

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 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.

1. Motivation

In this work, the Sandia blade aeroelastic stability tool, BLAST [1] has been modified to include the unsteady lift and moments caused by harmonic edge motion, in addition to the pitch/plunge motions of classical flutter theory. Rather than analyze specific wind turbine designs, we examine technology and design trends to predict whether flutter will be an issue for modern, highly flexible wind turbines in the future. The analysis presents scaling trends for blade mass and stiffness as wind turbines have become larger, including highly flexible blades for rail transport. While there have been no known catastrophic wind turbine failures due to flutter, previous studies of large wind turbine blades have been design specific and the question remains: do we expect flutter to be an issue for large wind turbine designs?

Only two published experiments on wind turbine blade flutter have been performed. The first is the Sandia 2 m vertical axis wind turbine [2], and the second is an experiment on a 7 MW Siemens wind turbine [3]. Kallesøe indicates that the edge degree-of-freedom (coupling of 1st and 2nd edge modes) is responsible for a flutter-like instability based on both modeling and a field test. The authors show this instability does not lead to catastrophic failure and appears as a limit cycle oscillation, likely due to non-linear damping and non-linear stiffness. The authors used a non-linear structural model to account for deflection more accurately, and showed a limit cycle oscillation in the time domain based on the modified BHawC aeroelastic code. It appears that this type of flutter instability can be identified as soft flutter in modal analysis in addition to the time domain, whereby the damping slowly becomes negative. This is in contrast to hard flutter, as distinguished by Owens and Lobitz [4, 5]. Therefore, this work

examines the importance of accurately modeling edgewise motion for flutter predictions of large blades using modal analysis.

As land-based machines have become larger in the United States, the transportation constraints of railways and their associated bridges and track curvature present a real constraint on blade size as identified in the U.S. Department of Energy funded super sized blade study [6]. Carron examined the required flexibility of large wind turbine blades designs that can bend along with railroad cars and train track shape while not exceeding the material strain limits [7]. In this paper, we also examine what effect reduced flapwise and edgewise rigidity has on flutter for large blade designs that could be transported by rail.

2. Background

Flutter analysis has been widely applied to wind turbine design. Classically, Theodorsen theory is used to model the aerodynamic forces and moments for harmonic pitching and plunging motion at an angular frequency ω . The problem is formulated in the Sandia flutter code, BLAST, as an eigenvalue problem whereby the structural mass, damping, and stiffness are combined with the aerodynamic forces and centrifugal forces:

$$[M] \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{z} \\ \ddot{\theta} \end{bmatrix} + [C] \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\theta} \end{bmatrix} + [K] \begin{bmatrix} x \\ y \\ z \\ \theta \end{bmatrix} = F_{cent} + F_{aero}. \quad (1)$$

The degrees of freedom include blade flap, edge, extension, and torsion for x , y , z , and θ respectively. Harmonic motion can be described as $x = x_0 e^{i\omega t}$, and therefore velocity and acceleration are $\dot{x} = i\omega x$, and $\ddot{x} = -\omega^2 x$.

The centrifugal force is written in terms of the steady state deflection due to rotor spin. In consideration of pitch/plunge motion, the aerodynamic forces and moments can be written in linear terms of blade motion and frequency [8]. This is convenient because the centrifugal and aerodynamic forces can be incorporated into the matrices M , C , and K on the left hand side of equation 1. After simplification we arrive at the eigenvalue problem formulation:

$$[A] \begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ \theta_0 \end{bmatrix} e^{i\omega t} = 0 \quad (2)$$

Where the matrix $A = M\omega^2 + Ci\omega + K - F_{cent} - F_{aero}$ and is a function of the blade structural properties, rotor speed, blade vibration frequency, ω , and relative airspeed. The iterative approach to solving the eigenvalue problem is summarized in [4] which uses the p-k method to solve for the complex eigenvalues, λ , which contain the damping and frequency information, $\lambda = \sigma + i\omega$.

The BLAST code has gone through a number of iterations in its development. Lobitz first developed the flutter tool based on the NASA NASTRAN finite element solver to find the eigenvalues of the rotor [5]. Owens improved the code by introducing Coriolis damping, spin softening, and centrifugal loading [4]. In addition, he added a real-valued representation of the unsteady aerodynamics due to a lack of complex conjugate pairs in the complex solution approach.

Griffith predicted that flutter may be an issue for large blade designs, such as the benchmark SNL100-00 100 m blade design where the flutter margin was only 1.04 [9]. Owens repeated the analysis using the real-valued aerodynamics of Wright and Cooper and found the 100 m blade design had a flutter margin of 1.75. Therefore flutter codes are sensitive to flow psychics included

in a given code. Including unsteady aerodynamics in the wake was shown to increase flutter speed by 5–10% [10]. A simulation of flutter has even shown the potential for the edge degree of freedom to be responsible for flutter [11]. So there remains the need for both experimental validation data for flutter data and examination of the importance of the edge motion forces previously ignored.

3. Improvements to Flutter Analysis

In this section the two improvements to Sandia’s flutter analysis code BLAST are presented. The first change is including aerodynamic lift and moment due to edge-wise blade motion. The second change is using the exact Theodorsen function in the form of Bessel functions as opposed to an exponential approximation.

3.1. Edgewise Aerodynamics

Edgewise aerodynamics were included since a few authors have shown that large blades have potential for flutter due to coupling of edgewise modes, either with themselves or with flap and torsion. It was also important to keep the additional lift and moment in the frequency domain for quick analysis of blade designs for flutter in optimization routines.

The inclusion of harmonic surging motion, that is blade motion in the plane of rotation ($y = y_0 e^{i\omega t}$), has been addressed before in various approaches including Isaacs [12], Greenberg [13], van der Wall [14], and Lehmann [15].

Isaacs [12] first modeled harmonic freestream velocity (surge) which is similar to harmonic blade motion in edge. Isaacs modeled harmonic surge and pitch together in the time domain using a Fourier series. Van der Wall generalized the theory of Isaacs to include pitch about an arbitrary axis as opposed to the mid-chord [14]. An issue with application of the Fourier series form to flutter analysis is that the lift forces are in the time domain as opposed frequency domain.

Greenberg was the first to couple all three harmonic motions for an airfoil (pitch, plunge, and surge) [13]. To apply the theory of Greenberg to flutter analysis requires a few assumptions. First, the harmonic variation of freestream velocity must be made equivalent to harmonic blade edge vibration, $U = U_0 e^{i\omega t} = \dot{y}$. There are two main issues with this approach. First, Theodorsen theory assumes equal vortex spacing in the wake which would not be captured in this approach [8]. Second, the unsteady lift and moment from Theodorsen theory now have non-linear terms anywhere freestream velocity previously appeared, for example $L = -2\pi\rho b C(k) \dot{x} \dot{y} + \dots$. This equation cannot be put into the eigenvalue matrix form without linearization.

Friedmann was the first to solve this linearization issue for flutter analysis for all 3 degrees of freedom and he applied it to helicopter rotors. He used the Galerkin linearization technique to formulate the flutter equations. However, he eliminates the effect of circulatory lift completely by making the Theodorsen function equal to 1 ($C(k) = 1$) for all analysis.

Another linearization of Greenberg’s theory [13] is proposed by Lehmann [15] and it arises from superposition of Greenberg’s solution (edge motion, $y = y_0 e^{i\omega t}$, with no pitch/plunge) and Theodorsen theory (pitch/plunge) [8]. This is the approach integrated into the Sandia BLAST code whereby the lift and moment are

$$L = L_{\text{Theodorsen}} + \frac{C_{l_\alpha}}{2} \rho b^2 \alpha \ddot{y} + C_{l_\alpha} \rho b W \alpha (1 + C(k)) \dot{y} \quad (3)$$

$$M = M_{\text{Theodorsen}} - \frac{C_{l_\alpha}}{2} \rho b^3 \alpha \ddot{y} - C_{l_\alpha} \rho b^2 W \alpha \left(a + \frac{1}{2}\right) (1 + C(k)) \dot{y}. \quad (4)$$

Continued interest in highly flexible blades for mass savings and rail transport in addition to the Siemens 7 MW flutter experiment motivated the inclusion of the aerodynamic loads due to edge motion. The importance of this effect is investigated in the results section.

3.2. Exact Theodorsen Function

Previously the BLAST code used R. T. Jones' exponential approximation of the Theodorsen function

$$C(k) \approx 1.0 - \frac{0.165}{1 - 0.0455i/k} - \frac{0.335}{1 - 0.3i/k}. \quad (5)$$

Whereas, the exact solution provided by Theodorsen is in the form of Hankel functions of the second kind and is easily evaluated in MATLAB

$$C(k) = \frac{H_1^{(2)}(k)}{H_1^{(2)}(k) + iH_0^{(2)}(k)}. \quad (6)$$

The error of the magnitude of the approximate Theodorsen function is below 2% for all reduced frequencies, k . And the error in phase angle never exceeds 1.5° . These errors, while small are now eliminated. The computational cost was not significantly impacted. One thousand function evaluations of the exact Theodorsen function were performed and the evaluation time in MATLAB only increased from 0.5 ms to 0.9 ms.

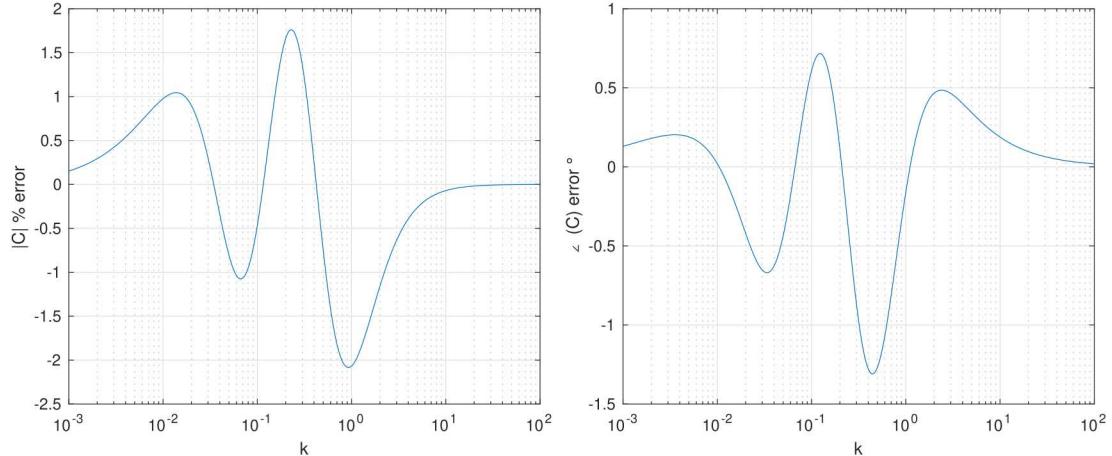


Figure 1. Error in magnitude and phase for the Theodorsen function using the R. T. Jones exponential approximation.

3.3. Blade Scaling

Previous work in aeroelasticity has shown what role the structure has in affecting flutter speed. Flutter margin is increased by the following methods: moving the center of gravity towards leading edge of blade, keeping second flap and first torsion modes as far apart in frequency as possible, uniformly reducing blade mass for the same stiffness properties, reducing tip speed, and moving aerodynamic center towards the trailing edge. The stability criteria is well demonstrated by Hansen [16]. Of specific note is the lack of blade size from this list.

In the following analysis, the WindPACT 1.5 MW blade was used as the baseline blade design [17]. 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, $m \propto L^{2.5}$ to match the historical trend of advanced blade designs [18]. The area moment of inertia was scaled geometrically which is to the 4th power, $I \propto L^4$. 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.

In the later results section, a rail transportable blade was also investigated. Carron describes how flexible a 100 m blade must be for transport along a typical railroad track in the United States [7]. For a blade mounted with the chord direction oriented vertically on a rail car, a blade must allow for flapwise bending to follow left/right turns and edgewise bending for elevation curvature. The ratio of flap and edge rigidity compared to the baseline 100 m blade was used to predict flutter effects of a highly flexible, rail transported blade. The blade had to following properties relative to the baseline blade. The flapwise bending rigidity was reduced by a factor of 1.6, $I_{rail,flap} = I_{baseline,flap}/1.6$, the edgewise bending rigidity was reduced by a factor of 2.1, $I_{rail,edge} = I_{baseline,edge}/2.1$, and the torsional rigidity was reduced by a factor of 1.9, $J_{rail,torsion} = J_{baseline,torsion}/1.9$.

4. Results

4.1. Large Blades and Flutter

The WindPACT rotor was analyzed in the BLAST code to solve for the eigenvalues, frequencies, and damping for a range of blade sizes based on the scaling discussed in the previous section. The damping ratios for a range of blade sizes from (33 to 113 m) and modes are plotted in Figure 2. Some flutter modes cross into negative damping at a very shallow angle and some at a more

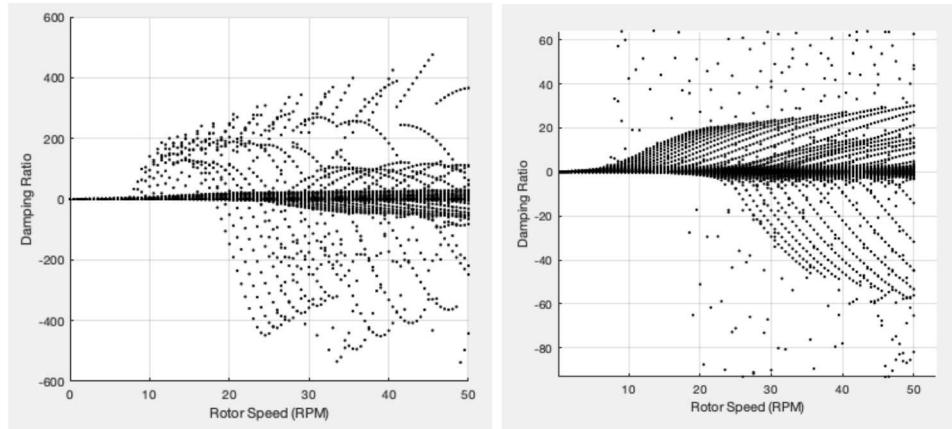


Figure 2. Damping ratio for a) hard flutter modes and b) soft flutter modes for a range of blade sizes, $33 \text{ m} < L < 113 \text{ m}$.

abrupt slope. The soft flutter modes have shallow crossings and negative damping for high mode numbers, $i > 7$, $\lambda_i = \sigma_i + j\omega_i$. For a real blade, the soft flutter modes could lead to limit cycle oscillations, but not failure because of nonlinear stiffness and damping. The abrupt negative damping ratios are associated with hard flutter and are the concerning, low-order flutter modes for first flap, first edge, second flap, second edge, third flap, first torsion, and third edge, $i \leq 7$. The rotor speeds at which flutter occurs are shown in Figure 3.

It was observed that as rotor speed increases, both hard and soft flutter frequencies reduce at a rate nearly equal to maximum rotor speed, $\Omega_{rated} = \frac{\lambda}{L} \sqrt[3]{\frac{2S_P}{\rho C_P}}$. And it can be shown that the natural frequency of an Euler-Bernoulli beam varies with the inverse of the scale as well, $\omega_n = \frac{\lambda_i^2}{2\pi L^2} \sqrt{\frac{EI}{\rho A}} \propto \frac{1}{L^2} \sqrt{\frac{L^4}{L^2}} \propto \frac{1}{L}$ [9]. Therefore, based on the area moment of inertia and mass scaling used, flutter is not a problem for large blades, because flutter speed decreases at the same rate as maximum rotor speed, $\Omega_{flutter} \propto \Omega_{rated} \propto \frac{1}{L}$. The flutter margin is not concerning, and is greater than 2.7 for almost the entire range of blade lengths. However, blade technology such as aeroelastic tailoring and highly flexible blades do not follow these assumed trends. The

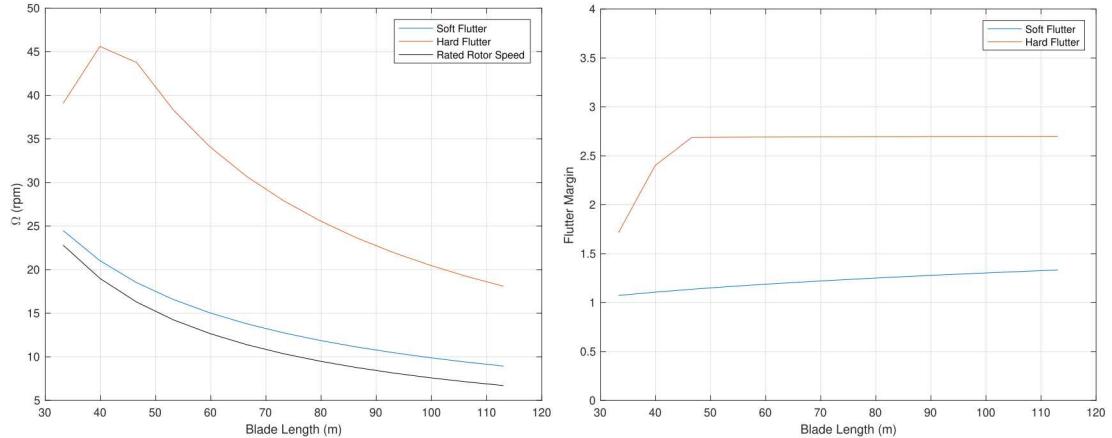


Figure 3. a) Flutter speed for increasing blade size, and b) flutter margin for increasing blade size.

soft flutter margin is closer 1, indicating excessive fatigue motion could be likely, agreeing with the Siemens flutter experiment where a limit cycle oscillation was observed.

Large blade in this analysis past 100 m do not appear to have any hard flutter concerns based on size alone. The analysis showed hard flutter margin is above 2.7 and stays steady for all blade sizes. This is because the flutter speed decreases at the same rate as maximum rotor speed. The soft flutter margin is much closer to unity, and therefore the limit cycle oscillations may accelerate fatigue damage of large blades. Therefore it is recommended to model non-linear structures in flutter analysis as performed by Kallesøe for all wind turbine designs.

These results initially seemed in contrast to Resor [19] where the flutter margin decreased with blade size. The explanation for this difference is that the reduction in flutter margin kept including different blade innovations and was design specific, as opposed to being related to larger blades. For example the smallest blade in this trend was the Sandia CX-100, a blade that used carbon fiber and bend-twist coupling. Whereas the SNL-100 blade was a fiberglass design upscaled from a smaller blade design. Therefore, it is more accurate to say that innovative blade design technologies can change the flutter margins, as opposed to the size of wind turbine blades.

4.2. 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 [7]. The ratio of flap and edge rigidity compared to the baseline 100 m blade was used to predict flutter effects of a highly flexible, rail transported blade. Figure 4 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 composition or similar design choices to increase torsional rigidity and avoid flutter.

4.3. 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

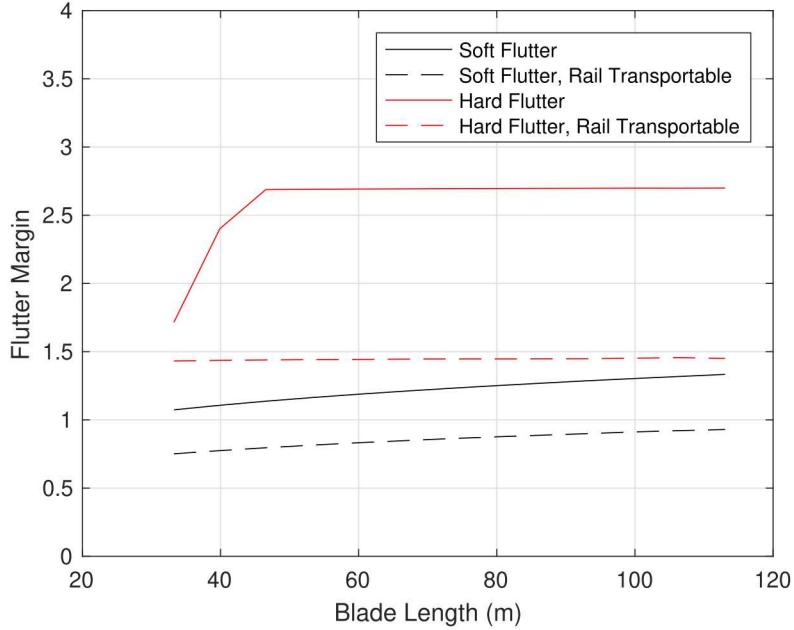


Figure 4. Highly flexible rotors for rail transport are likely susceptible to soft flutter.

previously described: $L_{edge} = \frac{C_{l\alpha}}{2} \rho b^2 \alpha \ddot{y} + C_{l\alpha} \rho b W \alpha (1 + C(k)) \dot{y}$ and $M_{edge} = -\frac{C_{l\alpha}}{2} \rho b^3 \alpha \ddot{y} - C_{l\alpha} \rho b^2 W \alpha (a + \frac{1}{2})(1 + C(k)) \dot{y}$. Figure 5 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. Further examination of the matrix terms of the modal analysis should be performed to answer why these terms do not impact the flutter results.

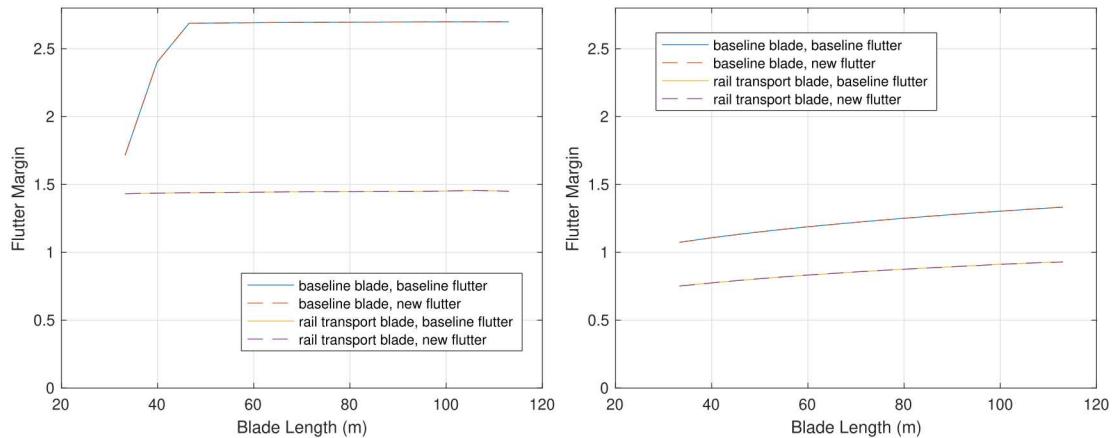


Figure 5. Flutter margins are not affected by the lift and moment due to harmonic edge motion.

5. Conclusions

In this paper the Sandia flutter code, BLAST, was updated for the possibility that the aerodynamic lift and moment due to harmonic edge motion would be important. However the analysis showed that these loads are not necessary, and there is no difference in flutter solution for a large variety of blade sizes, and even the highly flexible rail transport blade. The effect of mass reduction was more than outweighed by the coalescence of flap and torsion modes such that the flutter margin was decreased, by as much as 40%, or as low as 1.4, for hard flutter, and below 1 for soft flutter.

This means 100 m blades, flexible enough to be transported by rail, will likely exhibit the same load limit cycle oscillation seen by Kallesøe in the Siemens 7 MW flutter, even below rated speeds. Additionally, it was found that blade size is not the driver for flutter, as it was shown that a non-innovative blade design upscaled to over 100 m does not have flutter concerns because the flutter speed reduced at the same rate as maximum rotor speed, $\Omega_{flutter} \propto \Omega_{rated} \propto \frac{1}{L}$. Rather it was design specific choices of previous flutter analyses that yielded reduced flutter margins for large blades, such as aeroelastic tailoring. Finally, it is recommended that to produce a highly flexible 100 m blade design that does not experience load limit cycle oscillations, the torsional rigidity should be significantly increased, by means of biaxial composite layers or other structural changes.

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