Aeroelastic Instability of Very Large Wind Turbine Blades

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Abstract

The trend in per-revolution flutter speed for increasing length wind blades is such that aeroelastic stability should be considered in their design. A classical flutter analysis of the Sandia National Laboratories 100-meter all-glass baseline blade is performed. The margin of estimated flutter speed divided by rated operating speed is estimated at 1.27. A sensitivity study of important aeroelastic stability parameters is performed in order to understand factors that may lead to increased flutter robustness.

Keywords: aeroelastic, instability, flutter, offshore wind, large rotor, unsteady aerodynamics

1 Introduction

The Wind Energy Technologies Department at Sandia National Laboratories (SNL) focuses on creating innovations in technology to improve the performance of utility-scale wind turbine blades. Technology areas include structural dynamics, advanced materials, aerodynamics with airfoil improvements and passive and active load control. Classical flutter is just one aspect of blade behavior that is considered in new concepts. Flutter is a self-starting and potentially destructive vibration where aerodynamic forces on the wing couple with the wing structure's natural modes of vibration in a manner that produces large-amplitude, diverging periodic motion. Sandia developed and validated a flutter onset estimation tool for VAWT’s in the early 1980’s [1]. The tool was extended to HAWT’s in the 1990’s [2,3]. Historically, flutter has not been a design issue in utility scale wind turbines. Previous estimates of flutter speed for a variety of turbines have shown that as turbine size increases and blades grow in length, the margin of estimated flutter speed relative to turbine operating speed decreases (Figure 1).

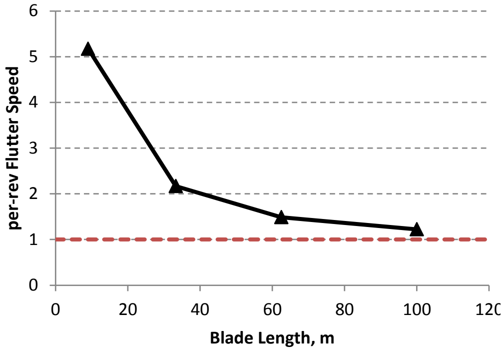

Figure 1: Per-rev flutter speed: ratio of the flutter rotational speed to the rotor operating speed

Data points in Figure 1 are from classical flutter analyses of a variety of wind blade sizes: SNL 9-meter CX-100 experimental blade [4], WindPact 33.25-meter 1.5MW concept blade [3], SNL 62.5-meter blade (preliminary design) and a SNL 100-meter blade concept. The 13.2MW, SNL 100-meter blade concept is documented in Reference [5]. Details regarding the calculation of its estimated flutter speed are the subject of this paper. Depending on the modeling assumptions and level of model fidelity used in the analysis, the estimated flutter speed of the baseline SNL 100m blade can be very close to its operating speed. This demonstrates a need for 1) design innovations to produce large blades that are robust with respect to flutter and 2) accurate and validated flutter analysis tools.

2 Objectives

This paper has two objectives. First, estimate the classical flutter speed of the current 100m blade concept to show that the margin of safety over operating speed at this scale is quite low compared to current utility scale turbines.

Second, demonstrate ways in which the blade can be modified to enable a higher flutter speed, thus improved flutter robustness. Three different approaches are examined and their relative effectiveness is quantified. The modifications are simulated in the blade by changing the beam properties and aerodynamic properties in the flutter analysis Future work requires detailed blade layup and airfoil design in order to realize these changes.

3 100 Meter Blade Background

A recent project at SNL has focused on the development of a 100-meter blade for a 13.2MW horizontal axis wind turbine, a blade which is significantly longer than the largest commercial blades of today (approximately 60 meters long). Reference [5] documents the development of the Sandia 100m all-glass baseline wind turbine blade, which employs conventional architecture and fiberglass-only composite material reinforcement. Follow-on studies for this baseline will include a variety of innovations targeting reductions in weight and improvements in structural and aerodynamic performance.

The seed for the blade concept was a scaled-up version of a 5MW blade design. The current baseline Sandia 100m all-glass baseline blade model represents a blade that meets the basic IEC and GL wind blade design standards [6, 7] with respect to strength, fatigue, deflection, and buckling. Important design drivers for a blade of this scale include blade root edgewise fatigue (due to per/rev gravity loading) and panel buckling. Currently, the weight of the all-glass 100m blade design is high at 114,172 kg. Increases in structural thickness to meet panel buckling criteria led to a blade weight that is above the desirable mass scaling exponent of three. See Reference [5] for more information. Estimates of the 100m blade per-rev flutter speed show that it is low (Figure 1). This is a concern for future work on very large wind turbine blades.

4 Wind Blade Aeroelastic Instability Background

The current investigation in wind blade classical flutter analysis benefits from the work of previous authors who have studied the aeroelastic instability issues that are unique to wind blades.

HAWCStab for turbine analysis, developed at Risø, is a very capable code for full-system aeroelastic stability analysis [8,9]. The structure is modeled by a finite beam element method and the aerodynamic loads are modeled by the blade element momentum method coupled with a Beddoes-Leishman type dynamic stall model and includes unsteady aerodynamics. The eigenvalues and eigenvectors can be computed at any operating condition to give the aeroelastic modal properties: natural frequencies, damping and mode shapes.

Reference [8] compares damping values predicted by HAWCStab to measured values from the field with good agreement. The comparisons indicate that it is possible to predict the qualitative and quantitative behavior of aeroelastic turbine modes.

Reference [9] includes quite a thorough examination of the aeroelastic stability issues that are specific to wind blades: both stall-induced vibrations for stall-turbines and classical flutter for pitch-regulated turbines. Blade tip speed, torsional blade stiffness and chordwise position of the center of gravity along the blades are the main parameters for flutter of pitch regulated turbines.

References [9] and [10] state that a wind turbine may have a risk of flutter if the following main criteria are satisfied:

- Attached flow. The flow over the blade must be attached to ensure that nose-up (towards stall) blade torsion leads to increased lift.

- High tip speeds. The relative speed of the attached flow must be sufficiently high to ensure sufficient energy in the aerodynamic forces. (Blade tip speed can become sufficiently high due to an overspeed or large yaw misalignment)
- Low stiffness. The natural frequencies of a torsional mode and a flapwise bending mode must be sufficiently low for them to couple in a flutter mode.
- Aft center of gravity. The center of mass in the cross sections on the outboard part of the blade must lie aft of the aerodynamic center to ensure the right phasing of the flapwise and torsional components of the flutter.

Reference [10] investigated the effects of moving the center of mass and reducing the torsional blade stiffness on the flutter limit of MW-sized blades using isolated blade analysis:

- The flutter mode for larger blades consists of the second flapwise and first torsional blade modes
- The flutter speed limit decreases when the natural frequency ratio between these two modes is reduced
- The flutter speed limit decreases when the center of mass is moved towards the trailing edge of the blade

5 An Isolated Blade Classical Flutter Tool

As demonstrated in References [3,2,10], flutter analysis at SNL is generally focused on qualitative understanding of issues governing wind turbine blades. While some experimental validation of classical flutter tools have been performed for a 2 meter VAWT turbine in the 1980's, no experimental validation of the SNL flutter analysis capability has been performed for a HAWT rotor. Still, the tool provides useful insight into qualitative trends that affect wind blade design.

The flutter analysis capability described in Reference [3] utilizes MSC Nastran for assembly of structural mass and stiffnesses matrices for the blade beam model. Modifications of the matrices to include unsteady aerodynamic forces, Coriolis, spin softening and spin stiffening. are performed as an intermediate step. Finally, the Nastran complex eigensolver is used to solve the final mass, stiffness and damping matrices.

In a subsequent effort, an updated and more efficient classical flutter analysis tool has been developed by SNL using Matlab, by Mathworks. The current version emulates the assumptions of the legacy tool of Lobitz [3]. The blade is modeled using beam finite elements with tapered properties. Rotor spin-up effects are included using an initial static calculation. Unsteady aerodynamic forces are described by Theodorsen theory. Coriolis effects due to rotor rotation are included. The rotor is simulated in still air, i.e. section airspeeds are calculated as rotor radius of section times the rotor speed. The aeroelastic modes parameters (frequency and damping) are determined at a variety of rotor rotating speeds through an iterative process managed by automated loops, utilizing the Matlab

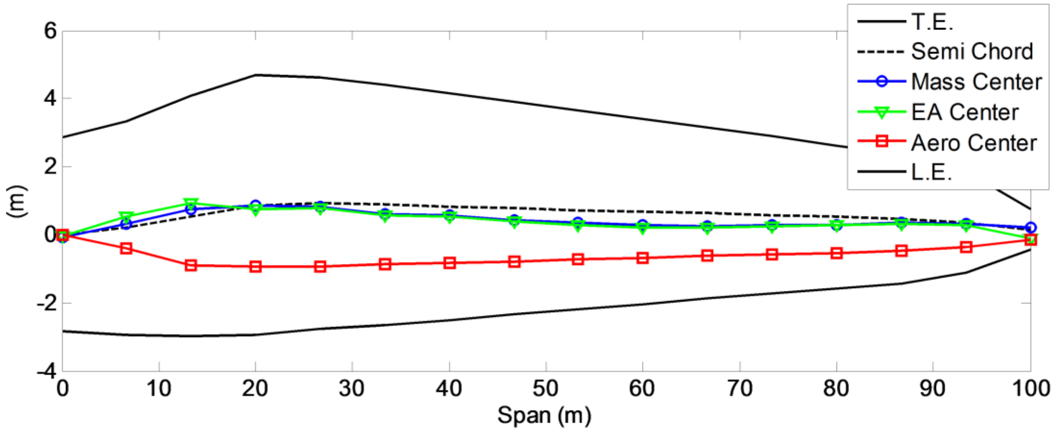

Figure 2: Locations of important structural characteristics of the current 100m blade.

eigensolver. The tool has been successfully verified against the Lobitz tool and has been verified qualitatively on simple problems. Future work will involve a rigorous verification effort for a wide range of problems.

6 Blade Information

Equivalent beam properties for the 100m blade are generated using BPE [11] using an ANSYS finite element shell element model of the blade. The following characteristics are computed as input to the flutter analysis: linear mass density, flapwise stiffness, edgewise stiffness, torsional stiffness, axial stiffness, flapwise inertia, edgewise inertia, edgewise center of gravity location, edgewise location of flexural axis or elastic axis. Important axes locations for the classical flutter analysis are shown in Figure 2. Distribution of mass and stiffnesses are shown in Figure 3.

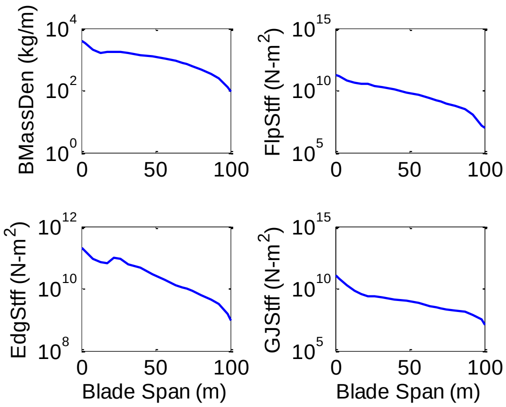

Figure 3: Important blade properties.

7 Baseline Flutter Speed

The entire blade is modeled using ten beam finite elements. The flutter analysis tool has not been verified at the time of this paper for representation of offset elastic axes. Most non-swept blades are designed such that the elastic axes, the shear web and the pitch axes are closely located. The elastic axes of the sections were shifted to align with the reference axis (pitch axis) of the blade while preserving the relative distances between elastic axis and section center of mass as well as elastic axis and aerodynamic center for unsteady aerodynamic calculations. Actual locations of these axes are shown in Figure 2. In the spirit consistency with the legacy flutter tool [3], values for half-chord length, aerodynamic center w.r.t half-chord, and elastic axis location w.r.t half-chord used in the unsteady aerodynamics calculation were constant along the span of the blade. However, the current tool is capable of representing each section accurately.

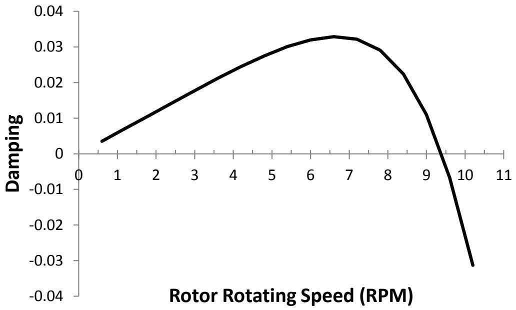

Figure 4: Damping trend for unstable mode

The damping trend for the iterative flutter analysis process for the baseline configuration is shown in Figure 4. The baseline blade becomes unstable at approximately 9.37 RPM rotor speed in a “hard” manner, i.e. the presence of structural damping will have little effect on the stability of this mode. The mode shape consists of flapwise motion and blade twist (Figure 5.)

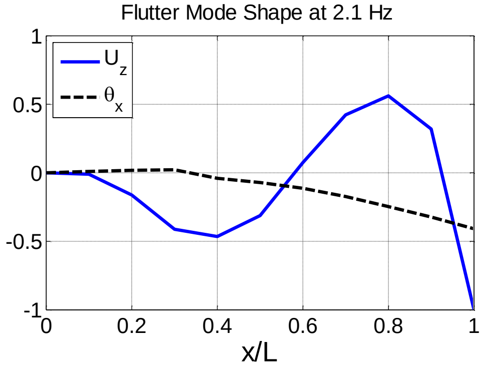

Figure 5: Flapwise translation (Uz) and twist (thetax) for the primary unstable aeroelastic mode shape: Mode 5, 2.1 Hz

The rated rotor speed for the 13.2MW machine is 7.44 RPM. Therefore, the per-rev flutter speed of this blade is 1.26. The safety margin between operating speed and unstable rotor speed is 26%. This margin is notable because it may be small enough to call into doubt certain aeroelastic stability modeling assumptions and model accuracy. Also, design for aeroelastic instability probably should be considered in this blade.

8 Flutter Speed Parameter Study

The parameters most likely to have a significant effect on the flutter of this blade are related to the blade mass and the associated distribution of mass centers as well as the choice of airfoils and their aerodynamic center characteristics.

The baseline 100m blade design is quite heavy. Ongoing tasks associated with the optimization of the details of the blade design involve innovations that lead to significant weight reductions. Therefore, the current parameter study focuses on removal of weight from the blade. The weight is removed by two methods. First, weight is removed from the trailing edge. The blade has a relatively heavy band of uniaxial trailing edge reinforcement that could be replaced with carbon, thus reducing weight and shifting the mass centers toward the leading edge. Second, mass is removed uniformly from the blade in an effort to simulate overall more efficient use of blade materials.

No airfoil, material or layup changes have been made to the detailed model of the 100m blade. The proposed changes are simulated through modification of distributed mass and inertia properties of the beam model in the flutter analysis. The assumption is that careful use of carbon instead of glass, in key locations, can decrease mass while maintaining sectional stiffness.

It is likely that new airfoil shapes will be used in the 100m blade in order to optimize the tradeoffs between aerodynamic performance and structural efficiency. In the new airfoils, it may be valuable to consider airfoil design for shapes that exhibit aft aerodynamic centers. The parameter study includes a demonstration of shifting the aerodynamic center for this blade 5% aft in order to evaluate the potential benefit of this modification. Again, no changes are made to the actual detailed model of the 100m blade. The change to aerodynamic center is simulated in the flutter analysis by simply shifting the original values aft by 5% of chord.

Table 1: Parameter study results

	Location of weight reduction	Unstable Rotor Speed, RPM
Baseline Blade		9.37
2% weight decrease	Trailing edge	9.70
4% weight decrease	Trailing edge	9.99
6% weight decrease	Trailing edge	10.3
10% weight decrease	Trailing edge	10.9
5% weight decrease	Uniform	9.47
10% weight decrease	Uniform	9.58
Aerodynamic center shift aft by 0.05 * chord		10.9

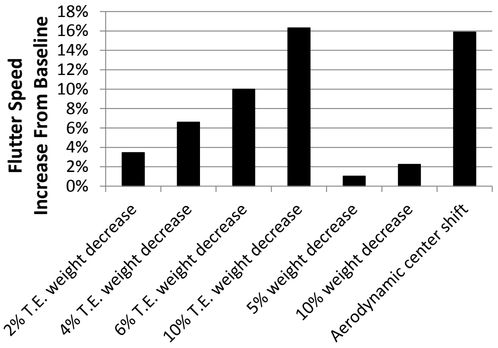

Figure 6: Graphical comparison of flutter speeds for all parameter variations.

Computed flutters speeds for various modified configurations are summarized in Table 1 and relative changes are shown in Figure 6.

9 Conclusions

This work has demonstrated only a small margin of safety of flutter speed with respect to rotor operating speed for the SNL 100m blade. The calculated margin of 1.26 is low compared to current megawatt-scale turbines, which are estimated at about 2.1 [3].

Two recommendations are made due to the small margin between operating speed and estimated flutter speed:

1) Increase confidence in flutter prediction accuracy by addressing simplifying assumptions in the current approach, as well as pursuing new, higher fidelity analysis methods. Extend the current analysis to investigate divergence. Gather test data for use in validation of the analyses.

2) Include consideration for flutter instability in design of very large rotors. Classical flutter robustness may be obtained through one or more of the following:

- Trailing edge weight reduction
- Blade weight reduction, uniformly distributed
- Utilization of airfoils characterized by aft aerodynamic centers

One may also assume that shifting the center of gravity forward by means of added mass to the leading edge would be effective in raising the flutter speed. However, this scenario was not investigated because addition of weight to an already heavy blade is not desirable.

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