Chapter 70
Dynamic Stability Analysis of Wind Turbines Through In-Field Vibration Tests

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Abstract Depending on their types and sizes, MW-scale wind turbines are usually designed to be operational for wind speeds between 4 and 25 m/s. In order to reach this goal, most of the turbines utilize active pitch control mechanisms where the angle of the blade (pitch angle) is changed as a function of wind speed. Similarly, the whole rotor is rotated toward the effective wind direction by using the yaw mechanism.

The ability of the turbine to adapt to the changes in operating conditions plays a crucial role in ensuring maximum energy production and the safety of the structure during extreme wind loads. This on the other hand makes it more difficult to investigate the system from the dynamic analysis point of view. Unlike ordinary engineering structures, the modal damping ratios identified for wind turbines are not constant; they change depending on wind speed, rotor speed, and blade pitch angle. Unexpected resonance problems due to dynamic interactions among the aeroelastic modes and/or excitation forces can always be encountered. Therefore, within the design wind speed interval, for each velocity increment, it has to be proven that there are no risks of possible resonance problems and that the structure is dynamically stable.

This work presents the results of in-field vibration tests and the corresponding data analysis performed on a 2.5 MW, 80 m diameter wind turbine. Within the scope of the research, 12 different modes were identified for the turbine at parked conditions. Similarly, seven different aeroelastic modes were extracted for the rotating turbine. These results were then qualitatively compared with a reference study in literature which includes in-field vibration tests and aeroelastic stability analysis performed on a similar size and capacity wind turbine.

Keywords Aeroelastic Stability Analysis • Wind turbine • Modal analysis • In-field vibration test • Aeroelastic damping

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70.1 Introduction

Identification of the dynamic properties and the corresponding structural response of wind turbines is essential for optimizing the energy produced, ensuring safe and reliable operation and increasing the lifetime of the system. As the sizes of modern wind turbines increase, their dynamic behaviors get more complicated, and it becomes more important to predict the response characteristics of new designs through simulations.

Modern computation and simulation tools provide designers with great opportunities to detect and solve most of the possible problems at very early stages and to improve their designs. Indeed, several important system properties such as eigenfrequencies and mode shapes, which govern the dynamic response of the turbine, can be estimated very accurately by using structural analysis programs. However, some important dynamic parameters (e.g., damping) cannot be modeled precisely without supplementary information obtained from in-field tests and measurements.

Damping, together with the abovementioned system characteristics, plays a crucial role in predicting maximum dynamic loads and fatigue stresses acting on the structure. The overall damping has a very complex mechanism which requires considering several physical factors simultaneously. Thus, it is very difficult to be modeled without supplementary information obtained from in-field tests and measurements. Some of its components like material damping can nowadays be reasonably well taken into account. However, modeling the damping occurring in bearings, joints, and gearing or the damping due to ground (soil)-structure interaction is still not possible. Similarly, identifying the aeroelastic component of damping which is due to the combined effect of structural deformations and aerodynamic forces is a very challenging task and always needs experimental verification.

Considering the fact that only the models based on real response measurements are able to represent the complicated interactions among different parts of the structure, several tests have been applied on both parked and rotating turbines [1–4]. Although there are numerous studies conducted on wind turbines at parked condition, the information related to dynamic testing and modal analysis of MW-scale large wind turbines during operation is quite limited. This work aims at making a contribution to this challenging field of experimental and operational modal analysis by presenting the results of the in-field vibration tests performed on a 2.5 MW, 80 m diameter wind turbine and the corresponding data analyses.

For this purpose, the dynamic response of the test turbine was monitored by using three different measurement systems, namely, conventional strain gauges, photogrammetry, and laser interferometry, while the turbine was both at parked condition and rotating. The recorded data was analyzed by using OMA (operational modal analysis) methods, and eigenfrequencies and damping ratios were extracted. The obtained system parameters were then qualitatively compared with the results presented in a study from literature [3], which includes both aeroelastic simulations and in-field measurements performed on a similar size and capacity wind turbine.

70.2 Test Turbine

Our tests were conducted on a pitch-controlled, variable speed Nordex N80 wind turbine with a rated power of 2.5 MW. The turbine has a rotor diameter and tower height of 80 m. The photogrammetric measurements were performed by GOM mbH [5] (GOM Optical Measuring Techniques) at the ECN (Energy Research Center of the Netherlands) wind turbine test site located in Wieringermeer, the Netherlands. More detailed information about the facilities of the test site can be found through the related website [6].

The reference turbine used for qualitative comparison, General Electric NM80, is also a pitch-regulated, variable speed wind turbine with a rotor diameter of 80 m. This turbine has a rated power of 2.75 MW and is used as a test case for validation of new aeroelastic stability tools developed within the scope of the European Commission-supported STABCON project [3].

70.3 Measurement Systems

One of the main objectives of the research project is to investigate how optical measurement systems (photogrammetry and laser interferometry) can be used to measure the dynamic response of large wind turbines. Unlike conventional measurement systems (accelerometers, piezoelectric or fiber-optic strain gauges), optical measurement techniques do not require any sensors to be placed on the turbine. Therefore, no additional preparations such as cable installations for power or data transfer are needed inside the blade or the tower. However, some reflective markers should be placed (or painted) on the structure. These markers are made up of a retroreflective material, which is 1,000 times more reflective than the background blade material. Since the markers are in the form of very thin stickers, they do not have any effect on the aerodynamic performance of the blades.

These markers are essential for both photogrammetry and laser interferometry, but they are used for different purposes in each method. Photogrammetry is a proven measurement technique based on the determination of 3D coordinates of the points on an object by using two or more images taken from different orientations and positions. Although each picture provides 2D information only, very accurate 3D information related to the coordinates and/or displacements of the object can be obtained by simultaneous processing of these images. In photogrammetry, markers are used as targets to be tracked by the camera systems, and all the targets can be tracked simultaneously. The layout of the markers throughout the turbine can be seen in Fig. 70.1.

Although photogrammetry is efficiently used in smaller scales by a wide variety of disciplines, this method was applied for the very first time to a MW-scale wind

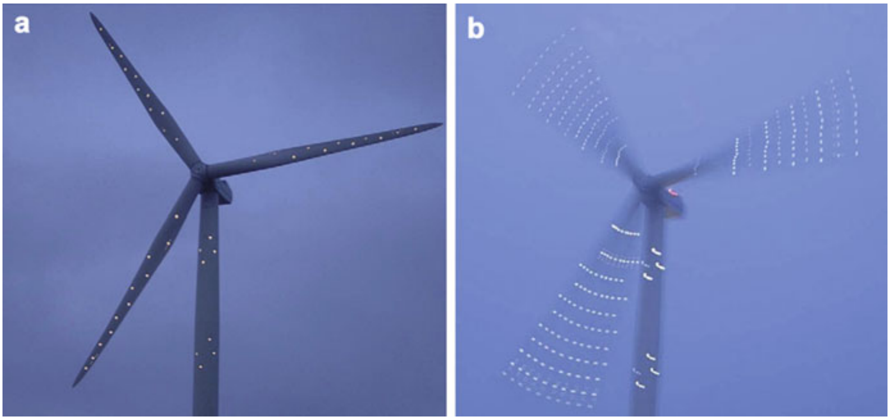

Fig. 70.1 (**a** and **b**) The layout of markers on the turbine

turbine within the scope of this research project. The analysis results showed that deformations of the turbine can be measured with an average accuracy of ±25 mm from a measurement distance of 220 m [7, 8]. Considering the fact that for a rotating turbine deformations measured in flapwise direction can be as high as ±1,000 mm, this accuracy can be considered as high.

In laser interferometry, a laser vibrometer continuously sends a laser beam to the target and receives the beam reflected from its surface. If the object is moving, this causes a frequency change and phase shift between the sent and reflected beams. By detecting this frequency change (Doppler principle), the velocity of the moving object can be found. If the object itself has a reflective surface, no extra retroreflective markers are needed. However, since the blade material was not reflective enough and the distance between the laser source and the turbine was very long, high-quality laser signals could only be acquired if the laser was targeted to the markers. Once the quality of the reflected laser beam is assured, laser vibrometer can measure the vibration of the blade with very high accuracy (in micron level) [9].

A third system, which has already been installed in the turbine as a part of a long-term wind load monitoring campaign conducted by ECN, consists of six strain gauges placed at the root region of the three blades (two strain gauges per blade) and two strain gauges located at the tower base. These strain gauges are used to measure the flapwise and edgewise vibration of the blades and fore and aft and side to side vibration of the tower at a sampling frequency of 32 Hz.

All the data recorded by three different systems were then synchronized by using a GPS clock whose absolute time accuracy is approximately 10 m. Considering the fact that frequencies that are expected to dominate the response of the wind turbine are mostly in the low-frequency range [0–5 Hz], this accuracy can be considered as sufficient. Table 70.1 summarizes the main features of measurements taken by these three different measurement systems.

Table 70.1 The main features of measurements

Measurement type	Strain gauge	Photogrammetry	Laser interferometry
Measurement block (s)	Continuous	21	294
Measurement accuracy	–	±25 mm	In micron scale
Measurement distance	On the turbine	220 m	200 m (max 300 m)
Sampling frequency (Hz)	32	28	1,280
Number of sensors	8	33	1
Parked turbine tests	X	–	X
Rotating turbine tests	X	X	–

70.4 Analysis Results and Identified System Parameters

Researchers [3, 9, 10] agree on the fact that performing modal analysis on a rotating turbine is much more challenging than performing the same analysis on a parked turbine due to the facts that:

- For a rotating wind turbine, some of the important turbine modes have very high aeroelastic damping ratios ranging between 10 and 30 % (in terms of critical damping ratio) which makes them very difficult to be detected by most of the identification algorithms that are currently in use. Aeroelastic damping is a combination of both structural and aerodynamic dampings but mostly dominated by the aerodynamic component caused by rotation of the blades. However, for a parked turbine, the aerodynamic component is small (at low wind speeds); therefore, the identified damping is generally considered to be composed of only structural damping which is usually less than 1 %. On the other hand, some exceptions to this are also described in this section.
- For a rotating turbine, integer multiples of rotational frequency (also called P harmonics where P denotes the rotational frequency) always dominate the response of the structure. These frequencies can be effective up to 24P and sometimes coincide with the true eigenfrequencies of the system [11–13].
- Besides, for rotating turbines, these P harmonics cause violation of the steady-state random excitation assumption which is one of the most important requirements of OMA algorithms.
- Another important assumption, time-invariant system requirement, is also difficult to accomplish for rotating wind turbines because of the rotation of the blades and yawing, pitching motion of the turbine. However, for parked turbines, all these motions of the different components are prevented which makes the time-invariant system assumption much easier to fulfill.

70.5 Tests on the Parked Turbine: Strain and LDV

This section summarizes the results of the analyses of strain gauge and laser interferometry measurements taken on the parked turbine. During the measurements, the turbine was kept at a fixed orientation and yawing motion was prevented by application of the yaw brakes. Blade pitch angles were fixed at zero degree where flapwise blade vibration exactly corresponds to the motion out of the rotor plane. This is the same as the angle of the blade during rotation below rated wind speeds (<15 m/s for the test turbine). Similarly, the brakes were applied to prevent the movement of the rotor.

Table 70.2 summarizes the modal parameters (frequencies and damping ratios) calculated by using strain gauge and LDV measurements. LDV measurements were taken on the markers that were close to the tip of the blades. Frequencies and damping ratios were extracted by using the NExT (Natural Excitation Technique) approach [1, 2] together with the LSCE (Least Square Complex Exponential) time domain identification method. When the turbine starts rotating, the name of the mode changes to the one indicated in parentheses. The abbreviations FW and BW stand for forward and backward whirling, respectively. Damping ratios are given in terms of critical damping ratio.

These modal parameters are important for the tuning and validation of numerical models and for the verification of prototype designs. They can also be used for health monitoring applications. As can be seen in the table, frequency values are relatively stable and do not change depending on the measurement block analyzed. However, damping values may differ slightly. The damping scatter encountered in the first flapwise and side to side tower modes is mostly related to the aerodynamic drag phenomenon [4]. Since the turbine is kept at a fixed orientation during the tests, the relative angle between the effective wind direction and the normal of the rotation plane continuously changes depending on the instantaneous wind

Table 70.2 Modal parameters calculated for the parked turbine

Mode	Frequency (Hz)	Damping
1st fore and aft tower	0.345	0.003
1st side to side tower	0.347	0.003–0.009
1st yaw (BW flapwise)	0.902	0.010–0.020
1st tilt (FW flapwise)	0.974	0.011–0.020
1st symmetric flapwise	1.077	0.010–0.020
1st vertical edgewise (BW)	1.834	0.004
1st horizontal edgewise (FW)	1.855	0.004
2nd tilt (FW flapwise)	2.311	0.005
2nd yaw (BW flapwise)	2.430	0.004
2nd symmetric flapwise	3.00	0.005
2nd edgewise	6.36	0.005
Tower torsion mode (needs further verification)	6.154	0.005

direction, resulting in a different aerodynamic coupling for each measurement. This also shows that it is not possible to completely eliminate the aerodynamic component of damping even for low wind speeds.

70.6 Tests on Rotating Turbine: Strain and Photogrammetry

This section summarizes the results of the analyses of strain gauge and photogrammetry measurements taken on the rotating turbine. During the test period, the response of the turbine was continuously measured by strain gauges. Therefore, modal parameters could be extracted for various operating conditions and wind speeds. Calculated modal parameters were then compared with the results presented by [3]. The work mentioned includes the results of both aeroelastic simulations performed by the stability tool HAWCStab [14, 15] and the real measurements taken on a wind turbine which has a similar size and capacity as the test turbine in our work. Therefore, some of the graphs presented below include the parameters extracted from our study and two additional graphs taken from the simulations and the measurements presented in the reference study [3].

Figure 70.2 shows the aeroelastic frequencies we identified for different wind speeds. As can be seen in the figure, some of the modes extracted for the parked turbine (shown in Table 70.2) could not be detected for the rotating turbine. The first tilt (FW flapwise), first yaw (BW flapwise), and first symmetric flapwise modes could not be identified due to their very high damping ratios. Hansen et al. [3]

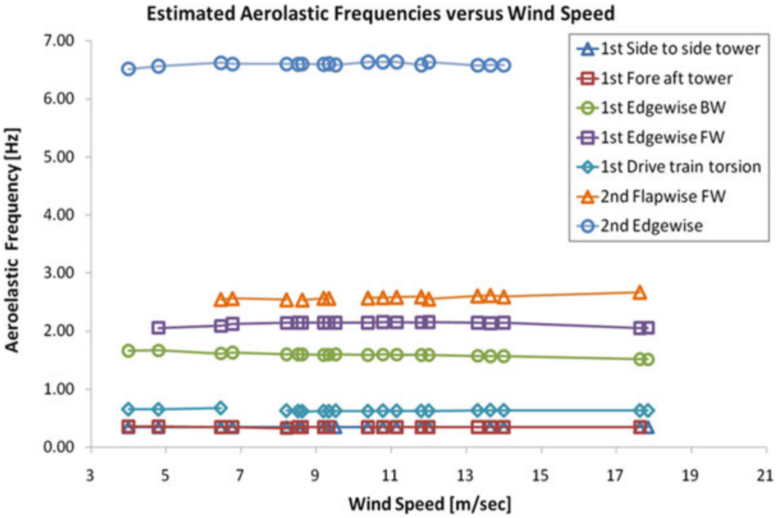

Fig. 70.2 Extracted eigenfrequencies

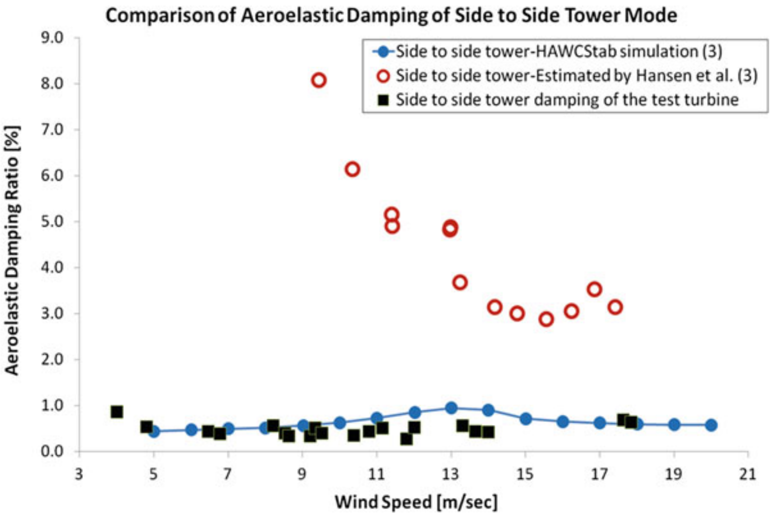

Fig. 70.3 Side to side tower mode damping comparison

experienced the same problem and reported that these three flapwise modes have too high aerodynamic dampings for identification in response to the excitation by turbulence. Similarly, the second BW flapwise mode, which has a relatively lower damping, could not be observed in the rotation data due to its weak modal participation in the overall motion.

Figure 70.3 shows the change in aeroelastic damping ratio calculated for the side to side tower mode as a function of wind speed. Identified values are in a very good agreement with the HAWCStab simulation results both in terms of trend and magnitude. The values found are less than 1 % through different operating conditions and wind speeds.

The same comparison is made for the fore and aft tower mode and the results are shown in Fig. 70.4. Although the two tower modes have almost the same frequencies, aeroelastic damping calculated for the fore and aft mode is greater due to the motion of the tower in the direction perpendicular to the rotor plane.

Comparison of aeroelastic damping ratios found for the first BW edgewise mode is shown in Fig. 70.5. The extracted damping ratios are slightly higher than the HAWCStab results, but are very close to the estimations [3] made by using in-field vibration data. Edgewise modes are very straightforward to identify because they have very high modal participation in the overall response of the turbine and low aeroelastic damping.

Similarly, Fig. 70.6 displays the same damping comparison for the first edgewise FW mode. Acquired damping ratios are again very close to both simulations and estimations given in [3].

Figure 70.7 shows aeroelastic damping ratios identified for the drivetrain torsion mode. This mode could not be detected by most of the sensors placed on the rotor and the tower. Edgewise direction strain measurements taken on the blades were the

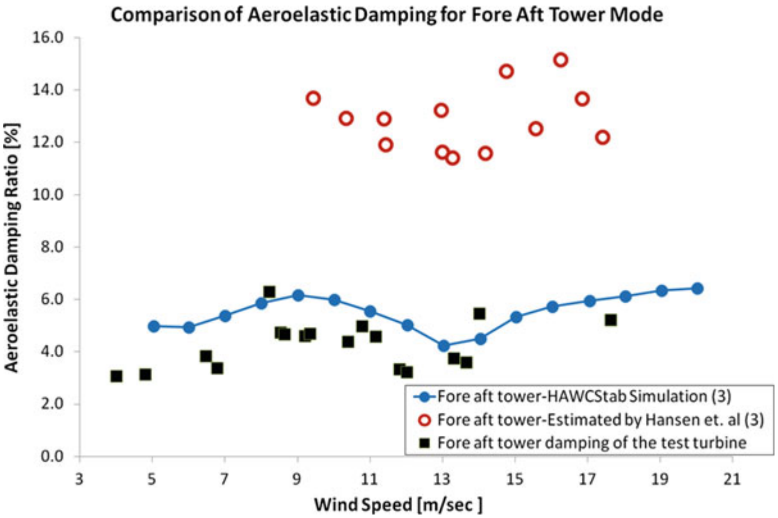

Fig. 70.4 Fore and aft tower mode damping comparison

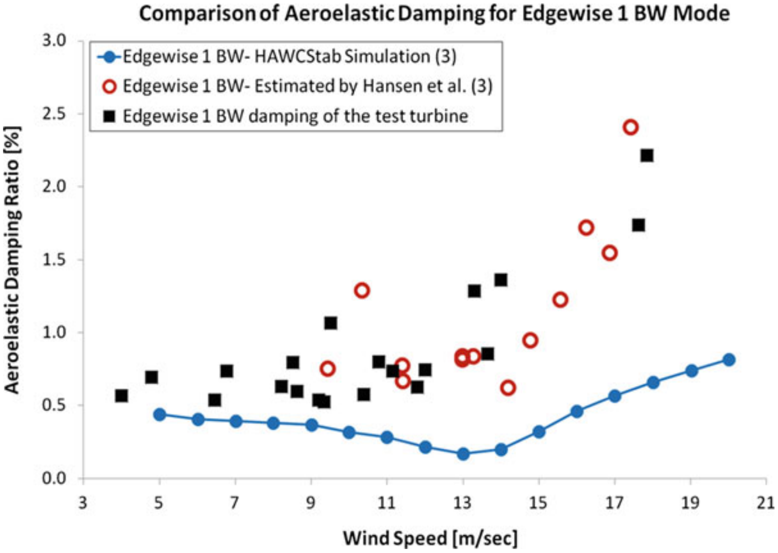

Fig. 70.5 The first edgewise BW mode damping comparison

only signals that could be used to analyze this mode. Obtained results are similar to those predicted by HAWCStab simulations. Since any damping estimation for this mode was not given in the reference study, the identified damping ratios could only be compared with the simulation results.

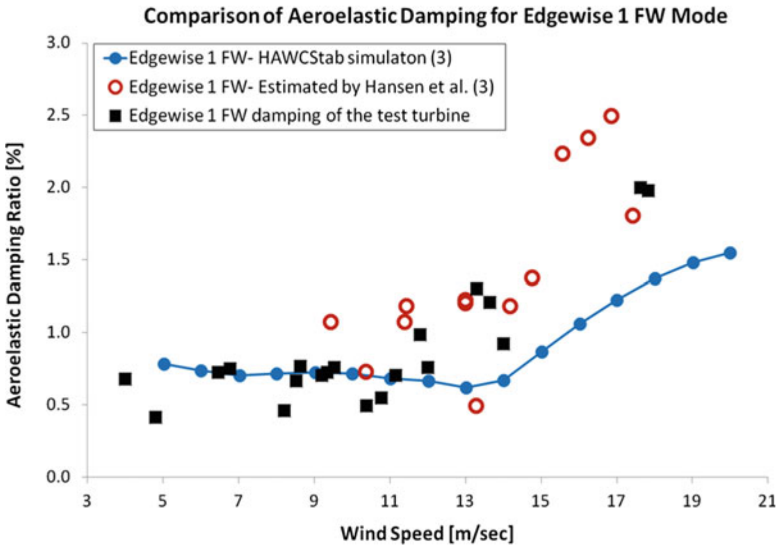

Fig. 70.6 The first edgewise FW mode damping comparison

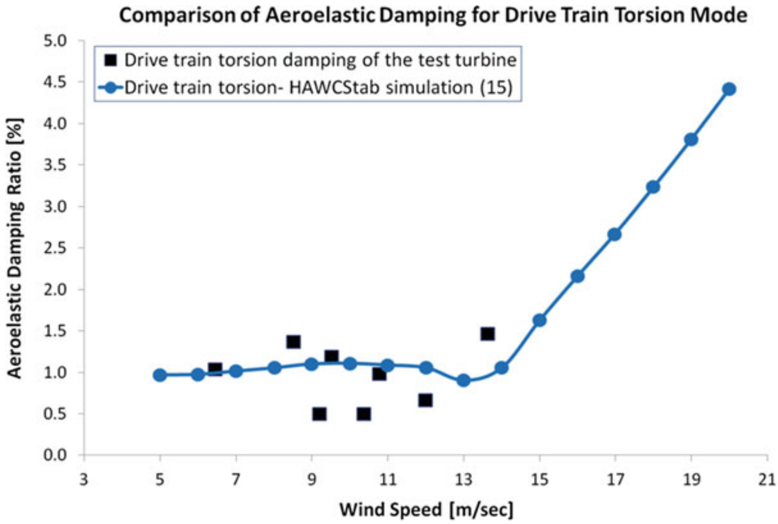

Fig. 70.7 The first drivetrain torsion mode damping comparison

Figure 70.8 shows aeroelastic damping ratios calculated for the second FW flapwise and second edgewise modes. Because Hansen et al. did not include the damping estimations or simulation results for these modes in their work [3], the identified damping ratios could not be compared with any reference values.

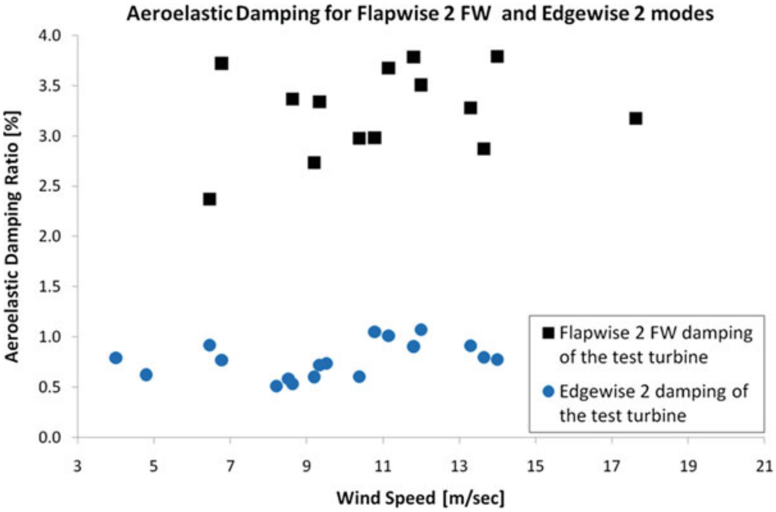

Fig. 70.8 Damping ratios extracted for the second FW flapwise and second edgewise modes

70.7 Conclusions

Identification of the modal parameters of wind turbines are very important for optimizing the energy produced, ensuring safe and reliable operation, and increasing the lifetime of the system. However, conventional dynamic testing techniques based on exciting the structure from several locations with sufficient force amplitudes cannot be easily applied to these challenging structures due to their size and the technical difficulties in providing very large forces that are required to reach sufficient excitation levels.

OMA (operational modal analysis) tools, namely, the analysis methods that do not require the forces acting on the system to be measured, can be a solution to some important problems encountered in dynamic testing of wind turbines. Since estimation of the modal parameters is solely based on the use of measured response, these methods can easily be used to extract the dynamic properties of these large structures excited by natural environmental inputs (winds).

Analyses performed by using OMA methods seem very promising in extracting the modal parameters. Within the scope of the research, 12 different turbine modes were successfully calculated from the measurements taken on the parked turbine using strain gauges and LDV.

Similarly, several turbine modes could be identified from in-operation measurements using strain gauges and photogrammetry. Obtained results are in good coherence with those presented in similar studies in literature.

Performing modal analysis on a rotating turbine is much more challenging than performing the same analysis on a parked turbine due to the high aeroelastic damping of some important modes, rotational P harmonics that dominate the dynamic response, and the difficulties in fulfilling some important system identification assumptions such as time-invariant system and steady-state random excitation.

During the analyses, it was observed that frequency values are more easily identified and the calculated values are mostly stable. However, some scatter can be encountered in estimated damping ratios. This scatter can be caused by physical factors such as the change in operating conditions or mathematical uncertainty related to the applied algorithms.

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