Chapter 13
Stability Control of Wind Turbines for Varying Operating Conditions Through Vibration Measurements

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Abstract Wind turbines have very specific characteristics and challenging operating conditions. Contemporary MW-scale turbines are usually designed to be operational for wind speeds between 4 and 25 m/s. In order to reach this goal, most turbines utilize active pitch control mechanisms where 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 dynamic analysis point of view. Unexpected resonance problems due to dynamic interactions among 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 resonance problems and that the structure is dynamically stable. This work aims at presenting the results of the dynamic stability analyses performed on a 2.5-MW, 80-m-diameter wind turbine. Within the scope of the research, the system parameters were extracted by using the in-operation vibration data recorded for various wind speeds and operating conditions. The data acquired by 8 strain gauges (2 sensors on each blade and 2 sensors on the tower) installed on the turbine were analyzed by using operational modal analysis (OMA) methods, while several turbine parameters (eigenfrequencies and damping ratios) were extracted. The obtained system parameters were then qualitatively compared with the results presented in a study from the literature, which includes both aeroelastic simulations and in-field measurements performed on a similar size and capacity wind turbine.

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13.1 Introduction

Growing energy demands require wind turbine manufacturers to design more efficient and higher-capacity wind turbines which inevitably results in larger and larger new models to be put into service. However, an important consequence of this increase in size and flexibility of the structure is the complicated dynamic interaction between different parts of the turbine. Motion of the blades interacts with aerodynamic forces, electromagnetic forces in the generator, and the structural dynamics of several turbine components (drive train, nacelle, and tower). Understanding these dynamic interactions, the corresponding structural behavior and response characteristics are essential for optimizing the energy produced, ensuring safe and reliable operation and increasing the lifetime of the system. This requires improving the design methodologies and in-operation control strategies.

Therefore, more attention is paid to developing theoretical models for estimating the behavior of new wind turbines. Contemporary aeroelastic simulation tools coupled with structural dynamics models enable designers to detect, understand, and solve most of the possible problems at very early stages and optimize their designs.

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. However, conventional dynamic testing techniques based on the exciting structure at 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.

Standard wind turbine testing includes estimation of the structural frequencies and damping of the turbine modes from manual peak-picking from frequency response spectra of measured response signals, or from the decaying response after exciting the structure through step relaxation or clamping of the brake (Carne et al. 1988; Molenaar 2003; Griffith et al. 2010; Osgood et al. 2010). However, estimations are often performed on turbines at parked condition. Although these estimated modal parameters are mostly related to the turbine structure and do not include aerodynamic effects that dominate the aeroelastic modes of an operating turbine, frequencies and damping ratios of the lower turbine modes are important for tuning and validation of numerical models and for the verification of the prototype design (Carne and James 2010; Hansen et al. 2006).

Carne et al. (1982) extracted natural frequencies and damping ratios of operational turbine modes by applying the step relaxation method on a small (2 m tall) rotating vertical axis wind turbine. The measured input excitation together with the recorded response enabled the authors to calculate frequency response functions (FRFs) and to estimate modal parameters for both parked condition and several rotation speeds.

Carne et al. (1988) also tested a 110-m-tall vertical axis wind turbine at parked condition by using the same step relaxation technique. The step excitation included input forces of 45 and 135 kN applied on one of the blades and the tower, respectively. As in the previous example, the authors calculated FRFs by using the measured input forces and response. However, in this work, Carne et al. also applied an initial approach of operational modal analysis (OMA) where the forces acting on the structure are not required to be measured and modal analyses are solely based on the recorded response. The authors compared the results obtained by using conventional FRFs and OMA approach and reported that they obtained a good coherence between the modal parameters extracted by the two different methods.

In the following years, several researchers also applied step relaxation technique to test turbines at parked condition. Molenaar (2003) performed similar tests on a 750-kW, 50-m-tall horizontal axis turbine by exciting the structure at parked condition with sudden release of a pretensioned cable loaded up to 40 kN.

Griffith et al. (2010) also conducted in-field tests on a 60-kW, 25-m-tall vertical axis wind turbine at parked condition by using impact hammer, step relaxation, and ambient wind excitation and compared the results obtained from various excitation methods.

Osgood et al. (2010) performed similar tests on a 600-kW, 37-m-tall horizontal axis turbine by exciting the structure at parked condition through shakers, which are connected to the tower by cables. Extracted modal parameters were then compared with those obtained by OMA methods while turbine was vibrating under the action of ambient wind forces.

Although step relaxation is successfully applied on wind turbines at parked condition, it is relatively difficult and time-consuming to use the same method for rotating turbines. The system involves specific mechanisms to be installed on the turbine to ensure the sudden release of pretensioned cables. The forces needed to excite a large commercial MW-size turbine with sufficient levels of energy can be very large (even larger than the 135 kN forces mentioned above). Besides, the device has to be reloaded for every input, which means bringing the turbine down to parked condition, reloading the device, and waiting for the turbine to reach a certain rotation speed. If numerous tests are planned to be performed for several wind speeds, this method can be very costly and time-consuming (Carne and James 2010). In fact, it is this time requirement that motivated researchers to look for alternatives to step relaxation, finally resulting in the development of new OMA methods.

Researchers (Hansen et al. 2006; Thomsen 2002) also tried to use different excitation techniques by assuming that a turbine mode can be excited by a harmonic force at its natural frequency, whereby the decaying response after the end of excitation gives an estimate of the damping. Simulations show that turbine vibrations related to several modes can be excited by blade pitch and generator torque variations and eccentric rotating masses placed on the turbine. However, results of the in-field tests performed on wind turbines showed that it is not possible to achieve the required pitch amplitudes to excite the modes with high modal frequency or high damping ratio due to the limited capacity of electrical pitch actuators. On the other hand, excited turbine vibrations are not pure modal vibrations and the estimated damping is therefore not the actual modal damping. In particular, for systems having vibration modes with similar frequencies, but different damping ratios, it is not possible to isolate a certain mode only and aerodynamic damping values cannot be estimated well because of the energy transfer between different modes (Hansen et al. 2006).

OMA tools, a common representation used for several analysis methods which do not require the forces acting on the system to be measured, can be a solution to all these problems. Since estimation of the modal parameters is solely based on the use of measured response signals, these methods can be easily and efficiently used to extract the dynamic properties of these large structures excited by natural environmental inputs (winds). Indeed, early versions of OMA tools were specifically developed to overcome the problems mentioned above and have been in use since early 1990s (James et al. 1992, 1993, 1995, 1996). Some of the researchers (Carne et al. 1988; Griffith et al. 2010; Osgood et al. 2010) mentioned above have also successfully used OMA methods and have reported that they have obtained very good coherence between the modal parameters identified by OMA and the conventional experimental modal analysis techniques. A more comprehensive review of the history and development of this technique can be found in the work by Carne and James (2010).

13.2 Test Turbine

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. Measurements were taken at Energy Research Center of the Netherlands (ECN) wind turbine test site located in Wieringermeer, the Netherlands. More detailed information about the facilities of the test site can be found at the related Web site (ECNWEB).[1]

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 European Commission-supported STABCON project (Hansen et al. 2006).

13.3 Analysis Results and Identified System Parameters

Researchers (Hansen et al. 2006; Ozbek et al. 2013; Chauhan et al. 2009) 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;

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[1] ECN Energy Research Center of the Netherlands. http://www.ecn.nl/units/wind/wind-turbine-testing/.

- 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, 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 (Ozbek and Rixen 2013).
- Besides, for rotating turbines, these P harmonics cause violation of 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.

13.3.1 Tests on the Parked Turbine

This section summarizes the results of the analyses of 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 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 13.1 summarizes the calculated modal parameters (frequencies and damping ratios). Frequencies and damping ratios were extracted by using the Natural Excitation Technique (NExT) approach (James et al. 1995, 1996), together with the least square complex exponential (LSCE) 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 tuning and validation of numerical models and for the verification of prototype designs. They can also be used for

Table 13.1 Modal parameters calculated for the parked turbine

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

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 (Carne and James 2010). 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 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.

13.3.2 Tests on the Rotating Turbine

This section summarizes the results of the analyses of the 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 Hansen et al. (2006). The work mentioned includes the results of both aeroelastic simulations performed by the stability tool HAWCSstab (Hansen 2004; Riziotis et al. 2004; Marrant and van Holten 2004) 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 (Hansen et al. 2006).

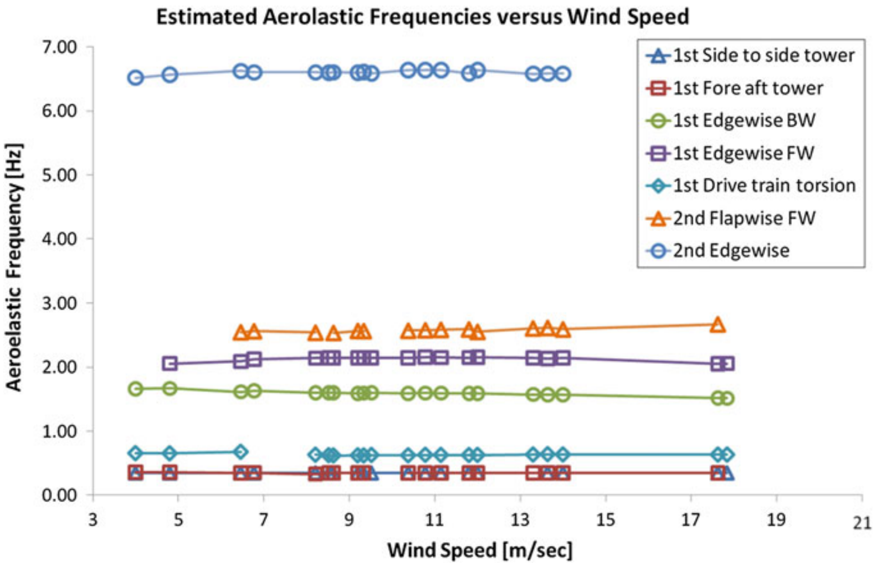

Fig. 13.1 Extracted eigenfrequencies

Figure 13.1 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 13.1) 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. 2006 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 lower damping, could not be observed in the rotation data due to its weak modal participation in the overall motion.

Figure 13.2 shows the change in aeroelastic damping ratio calculated for 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. It should be noted that damping ratios are given in terms of critical damping ratios.

The same comparison is made for the fore–aft tower mode, and the results are shown in Fig. 13.3. Although the two tower modes have almost the same frequencies, aeroelastic damping calculated for the fore–aft mode is greater due to the motion of the tower in the direction perpendicular to rotor plane. The identified damping ratios are smaller than HAWCStab estimations, but can still be considered as close.

Compared with side-to-side mode, analyzing the fore–aft tower mode and estimating the corresponding modal parameters are more challenging. OMA tools utilized in this work are based on the use of correlation functions, which produce

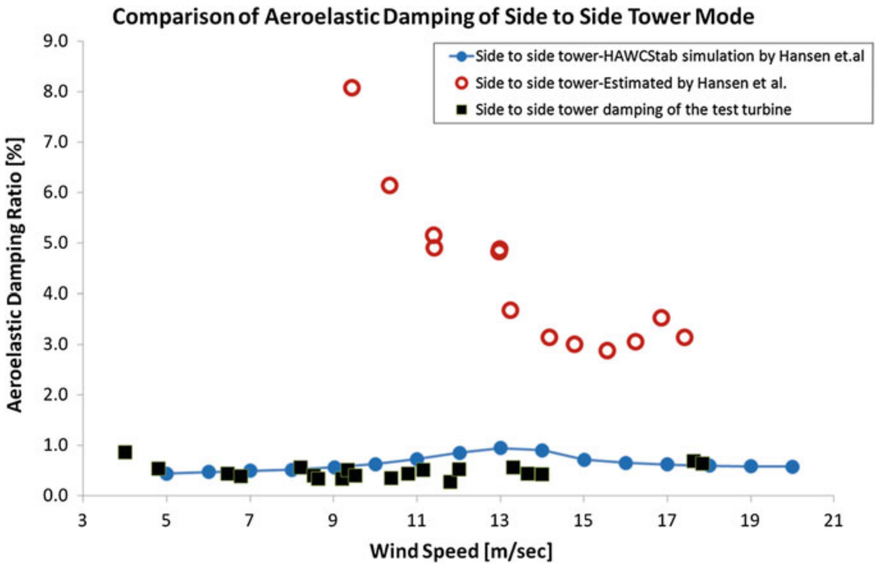

Fig. 13.2 Side-to-side tower-mode damping comparison

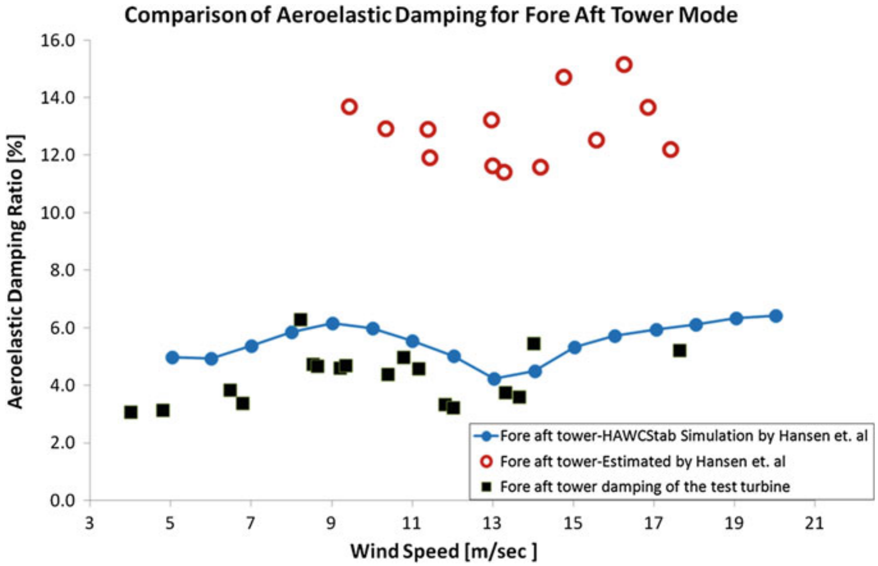

Fig. 13.3 Fore–aft tower-mode damping comparison

very accurate results in case of zero-average steady-state data series. However, changes in mean wind speed cause very slow variations in fore–aft tower movement and bending moment. These quasi-static variations cannot be fully eliminated by

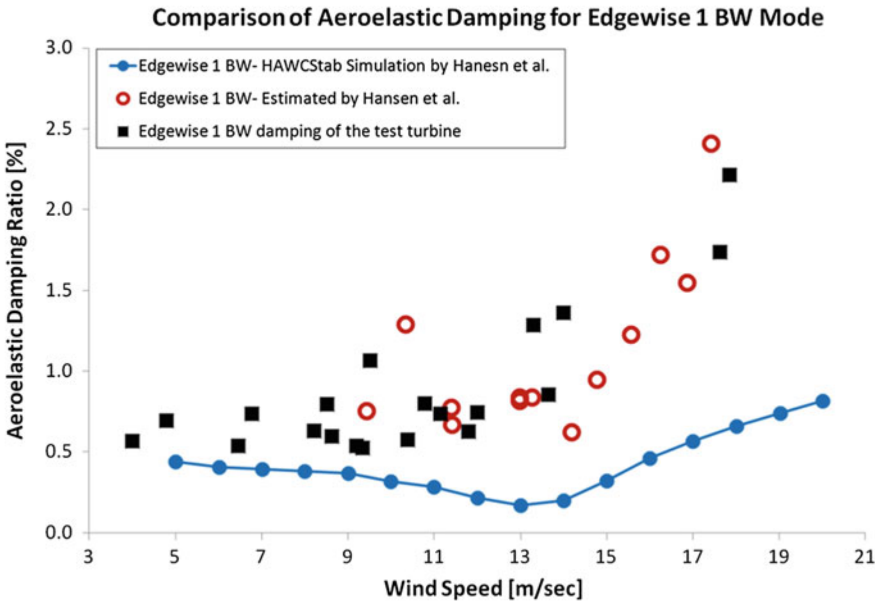

Fig. 13.4 The first edgewise BW-mode damping comparison

using conventional data processing techniques (such as detrending and filtering) and cause scatter in the estimated modal parameters. Therefore, the data series having a nonzero varying average should not be used in the analysis. Although such an approach limits the number of measurements that can be used in the analysis, it significantly increases the reliability of the extracted modal damping.

Comparison of aeroelastic damping ratios found for the first BW edgewise mode is shown in Fig. 13.4. The extracted damping ratios are slightly higher than the HAWCStab results, but are very close to the estimations made by Hansen et al. (2006) 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.

Unlike tower modes, they can be detected by using the strain gauges placed both on the blades and on the tower. Similarly, Fig. 13.5 displays the same damping comparison for the first edgewise FW mode. Acquired damping ratios are again very close to both simulations and estimations given by Hansen et al. (2006).

It should be noted that during the measurements that were used in modal analysis, operating conditions of the turbine (wind speed, rotor speed, and pitch angle) have to stay constant. Possible variations in these parameters result in a noisy input data and a scatter in identified modal parameters. Therefore, only the measurements corresponding to very low standard deviations of wind speed and rotor speed were selected and analyzed to obtain the results presented in this work. However, it should also be noted that some pitching activity was observed starting

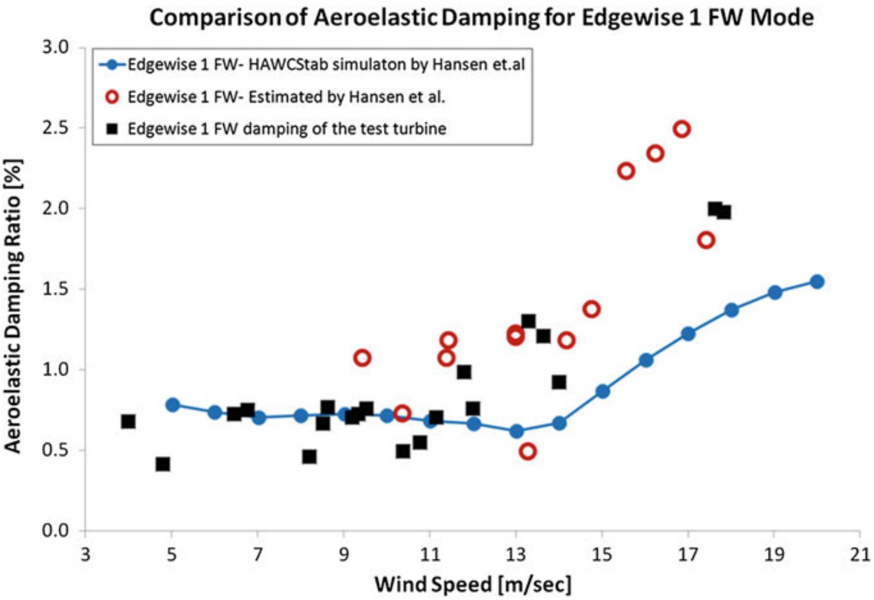

Fig. 13.5 The first edgewise BW-mode damping comparison

from the wind speeds close to the rated speed. As mentioned before, identification of modal parameters for these wind speeds can only be possible by tolerating some pitch activity, which definitely results in some scatter in the obtained values.

13.4 Conclusions

Identification of the modal parameters of wind turbines is 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 tools, namely the analysis methods that do not require the forces acting on the system to be measured, can be a solution to these problems. Since estimation of the modal parameters is solely based on the use of measured response signals, these methods can easily and efficiently 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, twelve different turbine modes were successfully calculated from the measurements taken on the parked turbine.

Similarly, several important turbine modes could be identified from the in-operation measurements. Obtained results are in good coherence with those presented in similar studies in the 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.

The turbine modes (first FW, BW, and symmetric flapwise modes), known to have very high aeroelastic damping ratios, could not be detected through the analyses of the rotation data. The second BW flapwise mode, which has a relatively lower damping, could not be extracted due to its low modal participation in the motion.

During the analyses, it was observed that frequency values are more easily identified and the calculated values are mostly stable and reliable. However, significant 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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