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Field Validation of the Stability Limit of a Multi MW Turbine

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Abstract. Long slender blades of modern multi-megawatt turbines exhibit a flutter like instability at rotor speeds above a critical rotor speed. Knowing the critical rotor speed is crucial to a safe turbine design. The flutter like instability can only be estimated using geometrically non-linear aeroelastic codes. In this study, the estimated rotor speed stability limit of a 7 MW state of the art wind turbine is validated experimentally. The stability limit is estimated using Siemens Wind Powers in-house aeroelastic code, and the results show that the predicted stability limit is within 5% of the experimentally observed limit.

1. Introduction

The continuous strive towards lower cost of wind energy is leading to rotor designs of increasing diameter and flexibility. Increasing flexibility will inevitably lead to a decreased margin between the normal operating rotor speeds and the critical rotor speed at which a rotor mode goes unstable. Aeroelastic codes including only linear dynamics can be applied to estimate the classical flutter limit. However, several numerical studies, e.g. [1], have shown that the long slender blades of modern multi MW turbines exhibit a flutter-like instability at rotor speeds above a critical rotor speed. The instability is caused by a coupling between edgewise and torsion blade deformations because of large blade deflections. The instability is only observed when large flapwise blade deflection is present.

Compared to classical flutter, the instability is observed at lower rotor speeds, and exhibits a slower increase of the negative damping with rotor speeds above the critical rotor speed [1]. Thus, compared to classical flutter, the observed instability has a less severe effect on the blade. Even though the observed instability is less severe than classical flutter, the instability will, if it arises undetected on a turbine, most likely lead to a catastrophic blade failure. Hence, knowing the critical rotor speed is crucial when designing and configuring the turbine safety system. In [1], it is shown that the instability is only captured using aeroelastic codes that include geometric non-linearities caused by large blade deflections, i.e. HAWC2 [2] and the Siemens Wind Powers (SWP) in-house aeroelastic code, BHawC. Aeroelastic codes that do not include the geometric non-linearities, caused by large blade deformations, will not capture the flutter-like instability, but only the classical flutter observed at higher rotor speeds. Thus, using codes that do not include the geometric non-linearities may lead to identification of non-conservative critical rotor speeds. The studies in [1] are based on blade element momentum theory (BEM). In [3], Georg R. Pirrung et al. shows that replacing the classical BEM model by a near wake model will increase the critical rotor speed with approximately 5-10%. Thus, even though the existence of the instability is well established, it appears that modelling accuracy is unclear and un-validated.

To ensure safe and robust design of large flexible rotors it is necessary to validate the modelling of the identified instability. The purpose of the present study is to validate the critical rotor speed identified using the SWP in-house aeroelastic code BHawC for the SWT-7.0-154, 7 megawatt (MW) turbine.

The outline of the paper is as follows. First, it is shown how the instability is identified through simulations, then the experimental setup is described, and finally the results of the validation campaign are presented.

2. Simulated Stability Limit

All simulations are performed using the SWP in-house aeroelastic code, BHawC. The BHawC code is based on a co-rotational structural model, enabling modelling of geometrically non-linear structures, and a BEM aerodynamic model expanded to allow skew and unsteady inflow, dynamic stall and 3D corrected lift data ([4] and [5]). The BHawC codes stable structural response is very well validated, and BHawC has been successfully applied in turbine design and design validation of all productions within the SWP product portfolio. This paper presents a validation of the capability of the BHawC code to estimate the onset of an instability, which has not yet been validated.

The stability limit of the SWT-7.0-154 turbine is estimated from simulations performed in deterministic conditions at discrete steps in wind speeds from cut-in wind and upwards. The present study is focused on the stability at fine-pitch. Therefore, the simulations are performed with zero power production and the blades at fine-pitch. At each simulated wind speed, a steady state rotor speed is achieved and the stability at the steady state rotor speed is assessed from the simulation results. Simulations where the instability is reached are identified as simulations where edgewise vibrations build up rapidly until a limit-cycle is reached. An example of a simulation where the stability limit is exceeded is shown in Figure 1, where oscillations at the frequency of the 2nd edgewise mode build up rapidly. The stability limit is easily identified by plotting the maximum simulated edgewise oscillation amplitude versus the steady state rotor speed.

Figure 2 shows the maximum edgewise bending moment oscillations at an out-board location on the blade for all of the performed simulations with deterministic inflow. A bifurcation from stable, low-amplitude edgewise oscillations to unstable high-amplitude edgewise oscillations is clearly observed in Figure 2, and the corresponding rotor speed is identified as the stability limit. For all of the simulations, the unstable mode is the 2nd edgewise mode. In addition to the stability limit, the rotor speed where an nP frequency intersects the frequency of the 1st edgewise mode is indicated in Figure 2. It is seen that the instability occurs right after the rotor speed has passed the nP intersection with the 1st edgewise mode. For deterministic inflow, the nP intersection will not lead to significant excitation of the 1st edgewise mode, and low-amplitude edgewise oscillations are observed up until the stability limit, after which the 2nd edgewise mode dominates the blade vibrations.

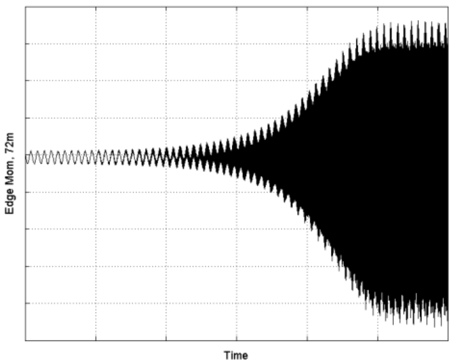

Figure 1 Example of simulation at a rotor speed that exceeds the stability limit.

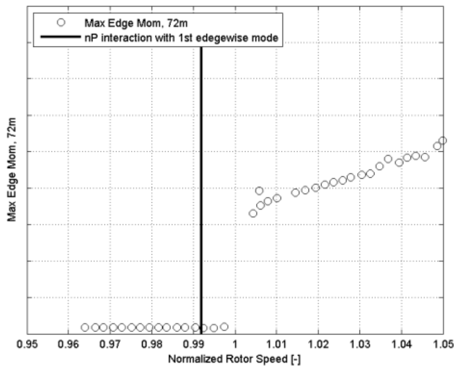

Figure 2 Maximum edgewise bending moments at a radial distance of 72m from the blade root as a function of normalized rotor speed from simulations with deterministic inflow, zero power production and

increasing rotor speed. The rotor speed is normalized with the identified stability limit.

In turbulent conditions, where the 1st edgewise mode is excited at the nP intersection, the blade edgewise oscillations will have a significant contribution from the 1st edgewise mode. However, as the rotor speed approaches and crosses the stability limit, the 2nd edgewise mode will dominate the blade edgewise oscillations. This is illustrated in Figure 3, which shows the results from simulations made in IEC 1B conditions with zero power production, blades at fine pitch and stepwise increasing mean wind speed. In Figure 3, the spectral amplitudes at the 1st and 2nd edgewise frequency extracted from a Fourier transform (FFT) of each of the simulations are plotted as a function of simulated rotor speed. It is seen that the contribution of the 1st edgewise frequency to the blade edgewise oscillations increases at the nP interaction. At the stability limit, however, the contribution of the 1st edgewise mode diminishes and the edgewise oscillations are dominated by the 2nd edgewise mode. The bifurcation from edge oscillation with a combination of the 1st and 2nd edgewise mode seems to occur only slightly after the stability limit which was identified from the deterministic simulations. Thus, the turbulence has little effect on the stability limit, even though it induces nP excitation of the 1st blade edgewise mode just before the stability limit.

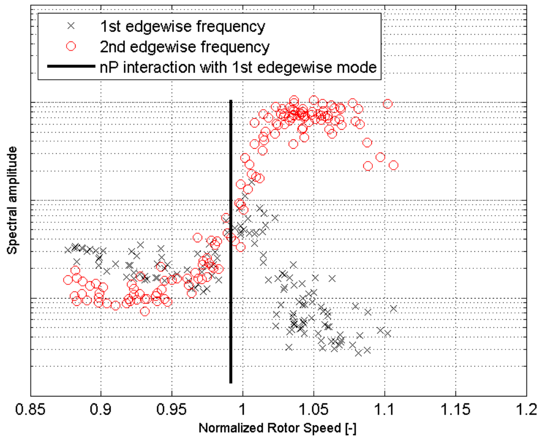

Figure 3 Spectral amplitudes at the 1st and 2nd edgewise frequency of the edgewise bending moment oscillations at a location 72 m from the blade root in simulations with IEC 1B turbulent inflow. The rotor speed is normalized with the identified stability limit.

3. Validation of Identified Stability Limit

The validation campaign is performed on the SWT-7.0-154 prototype turbine located at the DTU Wind Energy test site in Østerild, Denmark. In

Table 1, the main characteristics of the prototype turbine are summarized.

Table 1 Main characteristics of the SWT-7.0-154 prototype turbine in Østerild, Denmark.

SWT-7.0-154 Prototype Main Characteristics	
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 regulation

Figure 4 SWT-7.0-154 prototype turbine in Østerild, Denmark.

3.1. Measurement Setup

The prototype turbine is equipped with an extensive measurement system, which is collecting operational data as well as load measurements on all main turbine components. For the present study, only the blade load measurements from a Fiber Bragg installed in one of the blades of the turbine are utilized in addition to the standard operational measurements. Four fibers are installed in the blade; one on the leading edge, one on the trailing edge, one on the leeside and one on the wind side of the blade. From the measured fiber strains, the edgewise and flapwise bending moments are estimated at 10 positions along the blade. The measurement points are listed in Table 2

Table 2 Distribution of fiber bragg measurement points along the B75 blade.

Measurement No.	Radial distance from the blade root [m]
1	3.5
2	20
3	25
4	30
5	34
6	40
7	50
8	60
9	66
10	72

The studied instability is associated with the 2nd edgewise blade mode. Thus, vibrations are mostly induced on the outer part of the blade, and measurement point 9-10 are of greatest interest for the present study. Only measurements from measurement point 10 will be used in this study.

3.2. Validation execution

The validation is performed at wind speeds that will allow the rotor speed to reach the identified stability limit when the blades are at fine-pitch, and is initiated from a steady state operating point with 0 kW power production and nominal rotor speed. From the steady state operating point the test is carried out through the following steps.

1) The reference rotor speed is raised to $\omega_i = \omega_{nom} + \Delta\omega \cdot i$
2) When ω_i is reached, the rotor speed is held for at least 15 s
3) The rotor speed is decreased to ω_i
4) The loads are assessed, and if no indication of instability is found, steps 1-4 are completed with $i = i + 1$

where, ω_i is the test target speed, ω_{nom} is the nominal speed, $\Delta\omega$ is the test speed increment and i is the test number. The sequence is completed with increasing rotor speeds until a defined maximum speed is reached, or indications of instability have been observed. The Angle of Attack (AoA) is close to optimal AoA and varies less than 1 deg between the different tests. The test is performed at low free wind speeds; therefore the increased rotor speed only has a small effect on AoA.

The test is targeted at identifying an instability that will potentially lead to a blade failure, if the instability is not detected in time to modify the turbine operation. Therefore, relevant load channels are evaluated during, and after each test sequence. During and after each test sequence it is decided based on the observed behaviour whether the test is continued or aborted.

3.3. Validation Results

The outlined test sequence was performed successfully for target rotor speeds between 0.8 and 1.07 times the identified stability limit. A successful test constitutes a test where the target rotor speed is reached and sustained for more than 15 seconds with the blades at or close to fine pitch. The test results are summarized in **Error! Reference source not found.**. **Error! Reference source not found.** shows the spectral amplitudes for the 1st and 2nd edgewise mode observed during all of the test sequences. The spectral amplitudes are extracted from the measurements by applying short term Fourier transform (STFT) with a window size of 5 seconds to the load measurements on the out-board part of the blade sampled during each test sequence. The STFT is applied instead of the ordinary FFT to enable estimation of the vibrational amplitudes at all rotor speeds observed during a test sequence. Applying the STFT instead of the FFT leads to a more scattered plot with potentially both low and high amplitude oscillations at the same rotor speed. However, the envelope of the estimated spectral amplitudes can be used qualitatively for comparison to the results presented in Figure 3. To a large extend, the result from the validation campaign resembles the results observed in the simulations with turbulent inflow. Amplitudes of both edgewise modes are small at rotor speeds well below the nP and 1st edgewise mode intersection, the contribution of the 1st edgewise mode to the edgewise oscillations increases in the vicinity to the nP intersection, and above a particular rotor speed, the oscillations at the 2nd edgewise frequency builds up rapidly while the oscillations at the 1st edgewise frequency decreases. Compared to the simulations, it is seen that the contribution of the 2nd edge mode to the oscillations at the nP intersections is smaller relative to 1st edgewise mode. Furthermore, the validation results indicate that the stability limit of the real turbine is higher (~7%) than the estimated value. However, Georg R. Pirrung et al. [3] have shown that BEM based aeroelastic models, such as BHawC, will under predict the stability limit by 5-10% compared to a more comprehensive near wake model. Taking into account the known under prediction inherited in the BEM method brings the observed stability limit very close to the estimated value.

The test was stopped at a rotor speed ~7% above the estimated stability limit, where an indication of the instability is observed. A time series of part of the last executed test sequence is seen in Figure 6. The build-up of oscillations at the 2nd edgewise frequency when the target rotor speed is reached is clearly seen in the figure.

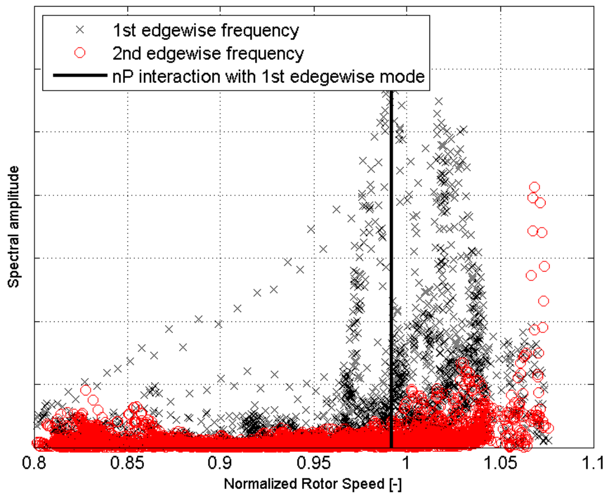

Figure 5 Spectral amplitudes at the 1st and 2nd edgewise frequency of the edgewise bending moment oscillations at a location 72 m from the blade root during the validation campaign. The rotor speed is normalized with the stability limit estimated from the simulations.

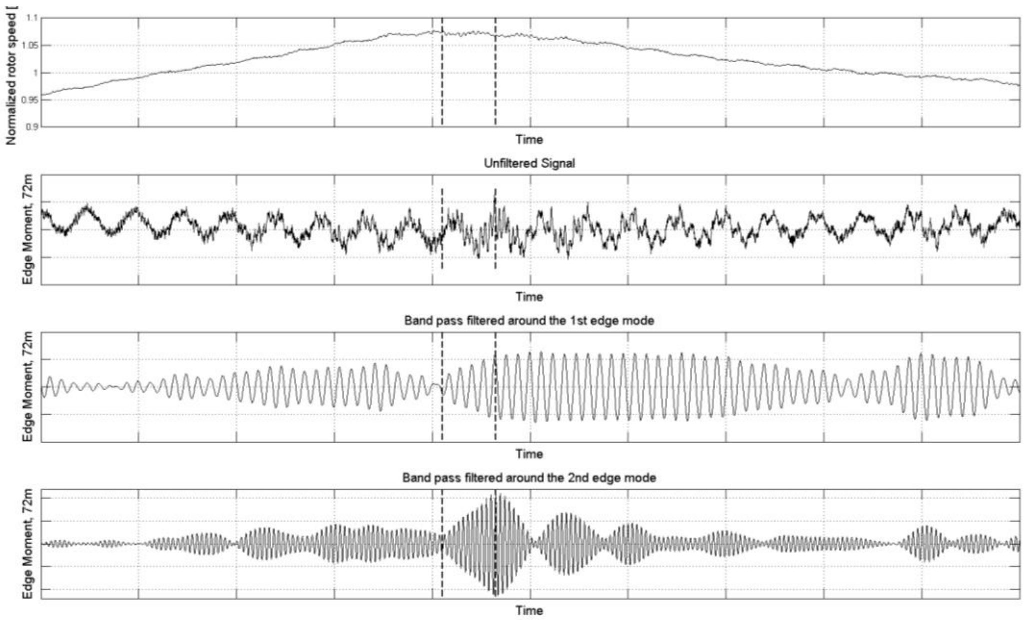

Figure 6 Time series of selected channels during part of the last executed test sequence. The rotor speed is normalized with the stability limit estimated from the simulations.

4. Conclusions

In the present study, the rotor speed stability limit predicted by BHawC for a 7 MW state of the art wind turbine has been validated experimentally. The results show that BHawC under predicts the stability limit by 7%. Part of the under prediction can be explained by the fact that the aerodynamic model applied in BHawC is based on BEM. Georg R. Pirrung et al. [3] have shown that BEM based aeroelastic models under predict the stability limit by 5-10% compared to a more comprehensive near wake model. Compensating for the inherent BEM under prediction, the estimated stability limit is within 5% of the observed limit, and it is concluded that the estimated stability limit is valid. Thus, the present study has shown that geometrically non-linear aeroelastic codes can be applied to accurately estimate the occurrence of the flutter-like wind turbine instability, which cannot be estimated using linear aeroelastic codes.

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