British, and European Wind Energy Associations Conference Proceedings for papers on the subject.

In studying the problem, I became to appreciate its difficulty. Even for simple models authors have presented several pages of derivations for the equations of motion. I would hope that the reader would not expect me to be able to perform a stability analysis as the result of undertaking this survey; only what approach should be taken for our unique problem.

II. Studies of Wind Turbine Instabilities

Instabilities in wind turbines are studied through the coupling between the degrees of freedom. Including all the coupling effects can be difficult. The choice of particular coupling effects to study had been dependent on observed instabilities and vibration in helicopter rotors. Nearly all modern wind turbines are analogous to the hingeless helicopter design, where the blade rotates as a unit at the pitch bearing for pitch changes and is flexible in flap, edge, and pitch. Differences arise between wind turbines and helicopters in blade planform; there is more solidity and twist in wind turbine blades. However there are similarities in twist and planform to tilt-rotor blades. Further study could be made in researching stability problems in tilt-rotors that would be analogous to wind turbines. Another difference between wind turbines and helicopters is that the aft position of the mass axis for wind turbine blades. Probably the most important difference is the continually changing operating frequency and torque for wind turbines.

There seems to be a variety of instabilities mentioned in the literature, and a variety of definitions for these instabilities. It is difficult to grasp for instance a single definition of flutter. Because each authors' treatment of stability problems in the literature varied so much, it is difficult to organize them by subject. Therefore we will look at each author individually.

A. Theodorsen 1935

This work was not part of the initial survey, but came up in nearly every reference list. Although the work was not related to rotors or wind turbines, Theodorsen's (1935) analytical treatment of flutter on wings can be considered a classic. The paper is a daunting mathematical description of a thin airfoil with pitching and plunging (flapping) motion. The potential flow solution is solved for this condition. The ease of analyzing a problem is relative to researcher; Theodorsen claims:

"The solution is of a simple form..."

But previously in the summary he states:

"The problem resolves itself into the solution of certain definite integrals, which have been identified as Bessel functions of the first and second kind and of zero and first order"

The result is a model of the unsteady forces due to the shed vorticity off the airfoil. The model requires the flutter frequency as input; therefore an iterative scheme is required to obtain a solution.

B. Eggleston and Stoddard 1987

Eggleston and Stoddard (1987) discuss in detail four types of wind turbine stability issues with several references to the rotorcraft literature. There are a miniscule amount of wind turbine related references; which can be explained by the date of publication. The four instabilities discussed are flap-lag instability, pitch-lag instability, classical flutter, and stall flutter.

1. *Flap-Lag Instability*

This instability is a coupling between flapping and lead-lag motions. The authors provide some conflicting information on its observed behavior in helicopters. They claim the instability is most likely to happen in high loading conditions with substantial flapping motions. Equations for the instability with simple blade geometry are developed and a stability boundary is presented. A critical parameter is that the flap and lead-lag frequencies must be equal and slightly above the rotor frequency. There is a possibility of this occurring with some wind turbine blades, where the cylindrical root section is the dominant structural member and the first lead-lag and flap modes are close in frequency.

2. *Pitch-Lag Instability*

This is an oscillation that can occur when the pitch angle is artificially coupled to lead-lag motion. It is usually seen as a complication and aggravation of the flap-lag instability. The authors state that bend-twist coupling can cause this instability in a hingeless blade. The equations for the stability boundary are again developed for simple geometries.

3. *Classical Flutter*

This book has an excellent description of flutter reproduced below:

> *"The mechanism is that, as the blade flaps, either elastically or via a hinge, the inertial forces act at the center of gravity or mass axis of the blade, and the aerodynamic forces act at the aerodynamic center of the blade (quarterchord). If these blade axes are not coincident ("mass balanced"), both inertial and aerodynamic pitching moments are introduced. Since these moments can be proportional to acceleration, velocity, or displacement, they have different phase angles and thus may lead to destructive interference."*

The typical turbine blade mass axis is approximately 30% of chord from the leading edge, primarily the outcome of the structural design. Therefore, the typical blade has a mass axis aft of the theoretical aerodynamic center. As the blade flaps, there is a component of the centrifugal force that opposes the flapping motion. This apparent force results in a pitch-up moment if the mass axis is aft. Another phenomenon, static divergence, can result if the torsional resistance is so small the nose up pitching moment brings the blade into stall, or rips the blade off.

The authors develop equations of simplified geometry for flutter and divergence boundaries. In the equations the Theodorsen (1935) model is reduced to a simplified model. This approximation will later be disputed by Lobitz (2004b) as much too conservative. Critical parameters for the stability are the pitch and flap frequencies, and the mass axis offset.

Two cases of actual flutter instabilities are described. One was for a thin-bladed turbine that had tips installed to move the mass axis forward and prevent flutter. The other was a design issue to determine the minimum torsion stiffness required to eliminate flutter.

4. *Stall Flutter*

This section in the book starts by introducing background information on dynamic stall. This was a research area important to helicopters in forward flight. No predictive methods are developed, but a description of stall induced vibrations is described for the Danish Nibe A turbine. The flutter was characterized by large excursions in flap, and it was claimed that the motion was aggravated by dynamic stall.

C. Yamane 1987

Yamane (1987) presented a stability analysis of an upwind, free yaw, two-bladed machine with a 6-kW rating. The turbine was represented by a six-degree-of-freedom model, using the Rayleigh-Ritz approach by expressing the deflection as linear combinations of natural vibration modes. The blade aerodynamic forces were modeled with momentum theory. Since the machine was two-bladed, the rotor/nacelle inertia depends on rotor position. This resulted in periodic coefficients in the equations of motion. Floquet theory was used in this used for stability evaluation, however it was not discussed in detail. Six different instabilities were named and studied; whirl flutter, aerodynamic divergence, stall instability, parametric instability, gyrostatic instability, and mechanical instability. Discussion of the mechanism of these stabilities is limited and more insight might be provided by the references in the paper. The actual machine was prone to stall stability, which was predicted in the model with quasi-static aerodynamics.

D. Hansen 2002

Hansen's (2002) work might be considered the shape of things to come for the wind industry. There had been minimal stability problems in the industry (more worry about gearboxes!), but engineers are getting worried as turbines grow in size. He discusses earlier problems in the industry regarding stall induced vibrations, and the approaches to solve the problem. He claims that there is much less opportunity to fix a flutter problem, however Eggleston and Stoddard (1987) discussed a flutter tip weight solution for a small turbine.

Hansen (2002) presents a model of a hypothetical 3.5 MW variable speed, variable pitch turbine. The clearly-described structural model has 16 degrees-of-freedom. The blades have a modal expansion of the bending modes with a Rayleigh damping model. A single-blade model was also used for comparison. The aerodynamic model was a blade element momentum formulation. The equations of motion were developed using a Lagrangian approach, and the blade equations used multi-blade formulation to eliminate the periodic terms. This formulation cannot be used for two-bladed machines or non-uniform inflow. The equations were linearized and solved with an eigenvalue approach.

The emphasis of the work was to reduce the torsional stiffness and determine the region of negative damping. Time domain solutions were made to verify flutter behavior, with large excursions of flap and pitch and limited edgewise motion. Comparisons were made with the single-blade solutions, showing higher critical frequencies for the full turbine. The cause of this result was explained by differences between the full-system and blade-only modes of vibration. Caution was placed on modeling a single-blade only, since the full turbine might have a reduced margin or will flutter. This result was not found in later work (Hansen 2004).

E. Hansen 2004

Hansen (2004) developed a completely different model in this later work. The turbine model was a hypothetical 5-MW machine. The structural model was composed of finite-elements, however the rotational speed was fixed as opposed to variable speed in the earlier model (Hansen 2002). The aerodynamic model was blade element momentum and included a Leishman-Beddoes dynamic stall model with state-space formulation of the Theodorsen (1935) theory. The equations of motion were developed again with Lagrange's method, including the multi-blade formulation and the Rayleigh damping model. A comparison was again made to a single blade model. The model was used as previously to study reductions in blade torsion. The results for this work contrasted with the previous model in that the full-turbine and single blade results had only small differences. Hansen suggests that the differences in the turbine model might account for this difference in results. The full system flap modes and the single-blade flap modes were closer for this larger model.

F. Lobitz 2004

Lobitz had two submissions in 2004, one for the Wind Energy Journal (Lobitz 2004a), the other for the ASME conference (Lobitz 2004b), with the latter essentially a subset of the former. He describes previous experience with studies of a Darrieus-style vertical axis turbine that was brought purposefully into flutter. The current work is due to concerns of new blade designs of bend-twist coupling for load reduction. Previous work with blades of 9-m in length showed a flutter speed six times the rotor speed; no cause for concern.

The WindPACT 1.5 meter blade is studied for flutter with and without bend-twist coupling. The structural model was a finite element NASTRAN model of the blade. The aerodynamic model was based on Theodorsen (1935), but modified for varying wind speed and lift curve characteristics over the span. A simple model of a blade with infinite span was compared to previous results published by Theodorsen. This aerodynamic model includes the effect of the shed vorticity, but not include the effects of the trailing rotor wake such as in Hansen's (2002) blade-element momentum. Lobitz emphasizes this difference when discussing Hansen's claim of the importance of modeling the full turbine, which was later contradicted (Hansen 2004).

An eigenvalue solution was obtained from the modeling to determine the stability. The flutter speed was found by identifying the mode with negative damping at the lowest rotor speed. The flutter mode was identified with the torsional mode coupling with the second flap mode. For the uncoupled blade, the flutter speed was twice the rotor speed. By comparison, the flutter speed for the coupled bend-twist blade was 12% less than the uncoupled blade. Studies were conducted of simplifications to the Theodorsen model, which were also made in Eggleston and Stoddard (1987). These simplifications essential remove the prior history from the aerodynamics. The results showed flutter speeds near the rotor speed and were not considered realistic.

The model results were also compared against an ADAMS/AeroDyn model of a single blade, modeled with and without the unsteady aerodynamics model. The unsteady case showed good agreement with the finite element approach. The quasi-steady case did show flutter behavior at a lower rotor speed, and required an impulse force on the blade to trigger the event. With the success of Lobitz initiating flutter in ADAMS/AeroDyn, there is a capability studying influence of turbulence with standard inflow models, such as TurbSim (NREL 2005).

G. Lobitz 2005

Lobitz (2005) reviewed previous work and how the theoretical flutter speed ratio to the rotor speed had reduced with blade length. An interesting claim is made that the flutter speed should remain the same with simple scaling of dimensions without changing materials or structure. The focus of this work is a comparison between the WindPACT 1.5 MW blade, scaled down to 9 m, and a 9 m blade for a 115 kW machine designated GX-100. The WindPACT blade had a flutter speed of approximately twice the rotor speed, whereas the GX-100 flutter speed was 5.4 times the rotor speed. The structural differences between the two blades were studied in order to close the flutter speed gap.

Lobitz lists textbook recommendations for minimizing the prospect of flutter, repeated below:

- Move the chordwise center of mass (inertia axis) forward. When the center of mass is ahead of the shear center (elastic axis) of the blade, flutter is unlikely at any speed.
- Increase the torsional natural frequency of the blade by increasing its torsional stiffness.
- Maximize the ratio of the torsional to flapwise natural frequencies of the modes that combine to produce the flutter mode.
- Move the elastic and inertia axes toward the line of aerodynamic centers (1/4 chord).
- Decrease the blade aspect ratio (span/average chord).

The aerodynamic and structural models were the same as in previous work (Lobitz 2004a). The scaling assumption was verified by a perfect match of flutter speed to rotor speed ratio for the full-scale and 9-m scale WindPACT blade. For more validation, the GX-100 was also scaled up to the 1.5 MW size and again the flutter speed ratio was matched. The author outlines various structural and geometric differences between the scaled WindPACT and 9 m GX-100 blades. Changes are then made to the WindPACT scaled-blade geometry, following the recommendations above. The greatest increase in flutter speed was obtained by matching the GX-100's lower aspect-ratio planform and the torsional stiffness. Matching the larger flap stiffness of the GX-100 had only a minor effect.

III. Conclusions

The earlier work in the subject of wind turbine stability was an evolution of the problem from helicopter research. Elementary models described in Eggleston and Stoddard (1987) can be used to check designs given very simple geometry. The flutter boundary obtained might be considered conservative from work by Lobitz (2004b). Eigenvalue approaches have been developed in later work by Hansen (2004) and Lobitz (2004a) require detailed finite-element structural modeling and unsteady aerodynamics. Lobitz verified models successfully against an ADAMS/AeroDyn model, offering the possibility of checking the stability boundary with an available tool. Further research would be to verify and ADAMS/AeroDyn model with a turbine that exhibited flutter characteristics. Also the impact of turbulent inflow on flutter characteristics could be studied with this model.

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