

# Parameter Sensitivities Affecting the Flutter Speed of a MW-Sized Blade

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With the current trend toward larger and larger horizontal axis wind turbines, classical flutter is becoming a more critical issue. Recent studies have indicated that for a single blade turning in still air the flutter speed for a modern 35 meter blade occurs at approximately twice its operating speed (2 per rev), whereas for smaller blades (5-9 meters), both modern and early designs, the flutter speeds are in the range of 3.5-6 per rev. Scaling studies demonstrate that the per rev flutter speed should not change with scale. Thus design requirements that change with increasing blade size are producing the concurrent reduction in per rev flutter speeds. In comparison with an early small blade design (5 meter blade), flutter computations indicate that the non-rotating modes which combine to create the flutter mode change as the blade becomes larger (i.e. for the larger blade the 2<sup>nd</sup> flapwise mode, as opposed to the 1<sup>st</sup> flapwise mode for the smaller blade, combines with the 1<sup>st</sup> torsional mode to produce the flutter mode). For the more modern smaller blade design (9 meter blade), results show that the non-rotating modes that couple are similar to those of the larger blade. For the wings of fixed-wing aircraft, it is common knowledge that judicious selection of certain design parameters can increase the airspeed associated with the onset of flutter. Two parameters, the chordwise location of the center of mass and the ratio of the flapwise natural frequency to the torsional natural frequency, are especially significant. In this paper studies are performed to determine the sensitivity of the per rev flutter speed to these parameters for a 35 meter wind turbine blade. Additional studies are performed to determine which structural characteristics of the blade are most significant in explaining the previously mentioned per rev flutter speed differences. As a point of interest, flutter results are also reported for two recently designed 9 meter twist/coupled blades.

## I. Introduction

Early and recent investigations of stability in wind turbine blades addressed the issue of classical flutter for smaller rotors<sup>1-3</sup> (~10m blades). These simulations, which apply linear aerodynamics to a blade turning in still air, indicate flutter rotational speeds of the order of 5 times the operating speed of the rotor. The mode shape associated with the onset of flutter generally consists of a coupling of the 2<sup>nd</sup> flapwise and 1<sup>st</sup> torsional modes of the stationary blade. In the recent past classical flutter investigations have also been completed for larger blades<sup>4,5</sup> (~35m blades). Results from these simulations indicate flutter rotational speeds in the realm of 2 times the operational speed of the rotor. As with the smaller rotors the flutter mode shape also consists of a coupling of the 2<sup>nd</sup> flapwise and 1<sup>st</sup> torsional modes.

Simple scaling of the dimensions of the blade without altering the materials of which it is made, indicate that the per rev flutter speed (ratio of the flutter rotational speed to the rotor operating speed) should not change with scale, nor should the character of the flutter. This observation is primarily motivated by the nondimensional form of the classical flutter solution for an infinitely long airfoil,<sup>6</sup> on which the simulations presented here are based. For the more structurally complex blades addressed in this work, this independence of scale still holds, as will be demonstrated. As nondimensional forms are not plausible for these complex blades, a modern larger blade can be scaled down to the size of a modern smaller one so that one-to-one comparisons of the two blades can be made. Using this comparison as a guide, parameters for the scaled larger blade can be artificially altered through

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simulation in an attempt to identify the critical parameters that lead to the noted marked reduction in the per rev flutter rotational speed.

A number of the important critical parameters are identified in text books.<sup>7-9</sup> These texts have also recommended parameter variances to minimize the prospect of flutter, as outlined 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 wing, 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)

Through simulation, this paper attempts to identify design changes that develop as a result of increasing blade size that may lead to significantly lower per rev flutter speeds. In the course of this analysis flutter speed sensitivities to various design parameters are developed which can assist the designer in raising the per rev flutter speed of a given blade.

The next section of the paper briefly outlines the technique used for the prediction of classical flutter speeds, physical comparisons between the scaled-large and small blades, and classical flutter details for each blade. Following this, results of the investigation into the possible causes of the flutter speed reductions that seem to occur as the blade size increases. Lastly, a summary with conclusions is presented.

## II. Methods and Models

Focusing on aeroelastic stability associated with the shed wake, the frequency-domain technique developed by Theodorsen<sup>6-10</sup> for predicting classical flutter in fixed wing aircraft has been adapted for use with a rotor blade. This method assumes that the flow always remains attached and in the linear aerodynamic regime. To simplify the analysis the rotor is assumed to be turning in still air, and, thus, for no inflow, unsteady aerodynamics caused by the trailing wake can be neglected. Consequently, the aerodynamics for a single blade is similar to that of a fixed wing with a free stream velocity that varies linearly from the root to the tip, assuming that the shed wake of the preceding blade dies out sufficiently fast so that the oncoming blade will encounter essentially still air. The blade also differs from the wing structurally in that it is centrifugally stiffened and rotating coordinate system effects are included in the equations of motion (i.e. Coriolis and centrifugal softening terms). Aerodynamic quantities that vary along the span of the blade, such as the semi-chord,  $b$ , the free stream velocity,  $U$ , and the lift curve slope are included using a finite element technique wherein the quantities are assumed to vary linearly over the length of the element and are then included within the integral over the element length associated with the principle of virtual work used in the development of the element.

Theodorsen's solution is couched in the frequency domain and contains both circulatory and noncirculatory aerodynamic terms. These terms are linear functions of the blade angle of attack, its first and second time derivatives, and the first and second time derivatives of the blade plunging motion (flapping motion perpendicular to the free stream). Moreover, the circulatory terms are multiplied by a complex-valued function (the Theodorsen Function) which depends on the reduced frequency and hence, the frequency of the flutter oscillation. The presence of this function necessitates an iterative solution procedure since the flutter oscillation frequency is not known a priori. Additional details of this procedure and the general technique used here for predicting classical flutter in wind turbine blades can be found in Ref. 4.

The blades selected for this study have both been designed in the recent past employing modern design practices associated with the use of glass fiber-reinforced plastics. The larger blade is the WindPACT blade,<sup>11</sup> which has a blade length of 33.35 m and a tip radius of 35 m. It is designed to operate on a 3-bladed 1.5 MW rotor having a maximum rotor speed of 20.5 rpm (0.342 Hz). The smaller blade is the GX-100 blade,<sup>2</sup> which has a blade length of 9.2 m and a tip radius of 9.86 m. It is designed to operate on a 3-bladed 115 kW rotor. For purposes of comparison to the larger rotor, this rotor is assumed to operate at a scaled maximum rotor speed of 72.8 rpm (1.213 Hz).

After scaling the larger blade down to the size of the smaller blade using a scale factor of 9.86/35.0, the superimposed planforms of the two blades are shown in Fig. 1. The bold curves depict the scaled WindPACT blade and the light ones, the GX-100 blade (This will be the case in Fig.s 1 through 5.). The dashed lines denote the 1/4 and 1/2 chord lines for each blade. The chord averages are nearly equal with scaled WindPACT blade at 0.5438 meters and the GX-100 blade at 0.5610 meters, yielding similar aspect ratios of 18.13 and 17.58 respectively. However, the

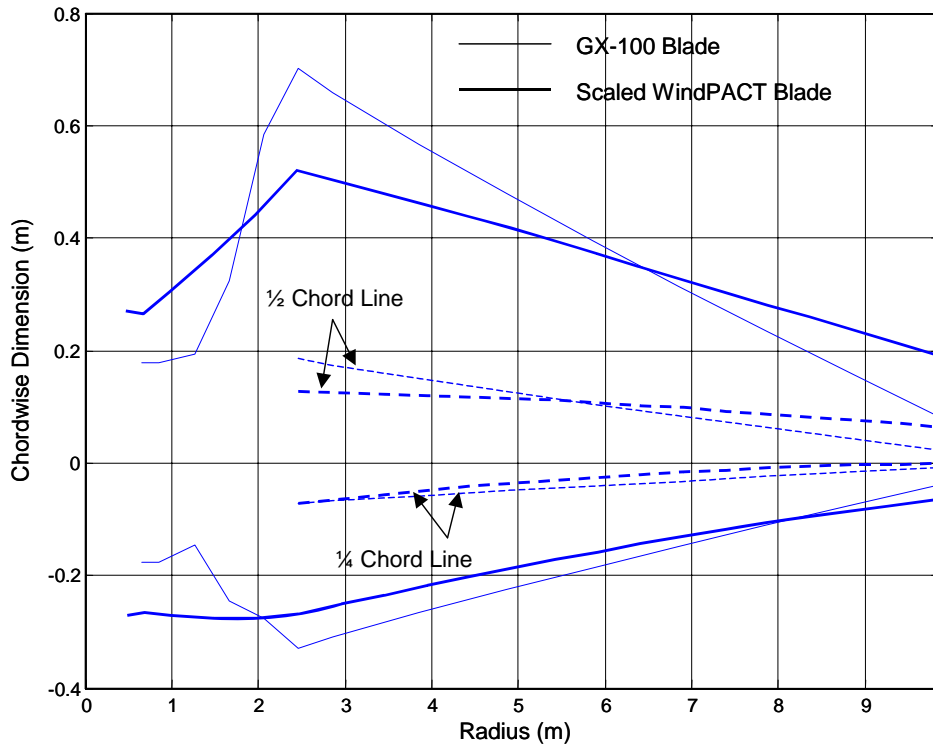


Figure 1. Planforms of the scaled WindPACT and GX-100 blades.

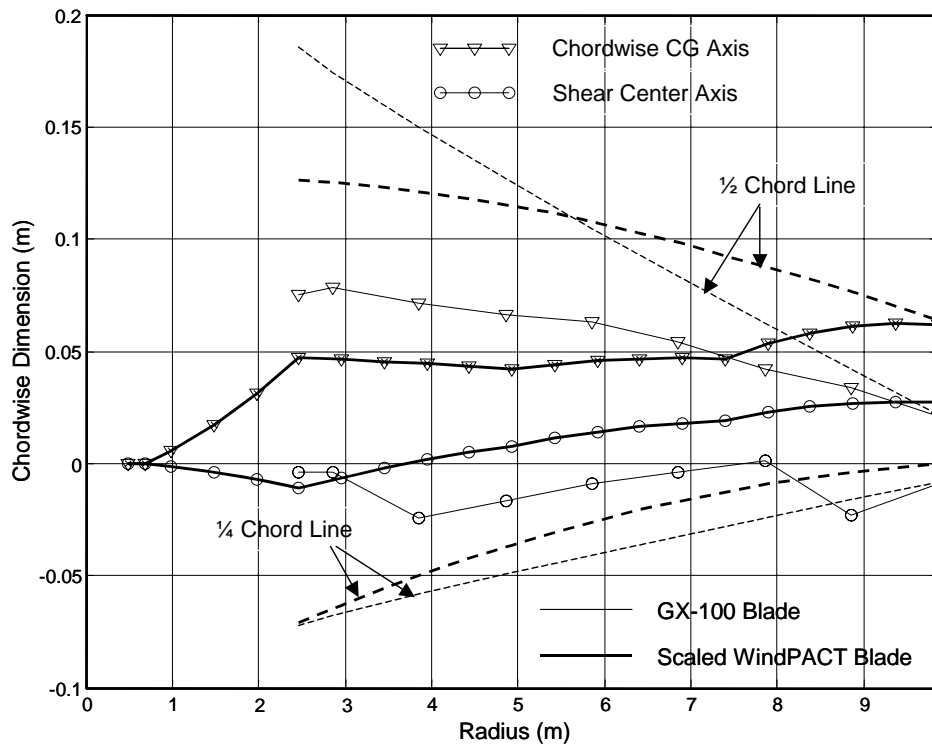
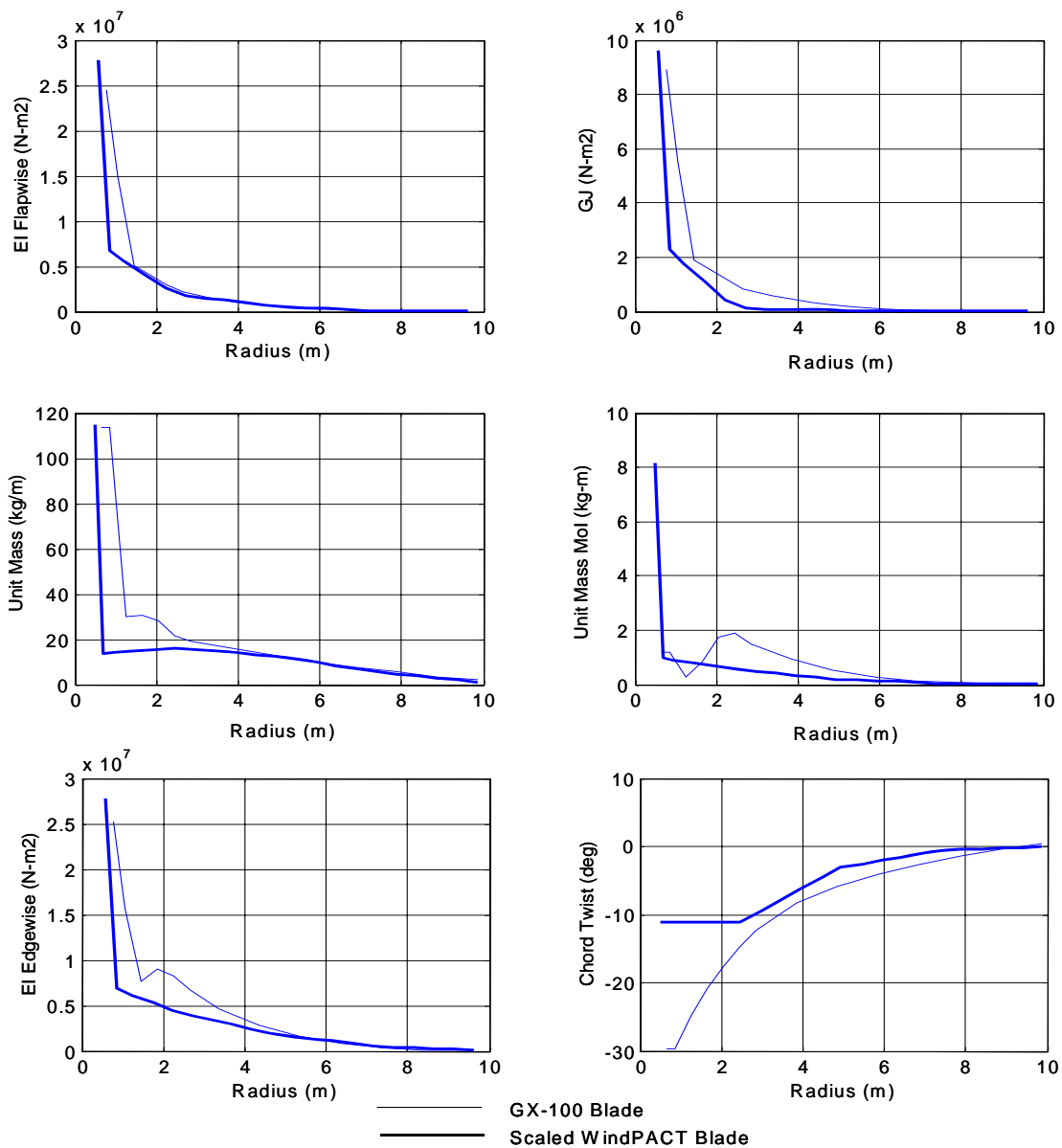


Figure 2. Chordwise CG and shear center axis locations for the scaled WindPACT and GX-100 blades.

blade tapers are significantly different, producing an added degree of “stubbiness” for the GX-100 blade (a quality also apparent in blades having lower aspect ratios).

Figure 2 provides a zoom-in of Fig. 1 showing additional information in the region between the  $\frac{1}{4}$  and  $\frac{1}{2}$  chord lines for each blade. As mentioned above, the bold curves depict the scaled WindPACT blade and the light ones, the GX-100 blade. The curves with the inverted triangles denote the chordwise center of mass axes, and the ones with the circles, the shear center axes. Note that for the GX-100 blade, the center of mass axis is generally further aft of the shear center axis than that of the scaled WindPACT blade. Also for the GX-100 blade, the shear center axis appears on average to be closer to the  $\frac{1}{4}$  chord line, i.e. further forward than that of the WindPACT blade.

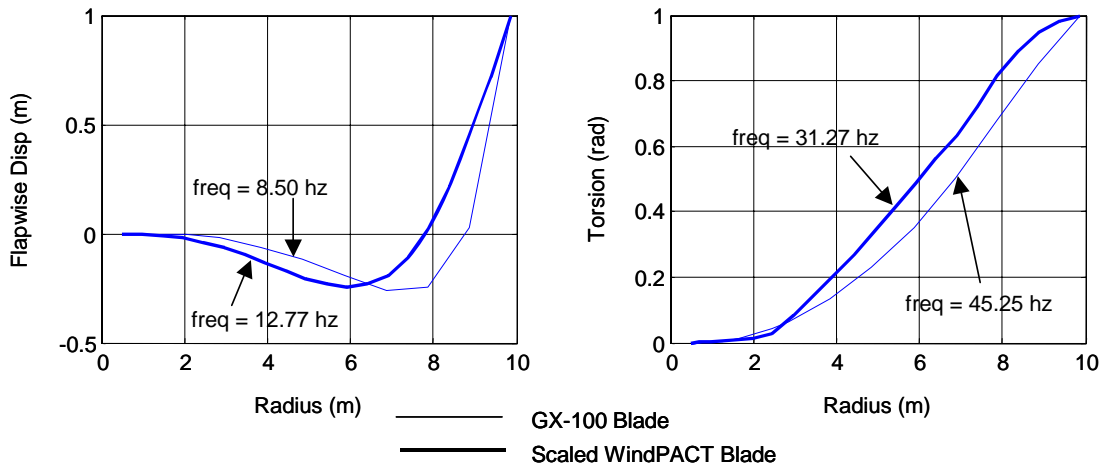
In Fig. 3 a comparison of critical distributed beam and mass properties for the two blades is presented. Comparisons of the flapwise flexural rigidity (EIf), the unit mass (mass per unit length), the torsional rigidity (GJ), the unit mass moment of inertia (mass moment of inertia per unit length), the edgewise flexural rigidity (EIe), and the chordwise twist distribution are shown as a function of span. Some of these properties are critical because they govern the flapwise and torsional natural frequencies of the blade, which strongly influence the onset of classical flutter. The flapwise flexural rigidity and unit mass curves track well beyond a radius of 4 meters, but deviate inboard of that point. The torsional rigidity and unit mass moment of inertia curves display significant deviations



**Figure 3. Structural and Mass Properties for the scaled WindPACT and GX-100 blades.**

over a larger region of the blade span than those of the flapwise flexural rigidity and unit mass, with the GX-100 blade exhibiting greater values for both the torsional rigidity and the unit mass moment of inertia. The dip in the unit mass moment of inertia between the radii of 1 and 2 meters for the GX-100 blade is the result of a thinning of the skin while preserving the outside diameter in that region. The edgewise flexural rigidity variations mimic those of the torsional rigidity except for a dip in the GX-100 curve similar to that of its unit mass moment of inertia curve. Generally the chordwise twist for the GX-100 blade is greater than that for the WindPACT blade, with significant deviations occurring inboard of 2.5 meters.

The critical mode shapes of the stationary blades (not rotating) are shown in Fig. 4. They consist of the 2<sup>nd</sup> flapwise mode and the 1<sup>st</sup> torsional mode, which are the two modes that seem to combine to form the flutter modes of these blades (as will be seen presently). For the GX-100 blade the 2<sup>nd</sup> Flapwise mode seems to exhibit greater activity near the tip than that of the scaled WindPACT blade. The natural frequencies are markedly different, leading to significantly different torsional to flapwise frequency ratios;  $45.25/8.50=5.32$  for the GX-100 blade and  $31.27/12.77=2.45$  for the scaled WindPACT blade.



**Figure 4. Second flapwise and first torsional stationary (non-rotating) mode shapes for the scaled WindPACT and GX-100 blades.**

Figure 5 shows a comparison of the flutter modes for the two blades. The modes are complex due to the effects of the aeroelasticity. In the flapwise direction the motion is consistent with 2<sup>nd</sup> flapwise mode behavior. Note the significant edgewise motion in the flutter mode for the scaled WindPACT blade. Due to blade design differences, the flutter speed for the scaled WindPact blade is significantly down from that of the GX-100 blade; 2.57 rps versus 4.45 rps respectively. Possible causes for this marked difference will be investigated in the next section of the paper. The flutter frequency of the scaled WindPACT blade is also significantly down from that of the GX-100 blade (21.50 Hz versus 31.32 Hz respectively). But, as expected, both are down from their respective torsional natural frequencies shown in Fig. 4.

It is of interest to note that the flutter speed for the scaled WindPACT blade scales perfectly from the parent full-scale WindPact blade, as indicated in Table 1.

**Table 1. Flutter results for the full and scaled WindPACT Blades.**  
(Scale factor =  $9.86/35 = 0.2817$ )

Quantity	Full-Size WindPACT Blade	Scaled WindPACT Blade
Flutter Frequency (Hz)	6.057	21.50
Flutter Speed (rps)	0.723	2.566
Operating Speed (rps)	0.342	1.213
Per Rev Flutter Speed	2.114	2.115

As shown, the flutter frequency also scales perfectly. The flutter mode shapes are slightly different in that the dominant motion for the full-scale blade was the flapwise displacement rather than the torsional rotation. Entirely similar behavior was noted when scaling the GX-100 blade up to the size of the WindPACT blade.

### III. Results

Reviewing the list in the “Introduction” section of this paper that identifies parameter variances for minimizing the prospect of flutter, the two parameters that have the most potential for explaining the flutter speed difference for the two blades are the torsional stiffness for raising the torsional natural frequency, and the ratio of the torsional to flapwise natural frequencies. These two parameters are related but can also be independent. As the aspect ratios of the two blades are close in value, this parameter is deemed not to be of much use in this study. Likewise, since the chordwise center of mass axis for the GX-100 blade is more aft of its corresponding shear center axis than that of the scaled WindPACT blade (and therefore less stable), this parameter will not be of use in explaining the greater per rev flutter speed GX-100 blade. For design purposes, however, results will be presented that show how this

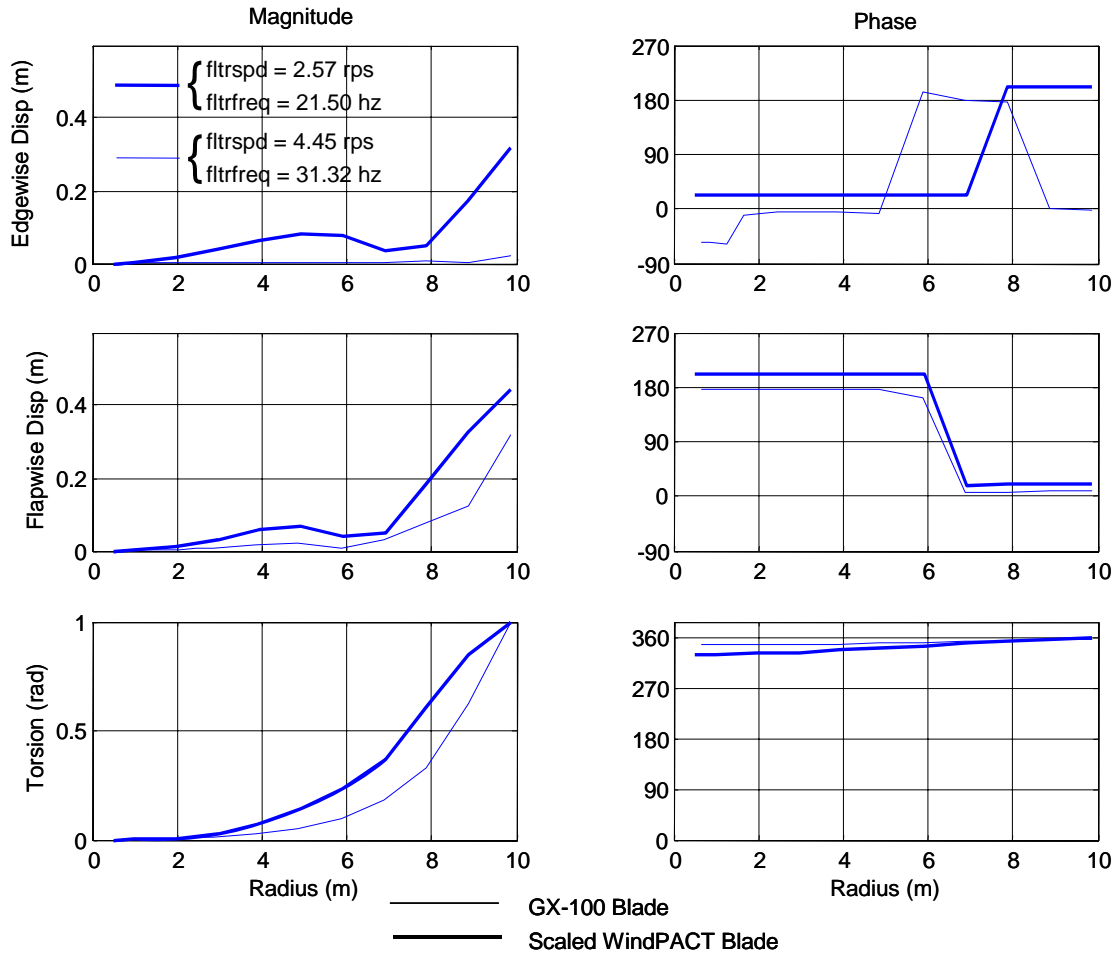


Figure 5. Classical flutter complex-mode shapes for the scaled WindPACT and GX-100 blades.

parameter affects flutter speed for the WinPACT blade. Lastly selected blade properties of the WindPact blade were systematically replaced by scaled up properties of the GX-100 blade to determine which ones, individually and/or in combination, were of most importance in raising the flutter speed of the WindPACT blade to that of the GX-100 blade.

For modifying the two promising parameters discussed above, two approaches were used. The first was to incrementally modify the torsional stiffness of the WindPACT blade from its design stiffness to a scaled stiffness equivalent to that of the GX-100 blade. This produces an increase in the torsional stiffness of the WindPACT blade. As all other blade properties remain unchanged, this alteration produces an increased torsional frequency and an increased torsional to 2<sup>nd</sup> flapwise frequency ratio, both of which should cause the per rev flutter speed to increase. In the second approach the rotational inertia of WindPACT blade was modified by symmetrically moving the blade mass fore and aft of the mass center, in order to alter the torsional frequency of the blade. As before all other blade properties remain unchanged with this alteration. When the rotational inertia is decreased the torsional frequency

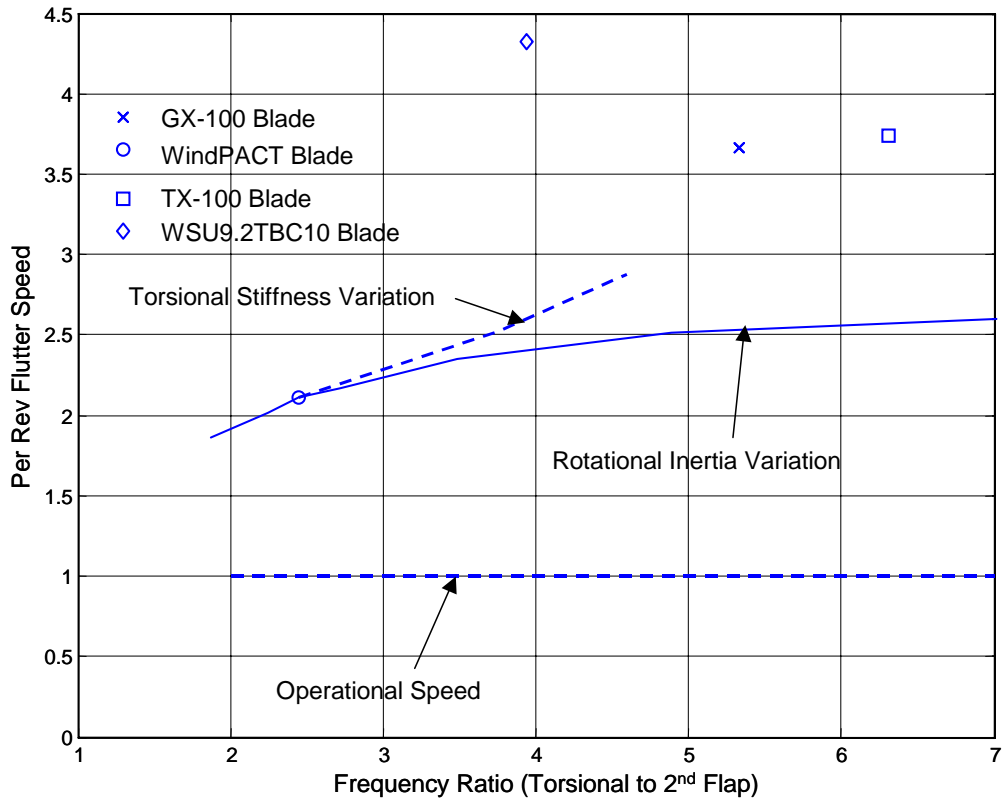


Figure 6. Per rev flutter speed variation with frequency ratio for the WinPACT blade.

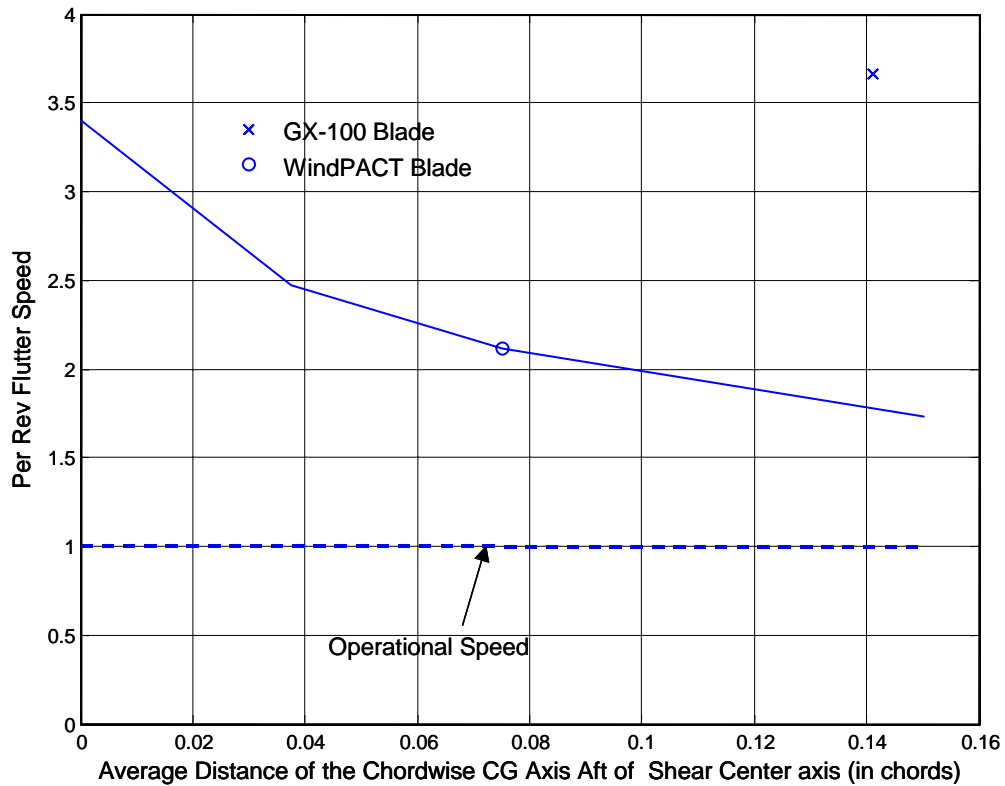


Figure 7. Per rev flutter speed variation with average chordwise CG and shear center axis separation.

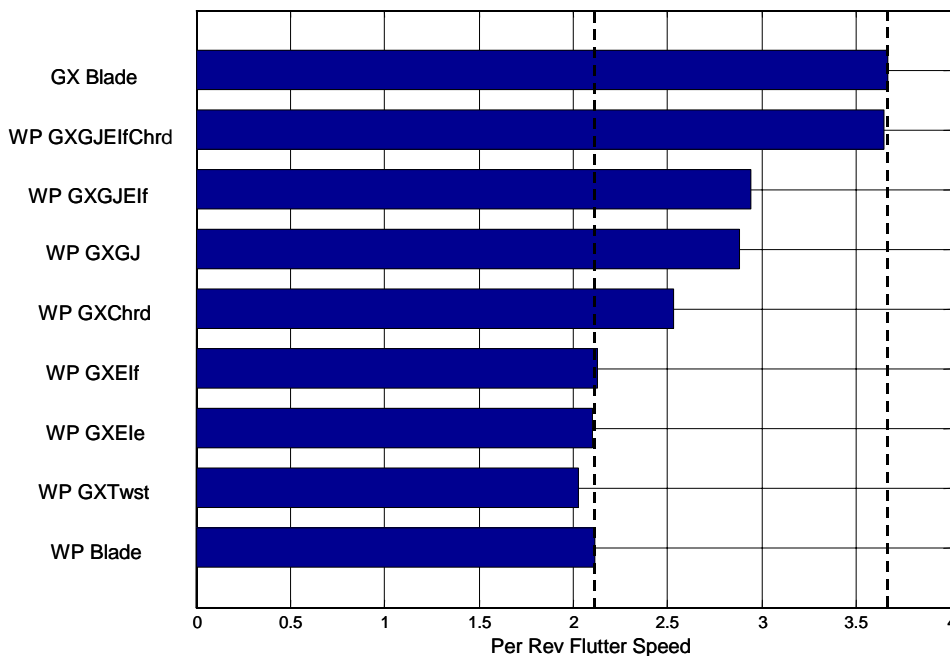
increases leading to an increase in the torsional to 2<sup>nd</sup> flapwise frequency ratio and an associated increase in the per rev flutter speed.

Results from these modifications are shown in Fig. 6 where the per rev flutter speed is plotted versus the non-rotating torsional to 2<sup>nd</sup> flap frequency ratio. The operational rotor speed is denoted by the horizontal dashed line at 1 per rev. The circle denotes per rev flutter data for both the full-scale and scaled versions of the WindPACT blade and the “x,” the GX-100 blade. The dashed curve in Fig. 6 labeled “Torsional Stiffness Variation,” tracks the per rev flutter speed of the WindPACT blade as its torsional stiffness is incrementally increased to a scaled stiffness equivalent to that of the GX-100 blade at the right-most end of the curve. Although the per rev flutter speed significantly increases, by itself the torsional stiffness variation is not enough to close the gap in per rev flutter speed between the WindPact blade and the GX-100 blade. Likewise, as indicated by the curve labeled “Rotational Inertia Variation,” when the frequency ratio is increased by decreasing the rotational inertia, the more modest increases in per rev flutter speed are not sufficient to close the gap.

Ideally, in order to show ramifications of design trends in moving from smaller to larger blade designs, flutter predictions for a number of smaller and larger blade designs are desirable. Unfortunately, details on many of the blades design are unavailable primarily because they are proprietary. However, as indicated in Fig. 6, details for two additional smaller blade designs are available, represented by the square and the diamond corresponding to flutter data for the TX-100<sup>2</sup> and the WSU9.2TBC10<sup>3</sup> blades, respectively. These blades are in the smaller blade category (~9 m), and are designed using a carbon-glass hybrid layup that twists as it bends.<sup>12</sup> They also exhibit higher per rev flutter speeds similar to that of the GX-100 blade. A possible explanation for the especially high flutter speed of the WSU9.2TBC10 blade in conjunction with a lower frequency ratio is that in that blade the chordwise center of mass axis is assumed to lie on the shear center axis. This tends to elevate the flutter speed relative to cases where that axis lies aft of the shear center axis (the usual case for the other blades investigated here).

As mentioned above, the position of the chordwise center of mass axis relative to the shear center axis will not be of use in explaining the greater per rev flutter speed GX-100 blade. However, for design purposes, results are presented in Fig. 7 that show how this parameter affects flutter speed for the WinPACT blade. In this figure the abscissa represents the average distance in chords that the Chordwise CG axis is aft of the shear center axis. When the distance is zero, they are collinear. As before the circle indicates the per rev flutter data for both the WindPACT blade and the scaled WindPACT blade, and the “x,” the GX-100 blade. As the location of the CG axis of the WindPACT blade is modified to more closely replicate that of the GX-100 blade the gap in the per rev flutter speeds widens, as expected.

In Fig. 8 WindPACT blade properties are systematically altered, individually and/or in combinations to provide



**Figure 8. WindPACT flutter speed variations resulting from the selective substitution of scaled GX-100 properties.**



explanations for the noted flutter speed differences. Blade properties that affect the various classes of mode shapes (flapwise, edgewise and torsional) are modified so as to be scaled replicas of those of the GX-100 blade. Blade twist and chord distributions are also replaced by scaled versions of those of the GX-100 blade. Finally combinations of these modifications are explored to fully understand the design differences between these to blades that lead to the significant differences in per rev flutter speed. The lowest bar in Fig. 8 corresponds to the per rev flutter speed of the unadulterated WindPACT blade, and the highest one, that of the GX-100 blade. The vertical dashed lines help to gauge where modified WindPACT configurations fall between these two flutter speeds. As indicated in Fig. 8, the individual substitution of the GX-100 twist distribution and edgewise flexural rigidity (EI<sub>e</sub>) both produce a reduction in the WindPACT blade's flutter speed, whereas the individual substitution of the flapwise flexural rigidity (EI<sub>f</sub>), the torsional rigidity (GJ) and the chord distribution all produce an increase in flutter speed (the torsional rigidity and chord distribution producing much more significant increases than the flapwise flexural rigidity). In combining the flapwise flexural and torsional rigidities (GJ/EI<sub>f</sub>) a slight synergistic effect is noted in that the combination produces a result that is a little larger than the sum of the individual contributions. An even greater synergistic effect occurs when these two scaled GX-100 rigidities are combined with the scaled GX-100 chord distribution (GJ/EI<sub>f</sub>Chrd), producing a per rev flutter speed nearly equal to that of the GX-100 blade. Replacing all WindPACT blade properties with scaled GX-100 ones is equivalent to scaling the GX-100 blade up to the WindPACT blade size, and, as noted previously, since the flutter speed scales perfectly, the GX-100 per rev flutter speed is attained.

#### IV. Summary and Conclusions

Clearly, from the discussion above, modification of the critical parameters that affect the per rev flutter speed cannot account for the difference between the per rev flutter speeds of the scaled WindPACT and GX-100 blades. Of the parameters investigated, increasing the torsional to 2<sup>nd</sup> flap frequency ratio by increasing the torsional stiffness of the WindPACT blade provides the greatest increase in per rev flutter speed for closing the flutter speed gap (~50% closure). Increasing the frequency ratio by decreasing the rotational inertia of the WindPACT blade produces lesser increases in per rev flutter speed, and is therefore less effective in closing the gap. Moving the Chordwise CG axis of the WindPACT blade further aft relative to the shear center axis to more closely replicate that of the GX-100 blade reduces the per rev flutter speed, increasing the per rev flutter speed gap.

Systematically altering WindPACT blade properties individually and/or in combinations provides a better explanation for the noted flutter speed differences. Blade properties that affect the classes of mode shapes (flapwise, edgewise and torsional) are modified to be scaled replicas of those of the GX-100 blade to determine per rev flutter speed sensitivity. Sensitivities are also determined for scaled versions of the GX-100 blade's twist and chord distributions. Finally combinations of these modifications are explored to identify design differences between these to blades that lead to the significant differences in per rev flutter speed. Results indicate that of the blade properties investigated the greater torsional rigidity and the more tapered chord distribution of the GX-100 blade primarily lead to its higher per rev flutter speed. Although significant individually, the combination of these two properties provides a substantial synergistic effect, enough to nearly close the gap between the unadulterated WindPACT and the GX-100 per rev flutter speeds. The greater flapwise flexural rigidity of the GX-100 blade turns out to be a minor contributor to its higher per rev flutter speed.

Studies such as this one (and hopefully more to follow) provide the blade designer with useful options for designing blades that are less likely to exhibit classical flutter. This may be especially important if, as this study indicates, the per rev flutter speed indeed tends to decrease with increasing blade size.

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