CLASSIFYING RESONANT FREQUENCIES AND DAMPING VALUES OF AN OFFSHORE WIND TURBINE ON A MONOPILE FOUNDATION FOR DIFFERENT OPERATIONAL CONDITIONS

Wout Weijtjens	Rasoul Shirzadeh	Gert De Sitter	Christof Devriendt
Vrije Universiteit Brussel	Vrije Universiteit Brussel	OWI-lab	OWI-lab
wweijtje@vub.ac.be	rshirzad@vub.ac.be	gdesitte@vub.ac.be	cdevrien@vub.ac.be

Abstract :

This paper shows the most recent results in the ongoing long-term monitoring campaign on an offshore wind turbine in the Belgian North Sea. Main focus will be on the behavior of the resonant frequencies and damping values of the fundamental modes over a full year, during which all relevant ambient and operational conditions have occurred. The latest results show that the damping values and resonance frequencies of the support structure are greatly influenced by the operating conditions of the turbine. We will therefore classify the dynamics of the turbine and provide the statistics for resonance frequencies and damping ratios for each operating condition.

Keywords: Offshore, Foundations, Monitoring, Frequencies, Damping

1 Introduction

Many large-scale offshore wind farm projects use monopile foundations to obtain a cost effective design. During the design of these monopile structures fatigue due to combined wind and wave loading is one of the most important problems to take into account. Coincidence of structural resonances with wind and wave forces or the harmonic forces induced by the rotor can lead to large stresses and subsequent accelerated fatigue [1]. Therefore, it is important to have a clear view on what parameters influence the resonance frequencies of structures and may potentially shift them into the range of these excitations.

Damping ratios are also crucial for lifetime predictions as the amplitude of vibrations at resonance is inversely proportional to these ratios. The overall damping of the tower modes of an offshore wind turbine consists of many different contributions, including aerodynamic damping and additionally installed dampers such as a tuned mass damper (TMD) [2]. The different dynamics of each type of damping and their relative contributions to the overall damping are a challenge for simulations and there is a desire for experimental damping measurements on wind turbines.

For onshore turbines several measurements have been done on operational turbines, e.g. to quantify aero-elastic effects on the damping of ao. blade-whirling modes [3]. Other short term measurements served as proofs of concept for different identification techniques [4, 5]. Long-term measurements of modal parameters mainly focus on structural health monitoring of the structural components [6] rather than to investigate the modal parameters themselves.

For off-shore wind turbines the added support structure as well as the unknowns in the structure-soil interactions have encouraged a further experimental research into the dynamics of the foundation and the tower. In [7] the resonance frequency and modal soil damping of offshore wind turbines for different soil conditions were determined by performing rotor-stop tests at five wind parks in the period from 2006 to 2011. In [8] the modal parameters (i.e. the resonance frequency, damping ratio and mode shapes) for a 5MW offshore wind turbine on a tripod structure located at German Alpha Ventus wind farm were determined through a long term measurement campaign.

This paper is part of an ongoing research project at the Belwind windfarm outside the Belgian coast. The Belwind farm consists out of 55 V90 turbines on a monopile foundation. As part of the Offshore Wind Infrastructure laboratory (OWI-lab) one of the turbines was installed with 10 accelerometers to investigate the vibrational and damping properties of the as-built structure. In 2012 a first overspeed test was performed to estimate the structural damping of the turbine. These results were presented in [9]. Simultaneously it was demonstrated that through operational modal analysis (OMA) it is possible to estimate the resonance frequencies and damping ratios using only the ambient vibrations of the structure. This meant that there is no longer a necessity to perform an overspeed stop and modal parameters can be estimated continuously over long periods of time. In 2013 the results were presented for two weeks of parked conditions [10] and showed how damping is influenced by the windspeed. This paper will continue this research and considers one year of data during which the turbine was subjected to different operational and environmental conditions.

2 Methodology

The first step is to acquire relevant information, from all available sources. This step is discussed in more detail in Section 2.1. The second step is to process the vibrational data with Operational Modal Analysis (OMA) which yields the structure's resonance frequencies and damping ratios, Section 2.2. Simultaneous to the OMA the vibrational data is also condensed by calculating statistical properties like the RMS values. These are mainly used for monitoring applications [10] and will not be addressed in this contribution. The final step is to analyse the obtained resonance frequencies and damping ratios. This step is partially automated by a case by case tracking algorithm, introduced in Section 2.4. The final analysis considers all available data to better understand the influence of meteorological and operational conditions upon the resonance frequencies and damping ratios.

2.1 Data acquisition

The monitored structure was originally equipped with 10 accelerometers at four levels of the structure located 19m, 27m, 41m and 69m above LAT. The setup is primarily aimed at the identification of tower bending modes in both Fore-Aft (FA) and Side-Side (SS) direction. As the sensors are fixed w.r.t. the tower structure the yaw angle from the SCADA is used to transform measured accelerations into the FA-SS coordinate system. Two additional sensors are installed at the top level to identify torsional vibrations in the tower. During the monitoring campaign the sensors at the lowest level were removed as they added little information. The accelerometers were chosen based on their high sensitivity (1V/g) and their frequency range of 0-250Hz. The lower frequency bound was crucial to capture the first structural mode which was expected at 0.35Hz. All accelerometers are connected to a NI Compact Rio system in the tower. Data is gathered continuously and transmitted at 10min intervals to an onshore server through a dedicated fiber connection. A more detailed overview of the sensor layout and the properties of the data-acquisition system is held in [10] .
The partial SCADA data of the monitored wind turbine (generated power, RPM, blade pitch, yaw angle and wind speed) is made available by BelWind. Simultaneously meteorological data is gathered from both the OHVS at Belwind (air temperature, tidal level and wave height) and from the Westhinder measurement buoy (wave period) operated by Meetnet Vlaamse Banken.
All data is processed to obtain datafiles of 10 min intervals which are synchronized with the measured vibrational datasets.

2.2 Automated Operational Modal Analysis

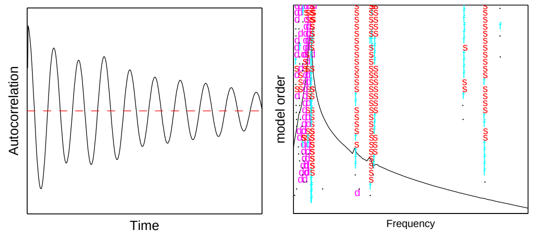
To derive the resonance frequencies and damping ratios from vibrational data several approaches are possible. It is for instance possible by analyzing the tower accelerations after an overspeed stop [9]. A similar analysis was done in [7] which used the accelerations measured after a rotor stop to determine the damping value. However, these methods have two limitations. First of all they don't allow to estimate the damping and resonance frequency continuously, but only when a rotor stop is performed. Secondly, they are not able to determine the damping and resonance frequency during any other operational condition than during a rotor stop. In [9] it is suggested to use Operational Modal Analysis (OMA) to resolve these limitations. In [10] an automated OMA methodology is introduced and demonstrated on two weeks of parked conditions.This paper uses the most recent version of that algorithm.
The automated OMA algorithm consists of three basic steps that are repeated for every ten minutes of data. These three steps are:

1. Calculate the autocorrelation of the vibrational data and process into the frequency domain

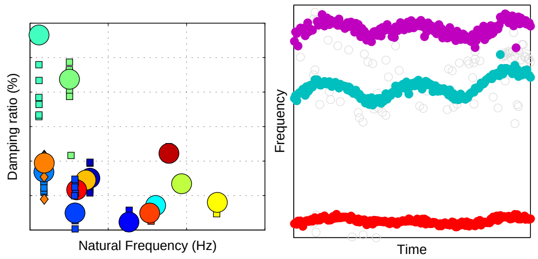
2. Apply the p-LSCF curve fitter to the frequency domain data to estimate the resonance frequencies, damping ratios and mode shapes

3. Process and condense the results of the curve fitter by a hierarchical clustering algorithm

To track the changes within a single mode these final results are compared to a set of reference values. These reference values represent the modes of interest. Each mode has an expected resonance frequency and mode shape, if the found results are within range of these expected values the result is linked to this mode. Results that cannot be linked to a known mode are rejected.
In Fig.1.a-c the three steps of the automated OMA algorithm are visualized for a dataset during parked conditions. In Fig.1.d the results of tracking over a period of parked conditions are shown. The tracking results show that the algorithm is able to track multiple modes even if their resonance frequencies vary over time, e.g. due to the tides [10].
The automated OMA used in this contribution uses the pLSCF-estimator but different techniques such as Stochastic Subspace identification (SSI) are



(a) Calculated autocorrelation of one output (b) The p-LSCF curve fitter gives a stabilization chart



(c) The stabilization chart is condensed into a cluster plot (d) Tracking results

Figure 1: (a-c) Illustration of the three steps of the automated OMA approach for a parked turbine (d) Example of the tracking

equally applicable. For instance a similar methodology of automated OMA using SSI followed by tracking is being used across Europe to monitor large civil structure such as bridges and soccer stadia. [11, 12]. Results in [11] show that the method is able to identify the interactions between modal parameters and environmental parameters.
The results in [8] also use an automated OMA algorithm based on SSI, but with an alternate approach to condensing the results, i.e. a different Step 3.

2.3 Limitations

The previous method showed good results in parked conditions. However, it cannot be readily applied to the monitor a fully operational wind turbine.

2.3.1 Influence of harmonics

The power spectrum plotted in Fig.2 demonstrates the altered dynamics of a turbine at 16 rpm. It shows little similarity with the power spectrum of a parked turbine, plotted in black in Fig.1.b. In parked conditions the power spectrum is dominated by the first FA and SS mode. At 16rpm the vibrations are dominated by the second order FA and SS modes at approx. 1.5Hz. The harmonics introduced by the rotor also clearly show as peaks in the power spectrum.
One of the key assumptions in all Operational Modal Analysis methods is that all measured vibrations are caused by the structure resonating. This assumption is violated when periodic forces act on the structure. These periodic forces inject energy in a small frequency band, forcing the structure to

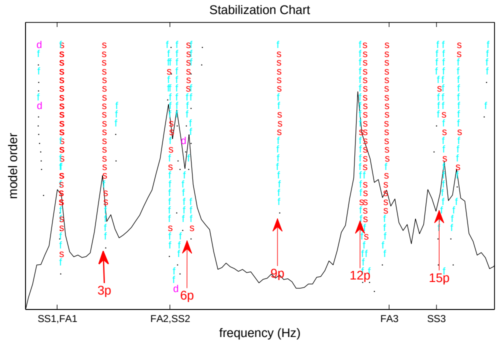


Figure 2: Stabilization chart for a dataset during which the turbine was constantly rotating at 16rpm which yields harmonics at 0.8, 1.6, 2.4, 3.2 and 4Hz. When the p-LSCF identifies a structural mode a **s** is plotted for different model orders.

vibrate at these frequencies. The OMA algorithms misinterpret this behavior as a structural resonance. Fig.2 shows how the output of the p-LSCF curve fitter identifies the harmonics as if they were structural modes. This misinterpretation of harmonics as structural modes is a known limitation in the application of OMA to wind turbines [13]. While several techniques exist to reduce their influence, they provide little added value when the regular OMA algorithm is able to identify both the harmonic as well as the structural mode [14–16] .This is the case in Fig.2 for all modes up to SS3. Yet, when the harmonic gets too close to the structural mode and the curve fitter is no longer able to separate them, e.g. in Fig.2 SS3 with the 15p harmonic, the result is a mix of the structural mode with the harmonic which has little physical meaning [15].
The latest version of our algorithm features a harmonic tracker based on the average rpm within each dataset. Basically, it flags every estimated resonance frequency that is within a 5% range of a known harmonic, e.g. 1p, 3p, 6p,... up to 15p. The analyst can then decide whether or not these flagged results are included in the analysis. In this paper we will reject all flagged results. As a consequence there are no results for given modes at given rotor speeds. E.g. the 6p harmonic passes through the second FA and SS modes at around 14-15 rpm, as such we were not able to obtain results for these rotational speeds. Additionally, special care should be addressed to datasets that are obtained during operational conditions with varying rotor speeds and thus varying harmonics. The average value over ten minutes might not be sufficient to adequately recognize results that were affected by the harmonics. It is for this reason we will not present any results of the second order FA and SS modes for rotational speeds above 10 and below 16 rpm.

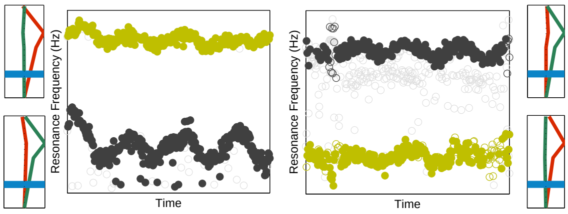


Figure 3: Tracking results of the third order FA and SS modes during parked (left) and rotating (right) conditions. Based on the mode shapes (Red: FA motion, Green: SS motion) it can be concluded that resonance frequencies can significantly shift between operational conditions.

2.3.2 Discontinuous behavior of the structural modes

The original algorithm assumes that the structural modes only slightly vary due to varying ambient conditions. This assumption holds under parked conditions. However, there is a significant difference between a rotating turbine and a parked turbine. E.g. during parked conditions the pitch angle is fixed between 80 and 90 degrees. However, during production the pitch angle is at max 20 deg. An eigenvalue analysis already shows that the resonance frequencies of the second and the third order FA and SS modes can shift because of this changed pitch.
As a demonstration Fig.3 shows the tracking results for the third order FA and SS modes. On the left side the turbine is parked and on the right hand side the turbine is rotating. Based on the mode shapes it is clear to see that the two modes have switched frequency. As a consequence both modes had a resonance frequency outside the predefined range in the original reference set. A solution would be to broaden the acceptance criteria and to allow for larger differences in resonance frequencies. This solution can however jeopardize the quality of the results. Another solution is proposed in the following section.

2.4 Case by Case tracking of tower modes

The key idea is to use the available SCADA information to link each dataset to a recurring operational condition referred to as a case. Each case is defined by the boundary conditions set by the analyst and these are easily modified for new turbines, control strategies or definitions of operational cases originating from norms.
Table.1 gives the boundaries used in this paper. These cases were defined by looking at the SCADA data of the turbine during 2012 and by recognizing the different operational states of the turbine. Fig.4 serves to illustrate the physical meaning of the set boundary conditions
By using a Case-by-Case approach it is possible to

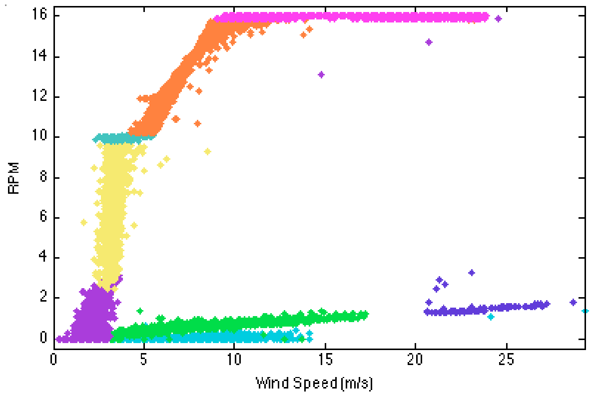


Figure 4: RPM vs. Windspeed with colors indicating the different cases as defined in Table.1

use multiple reference sets rather than just a single set. The discontinuous behavior of modes, discussed in Sec.2.3.2, can cause the modal parameters to shift within a few minutes. If a single reference set was used to capture all these measurements it would require a very broad setting. However, this problem is solved by allowing multiple reference sets for tracking with tighter acceptance criteria.
So for each case the expected resonance frequencies and mode shapes are defined and any result within range of these expected values will be accepted or rejected, finally resulting in a far smaller spread on the obtained results. The final results can then be presented case by case, which also is interesting for both analysis and design. If for example a designer wishes to perform a fatigue-life analysis for a turbine at rated power, then a case definition : Power $\geq$ 3MW will provide the statistics for damping and resonance frequency estimates for that particular case. In [8] the results are also presented in a similar case by case fashion on a wind turbine in the Alpha Ventus wind farm.

3 Results

This paper presents the results obtained in 2012. During the year it occurred that one of the sources mentioned in Section 2.1 , e.g. the waveradar, was offline. Because the main goal of this research is to analyse how modal parameters are influenced by ambient and operational conditions only complete datasets are considered. This results in total to eight months of complete data. All cases occur regularly throughout the year, with exception for the Cut-out case which only occurred a few days during the winter. Approximately one percent of all datasets falls outside the range of the predefined cases. This is due to a transition between cases within these datasets or an erroneous value in the SCADA data.

Table 1: Definition of the considered cases in the algorithm

	Wind speed (m/s)		rpm		Pitch angle (deg)	
	Min.	Max.	Min.	Max.	Min.	Max.
1:Pitch : >80	n/A	n/A	n/A	n/A	80	100
2:Pitch : ±80	0	20	n/A	n/A	70	80
3:Pitch : ±20	n/A	n/A	n/A	n/A	19.5	20.5
4:RPM : <10	n/A	n/A	2.5	9.8	n/A	n/A
5:RPM : ±10	n/A	n/A	9.8	10.2	n/A	n/A
6:RPM : <16	n/A	n/A	10.2	15.9	n/A	n/A
7:RPM: ±16	n/A	n/A	15.9	17	n/A	n/A
8:Cut-Out	20	n/A	n/A	n/A	70	80

3.1 Considered modes

With all sensors located in the tower the used sensor layout is focussed on tower/foundation modes. As such this paper will show the results of the first three sets of FA and SS modes that are consistently tracked over different operational conditions and involve significant tower motion, their mode shapes are plotted in Fig.5 Section.3.3 will feature a more detailed analysis of the first FA and SS modes to demonstrate the possibilities with the broad database of available data.

3.2 Overall results

Fig.5 shows the results of all datasets with the cases defined in Table.1. All six modes were consistently tracked in the majority of cases. Only the FA2 and SS2 were not always tracked as the 6p and 9p often interact with these modes and results were rejected by the harmonic tracker. Higher order harmonics do also interact with the third order modes but after rejection by the harmonic tracker sufficient data remains to draw results, with exception for SS3 at 16rpm. Low success rates for FA3 at Pitch:±20 and Cut-Out do not allow for a definitive result at this time. The plotted resonance frequencies are the trimmed (25%) means of the estimated resonance frequencies for each case. The damping estimates are provided as a box plot in which the center lines give the median value for estimates within a case. The outer lines of the box indicate the 25th and 75th percentile. Outliers are indicated with a +-sign.

The resonance frequency for the first order modes is not significantly influenced by the operational case. However, for both the second and third order modes the resonance frequency change significantly once the turbine starts producing (Case 3 to Case 7). Especially strongly affected are the third order modes which have switched resonance frequencies, as was already mentioned in Sec. 2.3.2. The cause of this switch is still part of ongoing research, but is possibly related to a strong blade-tower interaction.

The damping behavior of all modes is similar in parked and Cut-out conditions. All modes show a higher damping in SS direction than in FA direction. The damping ratios obtained during Cut-out (Case:8) always exceed the damping ratios during the regular parked (Cases 1 and 2) cases, which is consistent with the higher wind speeds in Cut-out.

The damping of the first and third order modes also show very similar behavior during production. In rotating conditions the FA direction becomes much higher damped than the SS-direction. Damping continuous to increase for both FA as SS direction as wind speed increases. However, the effect is less pronounced for the SS direction.

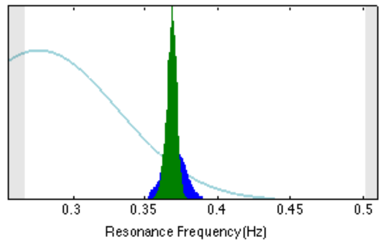


Figure 6: Histogram for the measured resonance frequencies of FA1 (Green) and SS1 (Mode). In light blue the normal distribution fitted to the observed wave frequencies at the Westhinder measurement buoy in 2012. Indicated in gray are the frequencies at which 1p and 3p harmonics can be found for 10 to 16 rpm.

3.3 Detailed analysis of FA1 & SS1

The resonance frequencies of both FA and SS modes vary very little over the course of one year. The tower is designed Soft-Stiff with the first FA and SS modes located in between the 1p and 3p harmonic. Both modes are only excited by the highest of wave frequencies. In Fig.6 the results for one year are plotted along with the observed wave frequencies at the Westhinder measurement buoy.

Fig.5 confirms that the resonance frequencies of both modes vary very little over different operational cases. However, a remarkable result is the significant drop in resonance frequency of FA1 between the *regular* parked conditions (i.e. Pitch:±80) and the Cut-out case. During both cases the pitch angle is fixed to approximately 80 degree so there is no real difference in the parameters of the turbine,

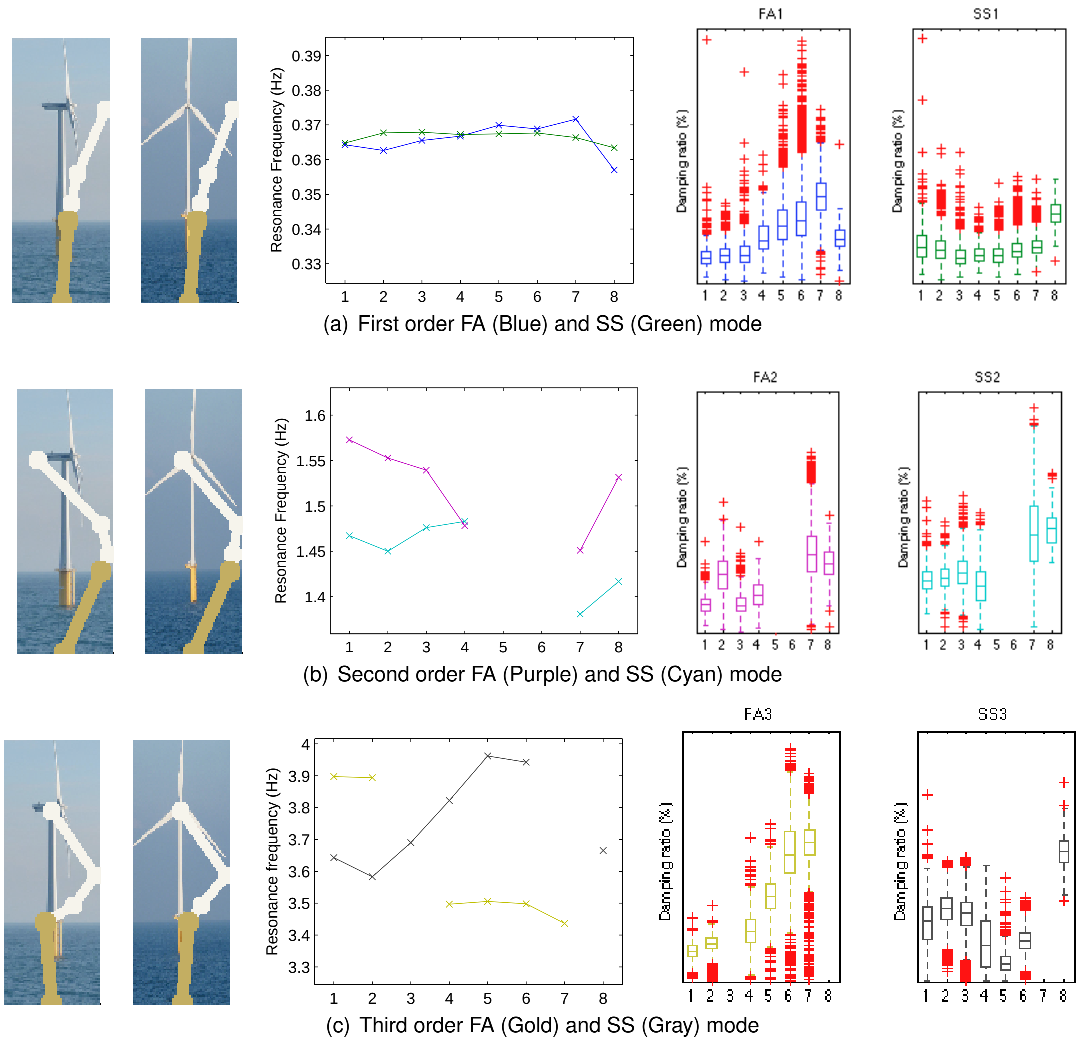


Figure 5: Obtained results for the first three orders FA and SS modes. With (left) Mode shapes of FA and SS mode (center) Resonance frequencies for the different cases (right) damping values for the different cases. With the X-values indicating the associated cases cfr. Table1, e.g. 1: Pitch >80, 2: Pitch ±80, ...

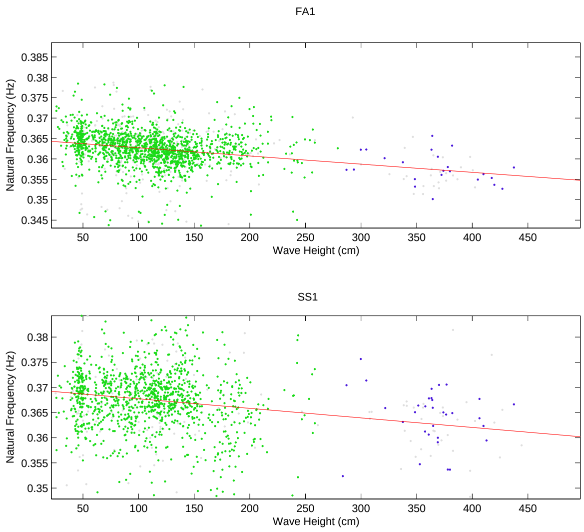
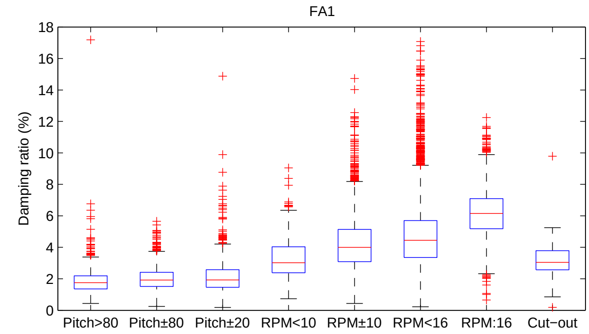
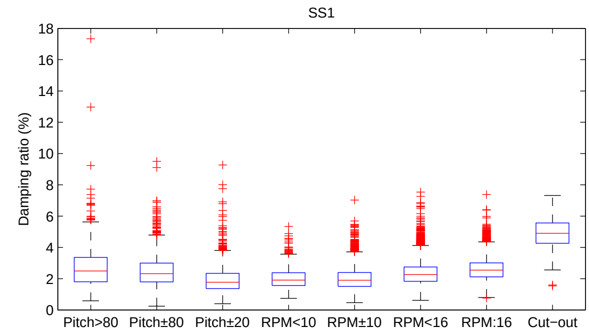


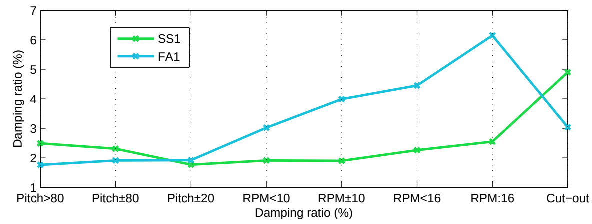
Figure 7: The resonance frequencies of the FA1 (top) and SS1 (bottom) vs. the wave height measured at the OHVS. A linear fit on the data during Parked conditions (Pitch:±80) shows that the lower resonance frequencies observed during Cut-Out might be linked to the increased waveheight.



(a) FA1



(b) SS1



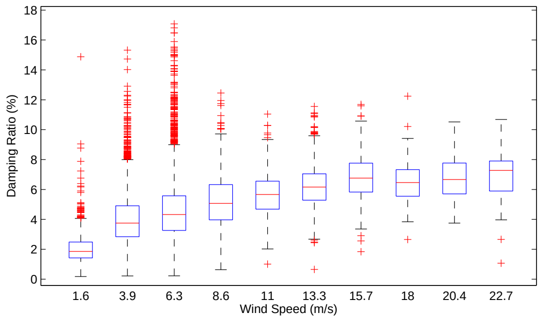
(c) Comparison of damping of modes FA1 and SS1. The plotted measurement values are the median values

Figure 8: Damping results for the first FA and SS mode

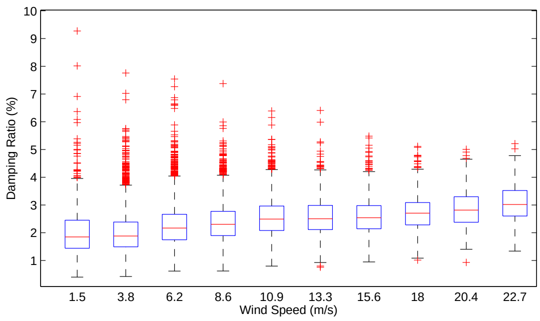
so the difference is most likely linked to the environmental conditions. During Cut-out the turbine is not only subjected to exceptional wind speeds, also other environmental parameters such as the wave height and wave period reach exceptional values. In Fig.7 the relation between resonance frequency and the measured wave height at the OHVS is plotted. A line is fitted to the data during the case Pitch:±80. A negative correlation is observed as with higher wave heights the resonance frequency drops. When we extrapolate this linear model to the wave heights that occur during Cut-out it shows that the found resonances do correspond well with this model. A similar result is obtained for SS1. It shows that ambient parameters can significantly influence the resonance frequency of the first FA and SS modes.

In Fig.8.(a,b) the obtained damping values for the first FA and SS modes are provided during the different cases. In Fig.8.c simplified versions, only median values, are plotted on top of each other for a better understanding of their relative values. These figures show that during parked conditions (Pitch : > 80, Pitch : $\pm$ 80 and Cut-out) the SS mode is better damped than the FA mode. As discussed in [10] this is mainly due to the pitched-out blades. The large blade surface in the SS direction introduces additional aerodynamic damping to the SS mode. With the addition of operational data it can be seen that at Pitch: ±20 the FA and SS modes are almost equally damped. Further pitching of the blades, together with the increased windspeed, aerodynamic effects of the rotating blades eventually lead to a far greater damping in the FA direction, up to 6% at maximum RPM, compared to 2.5% at max. RPM in the SS direction. Once the turbine cuts out at the maximum wind speed the overall damping of FA1 is again smaller than the damping of SS1 mode as the blades are again pitched out. The overall damping for both modes is greater than the overall damping during the regular parked conditions. For the FA1 the damping ratio has increased, from Pitch:±80 to Cut-Out, with approx. 1 percentage point (pp), Relative increase: 60%, while for the SS1 the damping even further increased with about 2.6pp (Relative increase: >110%). A similar analysis can be performed for the damping value as a function of any ambient/meteorological parameter for a chosen set of cases. Of special interest is the relation with the wind speed during production, so excluding the cases Pitch: >80, Pitch : ±80 and Cut-out . The damping ratios for different wind speed bins are shown in Fig.9. With increasing wind speeds the damping of the FA mode increases from 1.8% to 6.5-7%. The damping also increases for the SS direction but only from 1.8% to 3%.

This work also demonstrates that there is still a significant spread on the obtained damping ratios. This is partially due to the uncertainty on the estimates



(a) FA1



(b) SS1

Figure 9: Damping values of the first FA and SS during production for 10 different windspeed bins. The value on the x-axes indicate the center value of the considered windspeed bin.

but is also caused by variations in operational conditions and environmental conditions. As such a long term measurement campaign is preferred over just a single measurement which will only yield a single estimate for a single state of the turbine. This observation was also made in [7, 8].

4 Future work

The developed toolbox opens many opportunities for future research. A possible topic is to research how simulated data corresponds with the made observations for damping. A strategy which involved both experimental data along with a tuned model will be presented in [17] for a parked turbine. It is the next step to apply this strategy to investigate the current results and try to better understand the underlying physics.
Another topic is the continuation of the current monitoring campaign for structural health monitoring. Several studies have indicated that issues such as scour can cause a change in the resonance frequencies of the tower [1]. By tracking the resonance frequencies over long periods of time it might be possible to detect the early onsets of scour. One of the major challenges of this research will be to correctly determine whether a variation in the resonance frequencies is caused by the onsets of scour or is caused by natural variations. Earlier research already showed that the tides can

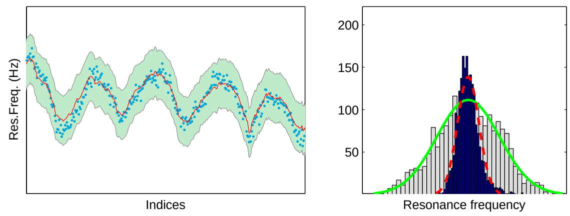


Figure 10: A topic of future research is (left) to model natural variations within the observed resonance frequencies and to remove these natural variations using the model. The result (right histogram) are estimates of the resonance frequency with a far smaller variability (blue) compared to the original naturally varying data (gray).

cause variations in the resonance frequencies. Additionally, this paper showed that e.g. the wave height might also cause a similar variation of the resonance frequency. A possible solution is to use regression models in order to model these natural variations of the resonance frequencies and to use this model to remove the natural variability from the data. The result is a detrended estimate of the resonance frequency with a far smaller variability over time, Fig.10. Alternatively, the model can be used to predict future resonance frequencies. Any significant deviations from the predicted values can than be used to trigger an alarm for inspection or maintenance.

5 Conclusion

In this paper we showed an automated methodology that allows us to identify and track modes with strong tower motion over one year of measurements at the Belwind windfarm. We showed the necessity to exert caution when looking at OMA results in the presence of harmonics. A case by case approach was introduced that is able to yield results for different operational cases and meanwhile assures a tight tracking on the structural modes. An in-depth analysis of the resonance and damping properties of the first FA and SS modes was given to demonstrate the possibilities of the broad database that was built over the past years.

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