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Large wind turbine edge instability field validation

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Abstract. Wind turbines can exhibit flutter-like edgewise instabilities past a critical rotor speed. These edgewise instabilities are dominated by an edge-torsion coupling due to flapwise blade deflection. This paper experimentally validates the predicted stability limit of a 7 MW machine. State of the art simulation software is used to compare against recorded test data and characterize the observed flutter mechanism. The critical rotor speed at which the edgewise instabilities occur at in field measurements can be predicted by time domain simulations and stability analysis with very good agreement.

1. Introduction
The wind industry continues to push blade length limits in search of low-cost energy. These longer blades are becoming more flexible with lower natural frequencies and solidity. As blade length continues to increase, turbine stability is becoming a greater concern. Ref. [1] presents the results of a test validation campaign, where an edgewise instability was observed on a test turbine, demonstrating the existence of this phenomenon, and the need to consider it for safe turbine design and operation. It is paramount to accurately predict these dynamic instabilities.

The detected flutter mechanism presented by Kallesøe [1] shows the unstable mode was at the 2\textsuperscript{nd} blade edgewise frequency. Once past the stability limit, edgewise blade bending moment oscillations build slowly with a maximum negative damping of only $-\frac{3}{10}$ logarithmic decrement indicating a shallow flutter crossing. At some point, the system reaches a new equilibrium and a limit cycle oscillation (LCO) forms. This is a less aggressive form of flutter compared to classical bending-torsion wing flutter, in which the flutter crossing of the damping curve can be steep causing large growth rates, which can quickly overstress the design. Since Ref. [1] was presented additional test data has been gathered. These additional measurements also show another shallow instability at the blade 1\textsuperscript{st} edgewise frequency, as observed in the rotating frame.

To ensure the safe and robust design of large flexible rotors it is necessary to represent the relevant physics in a numerical model, and then to validate this model against test measurements. Even in normal operating conditions, various authors highlighted the importance of accurately modelling large structural deflections and rotations [2, 3]. In Ref. [4] Pirrung and Madsen
have studied the effect of trailed vorticity on stability with the inclusion of a near wake model which captures the effects of the spanwise gradient of circulation at the blade tip. Their near wake model removes the need for hub and tip loss corrections. The purpose of this study is to validate the flutter predictions from HAWC2 and BHawC (Siemens Gamesa in house nonlinear aeroelastic solver) for the SWT-7.0-154, 7 megawatt (MW) turbine. The effect of using a near wake induction model will be examined.

The paper is organized as follows. Section 2 describes the test setup. Section 3 presents the measurements and related post processing. Section 4 explains the modeling of the test and validation. Finally, section 5 presents the main findings of this paper.

2. Description of the test
In Ref. [1] the authors conducted a test on a real turbine, that was brought to an rpm past the expected stability limit with the intent of observing an aeroelastic instability, and then validating BHawC. Since that test, additional data have been collected, which allow for a deeper understanding of the phenomenon, and better model validation. The test data presented in this report is from a second SWT-7.0-154 prototype turbine located at the DTU Wind Energy test site in Østerild, Denmark. This test data was collected on 5 December, 2018. In this test, the turbine was allowed to operate past the stability limit for a longer amount of time, allowing for the collection of cleaner data. The main characteristics for the test turbine are shown in Table 1.

Table 1: Characteristics of the SWT-7.0-154 prototype turbine, located in Østerild, Denmark.

| Parameter            | Value               |
|----------------------|---------------------|
| IEC Class            | 1B                  |
| Nominal power        | 7 MW                |
| Nominal speed        | 10.3 rpm            |
| Rotor diameter       | 154 m               |
| Blade length         | 75 m                |
| Hub height           | 120 m               |
| Power regulation     | Variable speed, pitch regulated |

2.1. Measurement setup
The prototype turbine is instrumented with many additional gauges and sensors to support load validation and flutter testing activities. The level of instrumentation is much higher than a typical production turbine. Operational data and load values were recorded for all major turbine components, and a fiber Bragg optical strain gauge system was installed at 10 spanwise locations along the blade. At each of these locations 4 gauges are installed: a leading edge, trailing edge, pressure side, and suction side gauge; which enabling flapwise and edgewise bending moment estimation. The main sensors monitored during flutter testing were the outboard fiber Bragg sensors, tower top accelerometer, and the blade root strain gauges, to ensure target load levels were not exceeded and excessive vibrations did not build.

2.2. Test procedure
The following test procedure was followed. The test was performed in conditions with sufficiently high wind speeds to induce a large overspeed event:

1. Turbine initialized in normal operation
2. Controller parameters changed:
A) Rated rotor speed increased to value 10% above expected stability limit
B) Fixed pitch of $-2 \, \text{deg}$ requested in speed-power control region

3. Turbine rotor speed kept at the specified value by the power controller
4. Load levels monitored closely in the event shutdown was required

3. Collected test data
The time history for the test segment is shown in Fig. 1. Since the observed instabilities are due to edgewise modes, only the time histories for the edgewise strain gauges are shown. The fiber Bragg data has proved to be the most reliable in detection of these instabilities, but is unfortunately only available in the test segment from 1000 to 1400 seconds. However, the observed instability is noticeably visible in the tower top acceleration sensor, and could be used for assessing stability in the test segment from 100 to 800 seconds.

As it is apparent from the time histories of the wind and rotor speed, the operating conditions are not stationary. For this reason, the spectral analysis has been performed using a Short Time Fourier Transform (STFT), i.e. a moving window Power Spectral Density. The STFT considerably limits the frequency resolution, but shows which frequencies are contributing to the instability. The STFT of the tower top acceleration and fiber Bragg sensor are also shown in Fig. 1.

In this report, all frequencies are non-dimensionalized by the measured 1\textsuperscript{st} edgewise blade frequency and all rotor speeds are non-dimensionalized by the measured critical rotor speed of the 1\textsuperscript{st} edgewise backward whirling mode.

The STFT shows two dominant modes: first and second edgewise backward whirling (BW). A bandpass filter was applied to the fiber Bragg data around the frequencies of the unstable modes. The bandpass filtered signals are shown in the second row of Fig. 2. The left plot is for the first edgewise mode and the right plot is for the second edgewise mode. Using the bandpass filtered signals, logarithmic decrement damping fits were performed on sections of data that showed vibrations clearly building or decaying. The results of this are shown in the third row of Fig. 2. Every point in the damping fit plots (third row) represents a different 5 point, 20 second window, logarithmic decrement fit. The blue points represent damping fits in the first section of the bandpass filtered signals where vibrations are building. Similarly, the black points represent logarithmic decrement fits taken on the first decaying section of the bandpass filtered signal. The estimated damping value for each fit is plotted against the center RPM value in the third row of Fig. 2, showing the turbine aeroelastic damping as a function of the rotor speed. These estimates are fairly smooth and have linear fits applied. The results of the HAWCStab2 blade-only aeroelastic stability analysis are plotted against the experimentally determined damping crossings. The first edgewise instability, which was found to be the critical mode, matches almost exactly compared to the test data. The damping fit for the second edgewise mode is slightly steeper in test compared to analysis, but the crossing point compares extremely well.

4. Modeling and simulation
This section will show the numerical modeling of the test and related model validation.

4.1. Description of the software
The test has been modeled using three aero-servo-elastic multi-body simulation software, namely BHawC, HAWC2 and HAWCStab2. All three codes model the turbine structural members using beam elements, and compute the aerodynamic loads using Blade Element Momentum (BEM) theory.

BHawC is an aerovservoelastic analysis code developed internally at Siemens Gamesa [5]. Each substructure is modeled using equilibrium-based nonhomogeneous anisotropic beam elements [6].
Figure 1: Measured time histories of: normalized rotor speed, power, wind speed, pitch angle, tower top acceleration and blade tip fiber Bragg sensor. Short Time Fourier Transform of tower top acceleration and blade tip fiber Bragg sensor.
Figure 2: Top, measured time histories of blade tip fiber Bragg sensor. Middle, the time history has been band-pass filtered around the 1\textsuperscript{st} and 2\textsuperscript{nd} blade edgewise frequencies. Bottom, identified aeroelastic damping, and comparison with the prediction from HAWCStab2.
Large displacements and rotations (in the following, deformations) are captured through a co-rotational formulation. The aerodynamics are represented via a Beddoes-Leishman type dynamic stall model, Prandtl blade tip and root loss correction, and a BEM-based induction model.

HAWC2 [7] is developed at DTU Wind Energy. It models the structure with Timoshenko beam elements. Large deformations are captured using floating reference frames [3, 8]. The implementation of the BEM model is described in Ref. [9], and the dynamic stall model in [10, 11]. Tip losses can be included with the classical Prandtl function, or by using the near wake model presented in Ref. [12]. This dynamic trailed vorticity modeling has been shown to reduce the aerodynamic work of prescribed flapwise and edgewise vibrations, and to increase the critical flap-torsion flutter speeds predicted by HAWC2 time simulations by 4-10% [4, 13].

HAWCStab2 [14] is a software for performing aero-servo-elastic stability analysis of wind turbines. It assumes a horizontal-axis three-bladed turbine with both an isotropic rotor and isotropic external conditions. These assumptions imply that for each operating condition, the system will reach a constant steady state. By writing the equations of motion in multi-blade coordinates, the linearization over this steady state provides a constant system matrix, and the eigenvalue problem can then be solved using standard algorithms. The turbine members are modeled using Timoshenko beam elements, while large deformations are obtained with a co-rotational formulation. Thus, the effect of flapwise deflection on geometric edge-torsion coupling is accounted for. This geometric coupling has been shown to have a significant effect on edgewise aeroelastic damping [2]. The system is completed by linearized dynamic stall and dynamic inflow models. The stability analysis can be performed for a single blade or the entire turbine. The frequency response of a HAWCStab2 model has been discussed in Ref. [15].

4.2. Simulation results
During simulation the rotor is initialized at a low RPM and allowed to freewheel without generator back torque. The wind speed is slowly increased until an instability is detected. This approach generates an operational point that is similar to the field test where the generator torque was lowered to reach overspeed. The pitch angle is set to a constant 2 degree towards stall. A similar approach was used earlier [4] to detect the onset of flap-torsion flutter for different modifications of the NREL 5MW turbine. The simulations are run in HAWC2 with a time step of 0.01 seconds. The wind speed ramping rate was chosen as 0.0025 m/s$^2$, half the value used in [4], to ensure that the instabilities with low negative damping have time to build up. The blades are discretized with one sub-body per element, to ensure converged results [8]. Wind speed and rotor speed obtained from a HAWC2 simulation are shown in Fig. 3. The rotor speed is normalized by the critical speed observed in the test measurements. At a normalized rotor speed of roughly 1.10, the blade vibrations extract enough energy from the system to cause a drop in rotor speed. This then appears to be the critical rotor speed of the turbine, but more detailed investigation is necessary to accurately determine the actual stability limit.

The HAWC2 model has been equipped with several displacement sensors over the three blades. The left plot of Fig. 4 shows the STFT of the tip of blade 1, in the edgewise direction, with the frequency axis normalized by the frequency of the first blade edgewise mode. It is clearly visible that the amplitude of the vibrations starts growing from 600 seconds, much earlier than the rotor speed drop in Fig. 3. The other strong peak becomes visible at roughly 850 seconds, at a non-dimensional frequency of 2.5, close to the frequency of the second blade edgewise mode. By converting the displacement of the three blades in multi-blade coordinates, and computing the STFT, we can see that in the rotor cos and sin signals both peaks are shifted in frequency by $-1P$, which indicates that they are the first and second edgewise backward whirling modes. The edgewise forward whirl and collective modes are not excited during this experiment.

Plotting the spectral amplitude at the frequencies of the edgewise modes as function of rotor
speed yields the right plot of Fig. 4. There are two resonance phenomena visible in this plot. At a normalized rotor speed of 0.98 the first edgewise backward whirling (BW) mode is excited by the 3P frequency, and at 0.994 the second edgewise BW mode is excited by the 9P frequency. These resonances make it more difficult to accurately determine the critical rotor speeds at which the damping for these modes become zero. Using the rotor speed where the amplitudes start increasing exponentially after the resonances yields a critical speed of 0.994 for the first edgewise mode and 1.025 for the second edgewise mode. This is in excellent agreement with the test. The HAWC2 results shown in Fig. 4 include the near wake model. Without near wake model, the plot looks qualitatively the same and the critical flutter speed for the first edgewise mode remains unchanged. For the second edgewise mode, the critical flutter speed without near wake model is reduced by less than 0.5%.

The BHawC results were processed in a similar manner, and a STFT of the blade tip edgewise deflection is shown in the left plot of Fig. 5. The second edgewise BW whirl is clearly driving the instability at a normalized frequency of 2.5 beginning at roughly 1100 seconds. Similar to Fig. 4, the spectral amplitudes of the first edgewise BW whirl and the unstable second edgewise BW whirl are shown in the right plot of Fig. 5. The first edgewise BW whirl, begins to grow exponentially at 0.96 normalized rpm. While the first edgewise BW whirl does not go unstable in the BHawC simulation, it is visible in the signal prior to the instability onset, coinciding with 3P resonance. However, at roughly 1.02 normalized rotor speed the blade vibrations of the second edgewise BW whirl extract enough energy to cause a rpm drop. The first edgewise BW whirl then stabilizes at this lower rpm. Once the rotor speed drops the turbine continues to operate below the first edgewise BW whirl stability limit, and remains stable. It is important to note, however, that at the stability limit both modes can be observed in the frequency spectrum. Since both modes reach zero damping at very close rotor speeds, it is not surprising that the second edgewise BW whirl begins to drive the simulation before the first edgewise BW whirl can also go unstable. Unlike the HAWC2 results, once vibrations begin to build, the amplitudes do not decrease after the 3P and 9P resonances. However, the predicted stability limit is again in excellent agreement with the experiment, and this may be because the BHawC simulated stability limit is lower than the 3P and 9P resonances.

4.3. Comparison of operational deflection shapes and predicted blade mode shapes
The Operational Deflection Shapes (ODS) of the edgewise modes are identified from the time simulations, using distributed sensors along the blade for edgewise, flapwise and torsional
Figure 4: Left, STFT of blade edgewise tip displacement for HAWC2 time simulation. Right, amplitudes at the 1st and 2nd blade edgewise frequencies, plotted with respect to the normalized rotor speed.

Figure 5: Left, STFT of blade edgewise tip displacement for BHawC time simulation. Right, amplitudes at the 1st and 2nd blade edgewise frequencies, plotted with respect to the normalized rotor speed.

deflection. The amplitudes and phases at each section are computed via STFTs at the frequencies of the first and second edgewise blade modes. Fig. 6 shows the ODS, where all amplitudes are normalized by the edgewise tip deflection, and all phases are relative to the phase of the edgewise tip deflection. These ODS have also been computed without shear and tower shadow and with a stiff support structure, so that they can be more directly compared to the results of a HAWCStab2 blade only analysis. The first edgewise ODS is almost unchanged due to the tower flexibility, while the flapwise component of the second edgewise ODS shows some dependence on tower flexibility.

Both modes have significant torsional and flapwise components, likely due to the geometric edge-torsion coupling caused by the flapwise deflection [2]. The aerodynamic forces due to the
torsion cause a flapwise component that lags a bit more than 90 degrees in phase behind the torsion. As a consequence the forces due to torsion are close to in-phase with the flapwise velocity (which is 90 degrees ahead of the position) and this can pump energy into the system. Similar behavior for an airfoil section with edge-torsion coupling has been observed previously [16].

There is generally excellent agreement between the operational deflection shapes observed in the HAWC2 time marching simulation and the blade-only mode shapes predicted by HAWCStab2, a frequency domain solution. This indicates that the observed instability is mainly driven by the aeroelastic behaviour of the blades. This is similar to flap-torsion-flutter, where it was observed in Ref. [17] that the critical speeds predicted by blade only and full turbine analysis are in very good agreement.

Figure 6: First (columns 1 and 2) and second (columns 3 and 4) edgewise mode shape from HAWCStab2 blade-only computations compared to operational deflection shapes from HAWC2 for runaway cases.

5. Conclusions
The design of longer blades has progressively increased the importance of aeroelastic stability, and brought the stability limit closer to the operating envelope of a turbine. It follows, that wind turbine simulation codes should also be validated in off-design conditions.

In this paper, we performed a test, where the rotor speed of a real 7 MW turbine was intentionally pushed past its critical stability limit. The turbine operated beyond its stability limit long enough for vibrations to be measured. During this time, load levels were monitored to ensure safe turbine operation. Once vibrations were observed, the controller reduced the rotor speed back to normal levels and the vibrations decayed. The measured time histories have shown that the first and second edgewise backward whirling modes become marginally unstable at similar rotor speeds.

Time series results from HAWC2 and BHawC as well as aeroelastic stability analysis from HAWCStab2 could accurately predict the stability limit within 4% of the values extracted from
the test, see Table 2. In particular, BHawC provides slightly conservatives estimates of the stability limit. It was found that the near wake model in HAWC2 has negligible effect on the critical rotor speed of both modes, which is different than previous conclusions for flap-torsion flutter [4]. It was also found that the critical rotor speeds can be predicted accurately with blade only analysis, and that the operational deflection shapes of the simulated rotor whirling modes are very similar to those obtained with a stiff support structure.

The modes have significant torsional and flapwise components, which is likely caused by the edge-torsion coupling due to the flapwise steady state deflection.

Structural damping has a large influence on the critical rotor speed of the unstable modes, because the rate of change in aeroelastic damping with respect to rotor speed is very small, leading to a shallow crossing point. This points to the importance of accurately modeling structural damping in aeroelastic codes and validating those models with tests.

Table 2: Comparison between the measured and simulated rotor speed of the stability limit.

| Mode                        | Experiment | HAWC2 | BHawC | HAWCStab2 blade-only |
|-----------------------------|------------|-------|-------|----------------------|
| 1st Edgewise backward whirl | 1.000      | 0.994 | –     | 0.980                |
| 2nd Edgewise backward whirl | 1.008      | 1.025 | 0.963 | 0.997                |

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