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Investigation of flutter for large, highly flexible wind turbine blades

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Abstract

Improvements to the Sandia blade aeroelastic stability tool have been implemented to predict flutter for large, highly flexible wind turbine blade designs. The aerodynamic lift and moment caused by harmonic edge-wise motion are now included, but did not change the flutter solution, even for highly flexible blades. Flutter analysis of future, large blade designs is presented based on scaling trends. The analysis shows that flutter speed decreases at a rate similar to maximum rotor speed for increasing blade sizes: $\Omega_{flutter} \propto \Omega_{rated} \propto \frac{1}{L}$. This indicates the flutter margin is not directly affected by blade length. Rather, it was innovative design technology choices that predicted flutter in the operational rotor speed range in previous studies. A 100 m blade, flexible enough to be rail transported, was analyzed and it exhibited soft flutter below rated rotor speed. This indicated that excessive fatigue damage may occur due to limit cycle oscillations for blades that incorporate highly flexible designs.

Objectives

- Modify Sandia Blade Aeroelastic Stability Tool (BLAST) to include harmonic lift and moment due to edgewise (in-plane) blade motion for classical flutter analysis
- Analyze the importance of edgewise motions for prediction of flutter speeds in modern, highly flexible rotor designs
- Investigate the flutter margins for blade length growth trends into the future
- Determine feasibility of highly flexible, and rail transportable blade designs with respect to aeroelastic instabilities

Incorporating Edgewise Motions

The edgewise (in-plane) blade motion, *y*, was incorporated in the BLAST flutter code using a linear combination of Greenberg [1] and Theodorsen [2] theory, as proposed by Lehmann [3]. The harmonic lift and moment per unit span appear in the following equations. This methods ignores the effect of harmonic relative wind speed (*W*) due to surging blade motion in order to keep the code in an eigenvalue form. This linear flutter problem can be solved quickly, and flutter can be checked in design studies.

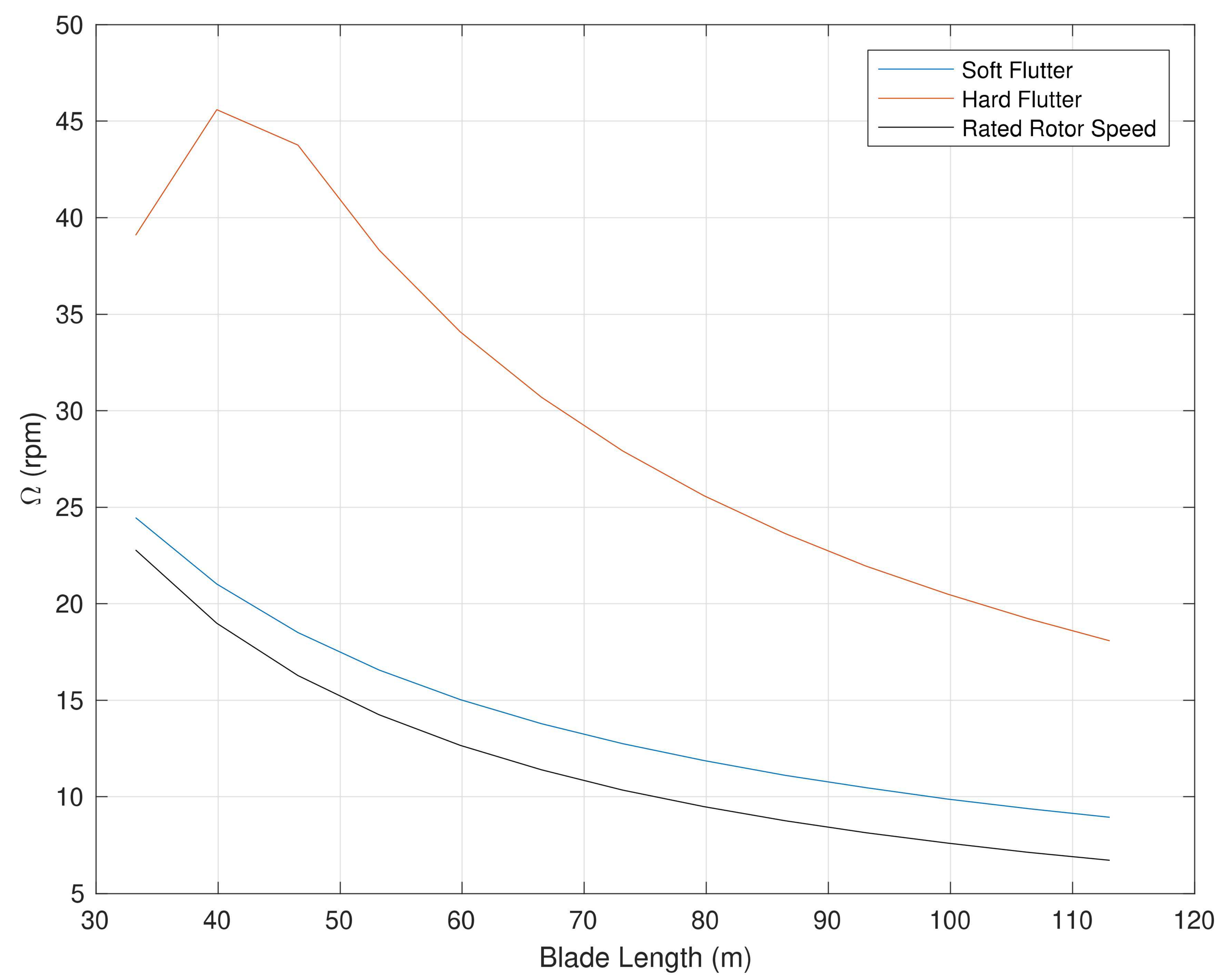
$$L = L_{Theodorsen} + \frac{C_{l_\alpha}}{2}\rho b^2 \alpha \ddot{y} + C_{l_\alpha}\rho b W \alpha (1 + C(k))\dot{y}$$

$$M = M_{Theodorsen} - \frac{C_{l_\alpha}}{2}\rho b^3 \alpha \ddot{y} - C_{l_\alpha}\rho b^2 W \alpha (a + \frac{1}{2})(1 + C(k))\dot{y}$$

Large Blades and Flutter Margins

In the following analysis, the WindPACT 1.5 MW blade was used as the baseline blade design [4]. It was scaled from its actual size, 33.25 m, through a range of values up to 113 m. Blade mass was increased by the scaling exponent 2.5, mass ∝ $L^{2.5}$ to match the historical trend of blade designs [5]. The area moment of inertia was scaled geometrically which is to the 4th power, I ∝ L^4. In this way, the effect of flutter could be investigated for a range of blade sizes without introducing unique design concepts such as aeroelastic tailoring or innovative materials as in previous flutter studies.

The BLAST simulations for a range of blade sizes are seen below. It was observed that as rotor speed increases, both hard and soft flutter frequencies reduce at a rate nearly equal to maximum rotor speed seen in the following figure. The flutter margin stays constant with blade length based on the previous scaling. Therefore, flutter is not expected to be a problem for large blade designs that follow the historical mass change with blade length, and the increase of area moment of inertia with blade length to the fourth power. However, innovative design changes could disrupt this trend.



To explain why flutter margin is constant with blade length the following scaling relationships are mentioned. It can be shown that the natural frequency of an Euler-Bernoulli beam varies inversely with its length:

$$\omega_n = \frac{\lambda_i^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \propto \frac{1}{L^2}\sqrt{\frac{L^4}{L^2}} \propto \frac{1}{L}$$

It can be shown the rated wind speed of a turbine also varies with the inverse of the blade length:

$$\Omega_{rated} = \frac{\lambda}{L}\sqrt[3]{\frac{2\,S_P}{\rho C_P}}$$

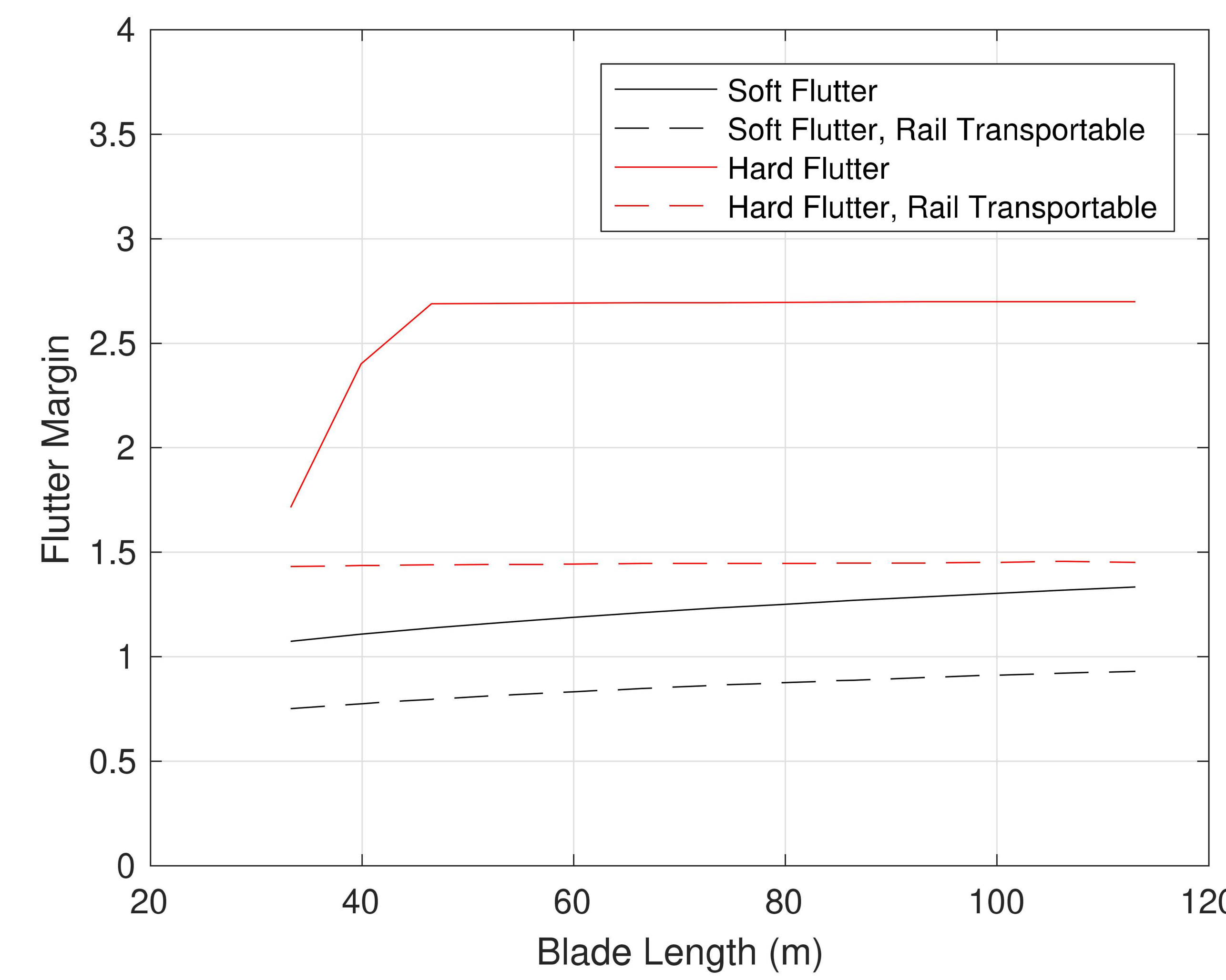
Therefore this explains the flutter analysis whereby the flutter margin is constant with blade length for non-innovative design changes.

$$\Omega_{flutter} \propto \Omega_{rated} \propto \frac{1}{L}$$

Rail Transportable, Highly Flexible Blades

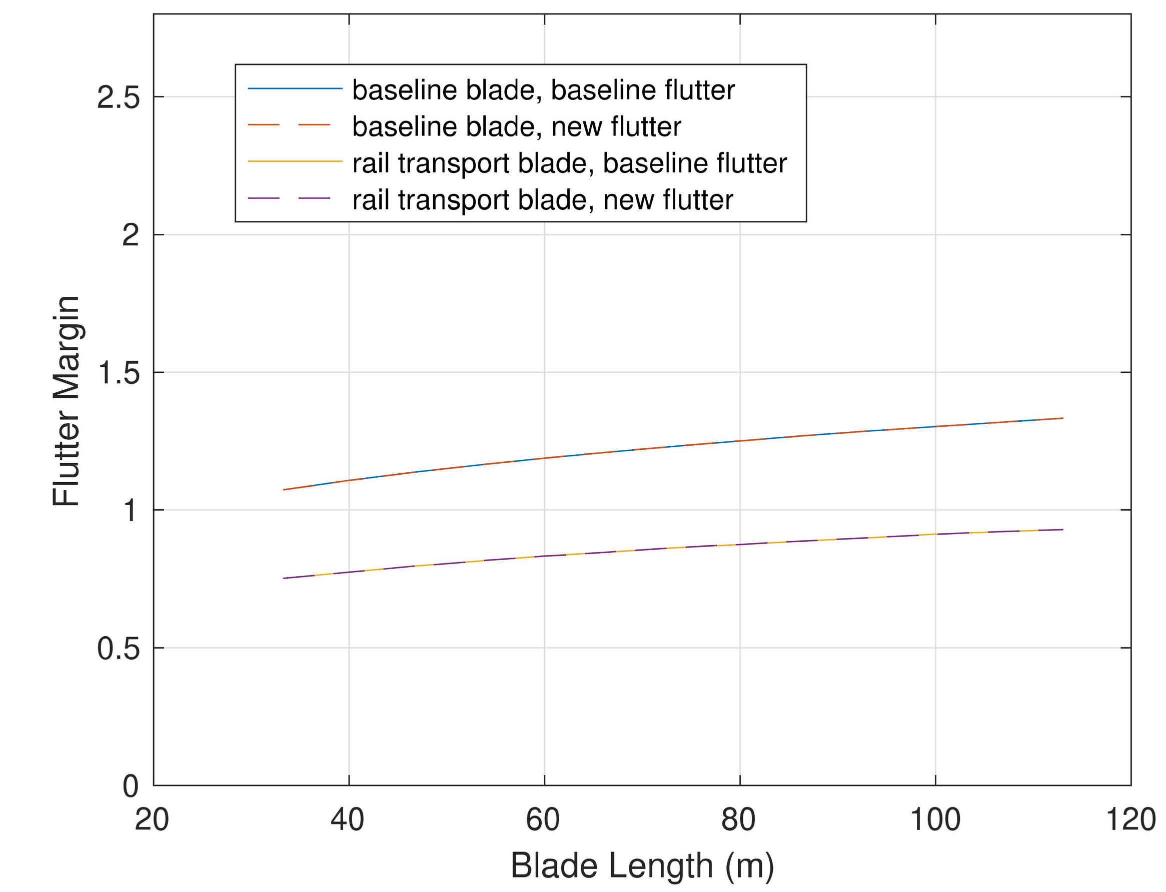
Carron describes how flexible a 100 m blade must be for transport along a typical railroad track in the United States [6]. By adjusting our WindPACT baseline blade, the rail transportable blade in this flutter analysis had the following properties: The flapwise bending rigidity was reduced by a factor of 1.6, the edgewise bending rigidity was reduced by a factor of 2.1 and the torsional rigidity was reduced by a factor of 1.9.

The following figure shows that a highly flexible blade has a much lower flutter margin. For example, the hard flutter margin is reduced from 2.7 to 1.4. This would be concerning to a blade designer as there is some allowable overspeed in turbulent winds which could push a turbine close to its flutter speed. And the soft flutter margin is below 1 for all blade sizes that are transportable by rail, indicating a limit cycle oscillation could occur for this type of blade. The flutter speed was reduced for a rail transport blade design because the ratio of second flap and first torsion frequencies was reduced due to the reduction in rigidity. Therefore it is recommended that highly flexible blade designs increase their biaxial skin composition or similar design choices to increase torsional rigidity but still allow significant flapwise bending for rail transport.



The Effect of Edgewise Aerodynamics

To evaluate the effect harmonic edgewise aerodynamics on flutter, the BLAST simulations were run for a range of blade sizes with and without the new edgewise lift and moment terms previously described. The following figure shows the effect of flutter margin with the new edgewise aerodynamic loads and the change for rail transportable blades. In the legend, "baseline flutter" refers to standard pitch/plunge aerodynamic lift and moment from Theodorsen, and "new flutter" indicates the additional edge loads. The result is no change due to the harmonic edge lift and moment. The change is so small even for the highly flexible, rail transport blade that these forces are likely not required in any aeroelastic analysis.



Conclusions

- Flutter margin appears to stay constant even for large blade designs over 100 m in length for historically scaled mass and inertia trends because flutter speed decreases at the same rate as maximum rotor speed.
- The flutter solution is not changed with the addition of lift and moment due to edgewise (in-plane) blade motion, even for large displacements on highly flexible rotor designs.
- Classical flutter codes do not predict edgewise aeroelastic instabilities even when the forces with edge degree of freedom are added.
- The reduction of torsional rigidity and the coalescence of flap and torsion modes is the prime contributor to flutter margin reductions in a highly flexible, rail transportable blade designs.
- Biaxial skin would be a potential solution to keeping the first torsion mode high while still allowing a blade to have low flap-wise rigidity for rail transport.

References

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Acknowledgements

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