Damping Estimation of an Offshore Wind Turbine on a Monopile Foundation

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1. Abstract

The work presented in this paper describes a comparative study between different techniques aimed at identifying the damping values of an offshore wind turbine on a monopile foundation. It will be shown that damping ratios can directly be obtained from vibrations of the tower under ambient excitation from wave and wind loading. The results will be compared with the damping values obtained from a commonly used overspeed stop. Ambient vibration tests have the strong advantage of being more practical and less demanding for the wind turbine in comparison with the overspeed stop. Several identification algorithms, the standard exponential decay method, alternative procedures in the time domain as well as more advanced operational modal analysis techniques in the frequency domain will be applied to the experimental data. This data has been obtained during a short measurement campaign on an offshore wind turbine in the Belgian North Sea. The theory and results of the used methods for estimating the modal damping of a wind turbine excited by ambient excitation will be presented and compared. The paper will also discuss and illustrate various aspects related to the practical implementation of the measurements.

2. Introduction

2.1. Relevance

Many large scale offshore wind farm projects use monopile foundations to realize 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 turbine dynamic forces can lead to large amplitude stresses and subsequent accelerated fatigue. For this reason, the wind turbine rotor blades and support structure are designed to avoid resonance coincidence. In particular, the current practice is to design the wind turbine support structure in such a way that the tower fundamental resonance does not coincide with the fundamental rotational (1P) and blade passing (3P for three-bladed turbines) frequencies of the rotor [1].

In recent studies [2] it was however suggested that for the commonly used “soft-stiff” design methodology designers should not only consider discrete coincidence of 1P and 3P with the fundamental support structure resonance but should also acknowledge the fact that the dynamic amplification associated with the fundamental resonance has finite bandwidth. Even those systems with 1P and 3P away from resonance can still be excited in the fundamental mode. Experiments performed by the Maritime Research institute Netherlands (MARIN) and the Energy Research Centre of the Netherlands (ECN) confirmed, by using model tests of breaking waves against an offshore wind turbine model with realistic flexibility, that breaking waves can induce significant oscillations and accelerations in the turbine [3]. This can have significant effect on the lifetime of the wind turbine.

Damping ratios are crucial for lifetime predictions as the amplitude of vibrations at resonance are inversely proportional to these ratios. The overall damping of the first bending mode of an offshore wind turbine consists of a combination of aerodynamic damping, damping due to vortex shedding and damping due to constructive devices, such as a tuned mass damper, and additional offshore damping, e.g. structural damping [2]. Compared to onshore support structures, the additional damping is further influenced by effects such as soil damping and hydrodynamic damping [3]. Real damping ratios are very difficult to predict by numerical tools and therefore measurements on existing offshore wind turbines are crucial to verify the existing design assumptions.

Damping has an important impact on the fatigue damage. Therefore research is still required to gain more knowledge of the damping affects of offshore wind turbines and to make them an explicit design factor [1]. We therefore still consider it as an important challenge to develop additional procedures, complementary to the presently available standards and guidelines for damping measurements and fatigue assessment. This will enable validation of the design models, verification of the component design and allow for accurate lifetime prediction and online lifetime evaluation.

2.2. Offshore Wind infrastructure Project

The research presented in this paper is conducted in the framework of the “Offshore Wind Infrastructure Application Lab” (www.owi-lab.be). The OWI-lab is a Flemish R&D initiative which aims to increase the reliability and efficiency of offshore wind farms. The project consists of investments in test and monitoring infrastructure for offshore wind resource assessment and for system and component testing. Next to the investment program this R&D project aims to set up innovation projects with companies, universities and knowledge centers based on the equipment purchased in this project. OWI has the ultimate goal to look into research and development topics which have direct impact on the reduction of kwh-cost of offshore wind energy (installation, component design, O&M, resource planning,…). This project was initiated by 3E, GeoSea, ZF Wind Power, and CG Power Belgium in close collaboration with the Agoria Renewable Energy Club and Generaties. Sirris and the Vrije Universiteit Brussel (VUB) coordinate this initiative. The test infrastructure is implemented and operated by Sirris. The VUB is the lead academic partner in this project. Topics in this project are resource monitoring using floating LIDAR systems, condition monitoring systems (CMS), structural health monitoring (SHM), cold climate testing, accelerated lifetime testing and operation and maintenance strategies for offshore wind turbines.

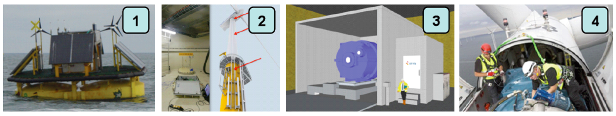

Figure 1: OWI-lab Research Topics: resource monitoring using floating LIDAR systems (1), condition monitoring and structural health monitoring (2), cold climate testing and accelerated lifetime testing (3) and O&M strategies (4)

2.3. State of the Art in Operational Modal Analysis

Identification of modal parameters on a full-scale operating wind turbine is particularly difficult and in the research community a lot of effort still goes into the development of suitable methods to tackle this problem [4]. Classical Experimental Modal Analysis methods cannot be applied because the input force due to the wind cannot be measured. For this reason, Operational Modal Analysis methods were developed to identify the modal parameters from the response of a mechanical structure in operation to unknown random perturbations [5][6][7].

In the past few years, the identification of output-only data has received a considerable amount of attention. Adapting model-based system identification techniques (e.g., maximum likelihood (ML) estimator, Least-Squares Complex Exponential estimator, Subspace techniques) for use with output-only data, has created the possibility of estimating modal models for in-operation structures excited by ambient noise and vibration (wind, waves, etc.) [8][9][10][11].

These algorithms require the spectral densities of the outputs as primary data. It has been shown that output spectra can be modeled in a very similar way as Frequency Response Functions [7]. These output spectra form the basis for frequency-domain output-only modal analysis.

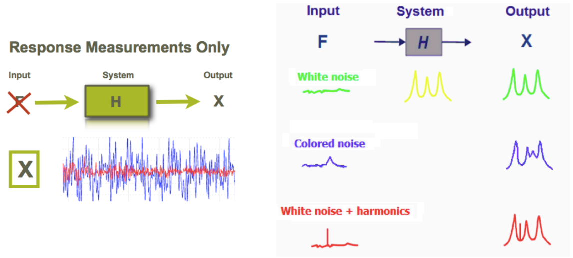

Figure 2: Operational modal analysis uses responses only (left), White noise and the effect of non-white noise contributions on response spectra (right)

These methods work under the assumption that the system is linear time invariant in the analyzed time interval and that the excitation is white noise in the frequency band of interest. Only in this situation the output spectra perfectly represent the system (See Figure 2). However, because of the presence of rotating components and their corresponding harmonic force contributions or due to the wind wave interaction with the structure, introducing colored noise contributions , wind turbines can fail to comply with the Operational Modal Analysis assumptions. Depending on the operating conditions, some of the non-white noise force contributions may coincide or be close to a natural frequency of the wind turbine, thus masking its contribution due to the higher energy and making the identification process to fail.

In [12] the applicability limits of operational modal analysis to operational wind turbines were discussed. It was clearly demonstrated that some important OMA-assumptions regarding the loads acting on the wind turbines are not satisfied for classic operational modal analysis techniques. As such the authors demonstrated that for weak and strong wind excitation the spectra of the aerodynamic forces are not flat but are characterized by peaks at rotational frequencies and few lower harmonics. They concluded that one must not expect classic OMA techniques to provide correct results in these frequency regions.

To solve these problems, current OMA methods need to be improved. Although some solutions have already been presented, they can usually only tackle one of the specific problems listed above [13][14]. Another difficulty is that in many applications such as helicopters or wind turbines the frequencies of the harmonic disturbances can vary in time. In order to deal with time varying harmonic disturbances a new method was proposed in [15] based on parametric modeling of the frequency variation combined with the use of a maximum likelihood estimator.

Recently a complete new OMA approach, based on transmissibility measurements, was proposed that increases the reliability and applicability of OMA techniques [16]. This innovative new approach does no longer require the assumption that the forces are white noise sequences. Therefore this new approach makes it possible to apply OMA in the presence of arbitrary operational forces (colored noise, impacts, ...). In recent work it was shown that the transmissibility based OMA approach is able to deal successfully with harmonics when the loads are correlated [17]. The proposed transmissibility based OMA approach therefore looks very appealing. However, despite the good results obtained so far there is a need for more basic research in order to continue to refine this approach and correctly position it in relation to other OMA methods.

3. Offshore Measurements

Within the OWI-project two measurement campaigns have been planned. The first short measurement campaign focussed on performing an overspeed test with the aim of obtaining a first estimate of the damping value of the fundamental for-aft vibration mode of the wind turbine. During the second long term measurement campaign we are continuously monitoring the vibration levels and the evolution of the frequencies and damping of the fundamental modes of the tower and foundation. Both the resonance frequencies and damping values are crucial to quantify the reliability and the lifetime of offshore wind turbines both in the design phase as during its life-cycle. These parameters will also be analyzed to see if they can provide indications about the current state of the soil and foundation characteristics for e.g. monitoring scour development [20]. The long term measurement campaign will last between 6 months and 1 year.

The measurement campaigns are performed at the Belwind wind farm, which consists of 55 Vestas V90 3MW wind turbines. The wind farm is located in the North Sea on the Bligh Bank, 46 km off the Belgian coast (Figure 4).

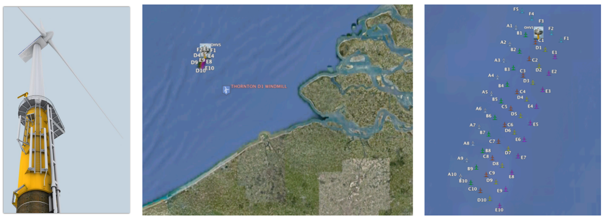

Figure 4: A render of an offshore Wind turbine at Belwind (1) location Belwind wind farm (2) park layout Belwind wind farm (3)

The hub-height of the wind turbine is on average 72m above sea-level. Each transition piece is 25m heigh and has a weight of 120 ton. The tests are performed on the BBCO1-turbine that is located in the north of the wind farm directly next to the offshore high voltage substation (OHVS).

The wind turbine is placed on a monopile foundation structure with a diameter of 5m and a wall-thickness of 7cm. The actual water depth at the location of BBCO1 is 22.9m and the monopile has a penetration depth of 20.6m. The soil is considered stiff and mainly consists of sand.

The structures instrumented in this campaign are the tower and transition piece. Measurements are taken at 4 levels on 9 locations using a total of 10 sensors. The measurement locations are indicated in Figure 5 by yellow circles. The locations are chosen based on the convenience of sensor mounting, such as the vicinity of platforms. The chosen levels are 67m, 37m, 23m and 15m above sea level. The interface level between the transition piece and the wind turbine is at 17m above sea level. There are two accelerometers mounted at the lower three levels and four at the top level. The chosen configuration is primarily aimed at identification of tower bending modes. The two extra sensors on the top level are placed to capture the tower torsion.

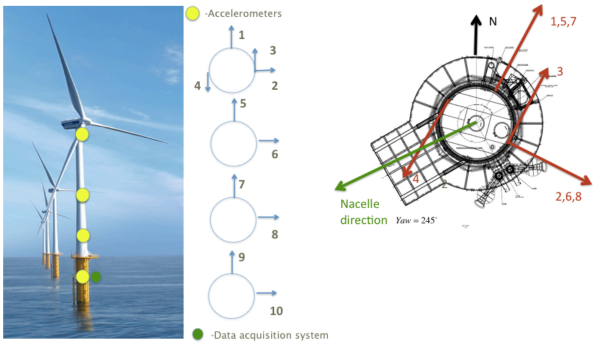

Figure 5: measurement locations on BBCO1

During the short measurement campaign, discussed in this paper, the sensors 7 and 8 were not yet installed.

In order to classify the operating conditions of the wind turbine during the measurements SCADA data (power, rotor speed, pitch angel, nacelle direction) is gathered at a sample rate of 1Hz. In order to monitor also the varying environmental conditions, the ambient data (wind speed, wind direction, significant wave height, air temperature, ...) is being collected at 10 minute intervals (Figure 6).

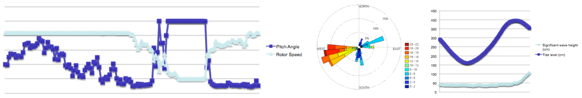

Figure 6: Example of measured SCADA data (left) and meteo data (right)

The data-acquisition system is mounted in the transition piece (green circle in Figure 5). The OWI-lab invested in a 'multi-purpose monitoring system' to support dedicated R&D projects in the field of offshore wind energy. It can be used to monitor several parameters, e.g. accelerations and strains, on existing offshore wind turbines. There was the demand for a robust data-acquisition system considering the harsh offshore conditions and any downtime had to be avoided taking into account the high cost related with working offshore. Since the project aims at characterizing the dynamics of an operational turbine under various operating conditions, it is also necessary that the data is acquired over a long period of time. This requires the data-acquisition system to be remotely monitored and capable of automatic startup in case of power shutdowns.

Bearing in mind the specific demands of the project a Compact Rio system of National Instruments was used. (Figure 7). An important reason for choosing this particular type of system is high flexibility to measure different types of signals. There is also the possibility to synchronize this Compact Rio system with other Compact Rio systems. This is especially interesting keeping in mind that the long term measurement campaign might be extended with measurements on the drivetrain and the blades.

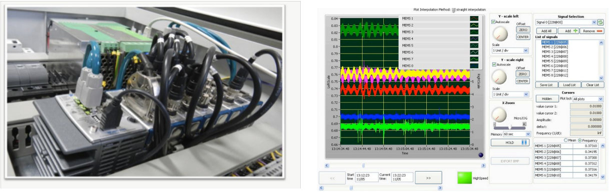

Figure 7: Data acquisition system based on NI Compact Rio System (left) and logger software (right)

The data acquisition software allows for the continuous monitoring of the accelerations. The software measures continuously and sends data every 10 minutes to the server that is installed onshore using a dedicated fiber that is running over the sea-bed. All data receives a time-stamp from an NTP time server in order to be able to correlate them with the SCADA and Meteo data. The measurements can be monitored real-time using the online scope-function.

Finally, accelerometers have been selected, which have a high sensitivity and are able to measure very low frequent signals. This is necessary considering that the modal frequencies of interest, for the wind turbine structure, are expected to be around 0.35Hz, and the expected vibration magnitude is very low, especially during ambient excitation.

4. Damping Estimation

4.1. Description of the tests

In this paper the damping will be estimated by using the data obtained during an overspeed stop and during ambient excitation. Figure 9 shows an example of a measured acceleration during an overspeed test and during the ambient excitation. The objective is to obtain an estimate of the additional offshore damping. This is the overall damping excluding the aerodynamic damping and damping due to vortex shedding or installed damping devices [21]. Therefore both during the overspeed test and during the ambient excitation test the tuned mass damper was turned off. During the ambient excitation the wind speed was always very low <4.5m/s and the pitch angle was around 80.5 degrees. This permits us to assume that the aerodynamic damping can be neglected. For the overspeed stop the wind speed was the minimum required 6.5m/s. This allows the wind turbine to speed up until 19.8 rpm. This is the speed at which the wind turbine is automatically stopped and the pitch angle is put on 88.2 degrees. So also here we can assume that the aerodynamic damping can be neglected a few seconds after the overspeed stop took place. Therefore the measured additional offshore damping will consist of damping from wave creation due to structure vibration, viscous damping due to hydrodynamic drag, material damping of steel and soil damping due to inner soil frictions [2].

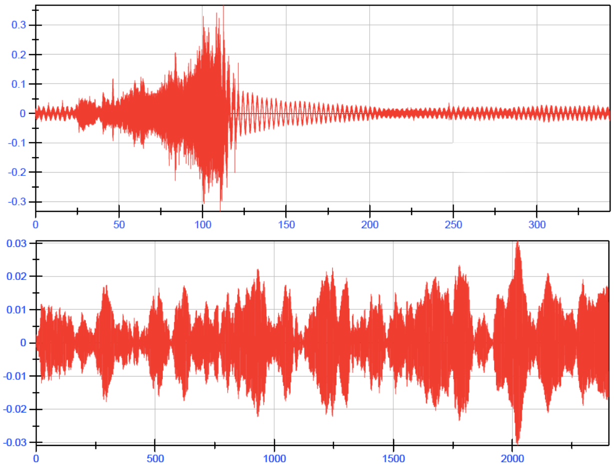

Figure 9: Example measured accelerations during overspeed stop (top) and ambient excitation (bottom)

The data-acquisition system was programmed to acquire data with a sampling ratio of 5kHz. Considering the frequency band of interest and in order to reduce the amount of data the recorded time series have been filtered with a band-pass filter and re-sampled with a sampling frequency of 12.5Hz. After the downsampling and filtering a coordinate transformation was performed. The accelerometers are mounted on the tower. Therefore, in order to measure the vibrations along the axis of the nacelle, it is necessary to take the yaw-angle into account by transforming them into the coordinate system of the nacelle [22].

4.2. Overspeed Stop

Time domain analysis

The overspeed test is generally used to accurately identify the modal damping ratios. The damping ratios are obtained by fitting an exponential function to the relative maxima of the decaying time series and extracting the damping ratio from the parameters of the fitted expression. This method assumes that the decay has only the contribution of a single mode. When this assumption is not met it may result in high scatter and might give wrong estimates for the damping. This is especially the case for closely spaced modes where it might not be possible to get a decaying vibration with just the contribution of one mode [23].

During an overspeed stop the wind turbine speeds up until it reaches 19.8 rpm. Then the wind turbine is automatically shut down. During this stop the pitch angle is changed to 88.2 degrees. The thrust release due to this sudden collective pitch variation excites the tower mainly in the wind direction as can be seen in Figure 10. Note that on the figure the wind direction is shown from bottom to top.

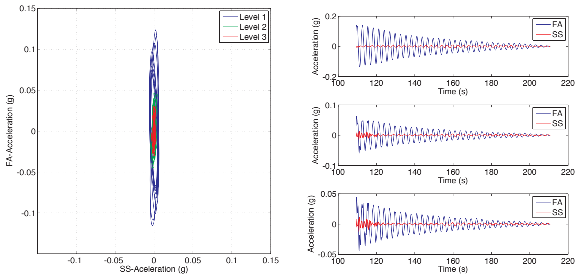

Figure 10: Movement seen from above (left) and accelerations (right) on 3 levels in FA and SS direction during overspeed stop.

In the beginning of the decay, the for-aft mode (FA) is dominant, but by the end of the decay both the for-aft mode and the side-to-side mode (SS) contribute to the movement. This can be observed in Figure 11.

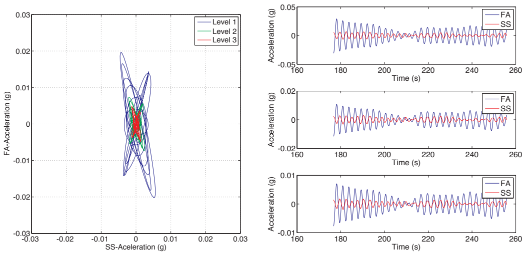

Figure 11: Movement seen from above (left) and accelerations (right) on 3 levels in FA and SS direction at the end of the decay of the overspeed stop

At a certain moment the phase between the for-aft and side-to-side responses changes 180 degrees causing the measured vibration to change direction. The figures show that it is definitely interesting to plot the for-aft movement and side-to-side movement to check if the vibration is dominated by one mode before applying the exponential decay method.

To conclude, we can assume that the decay in the beginning of the exponential decay is mainly dominated by the FA mode and that performing an exponential decay analysis is expected to give acceptable estimates for the damping of the FA mode. In order to have a better fit extra points by using a spline function have been interpolated between the extremes.

The method was applied to the measured accelerations of the highest 3 levels in the direction of the wind. The data was pre-filtered using 3 different band-pass filters. The fitting was performed between 0.8 and 0.2 of the maximum acceleration. The results are shown in Figures 12-14 and in Table 1.

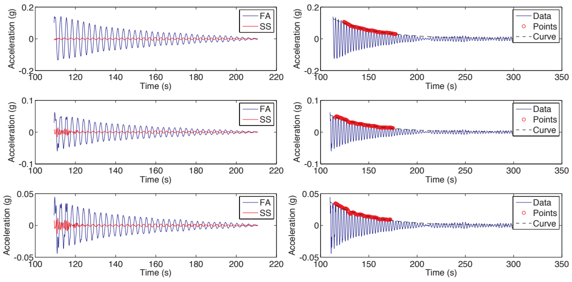

Figure 12: Accelerations on 3 levels in FA and SS direction after applying a band-pass filter of 0.01-1.5Hz (left) exponential fitting on FA acceleration on 3 levels

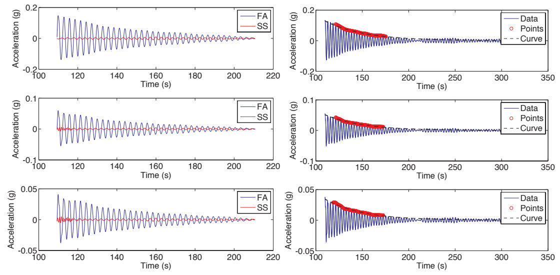

Figure 13: Accelerations on 3 levels in FA and SS direction after applying a band-pass filter of 0.1-0.8Hz (left) exponential fitting on FA acceleration on 3 levels

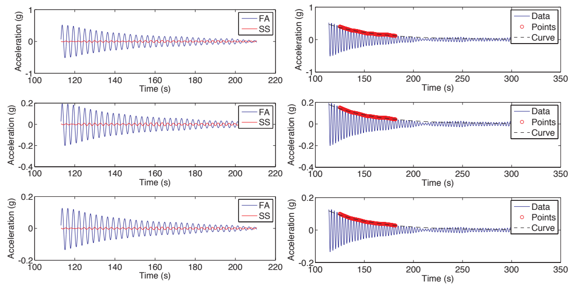

Figure 14: Accelerations on 3 levels in FA and SS direction after applying a band-pass filter of 0.3-0.5Hz (left) exponential fitting on FA acceleration on 3 levels

Band	0.01-1.5Hz	0.1- 0.8Hz	0.3-0.5Hz
Level 1	**1.10%**	**1.12%**	**1.04%**
Level 2	**0.98%**	**1.15%**	**1.05%**
Level 3	**0.86%**	**1.16%**	**1.05%**

Table 1: Estimated damping ratios on the 3 levels using different band-pass filters

It is expected that the estimates using the narrow band-pass filter 0.3 - 0.5 Hz around the frequency of the first FA mode of the wind turbine are likely to be the most correct ones. As this band is filtering any effects of higher vibration modes of tower and blades. Moreover, as the offshore wind turbine is continuously excited by the ambient excitations coming from the wind and waves, we can no longer speak of a free vibration test. Also this may introduce errors in the damping estimation approaches. During this experiment the wave period was around 0.28Hz, as will also be discussed in the next section. Only the last band-pass filter excludes this continuous wave excitation.

We can conclude that the above technique is expected to give good damping estimates after applying a proper band-pass filters to isolate the contribution of the mode under analysis. This approach can face difficulties when several modes, e.g. first FA and SS mode, are present with close frequencies or when colored ambient force contributions are present, e.g. waves.

Frequency domain analysis

Instead of analyzing the data in the time domain, one can also perform the analysis in the frequency domain. The Fast Fourier Transformation of the decaying functions can directly be used as input for the analysis methods in the frequency domain.

Figure 15 shows the Fast Fourier Transformation of the accelerations obtained on the 3 different levels in both the FA and SS direction. One can clearly identify the dominant peak from the first FA mode around 0.35Hz. We can also identify some smaller peaks with a frequency higher then 1Hz. These peaks are related to higher tower bending modes or blade modes.

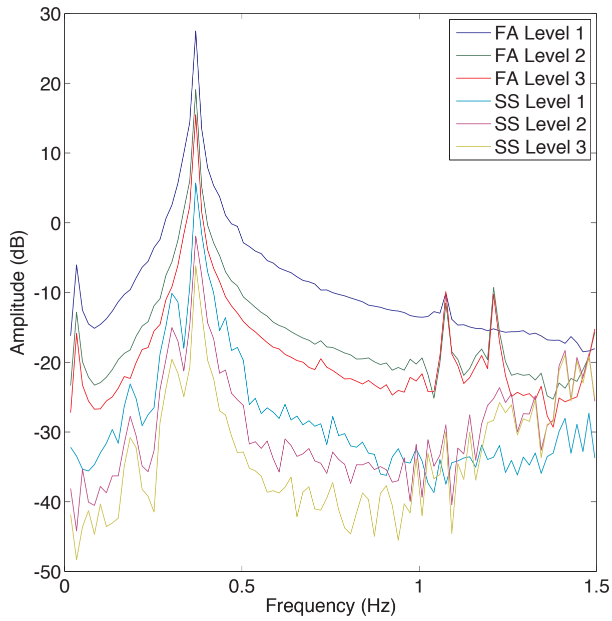

Figure 15: Fast Fourier transformation of the accelerations obtained on the 3 different levels in both the FA and SS direction

We can also clearly observe some peaks below the dominant frequency. These peaks are likely to be related to the waves. The significant wave height during the tests was 0.5m and the wave period was around 3.5 second.

The identification algorithms can now be applied to a matrix with a single column containing the Fast Fourier Transformation of the free decays measured during the overspeed test. During this analysis we used again the data between 0.8 and 0.2 of the maximum acceleration.

An initial estimate of the damping ratios was obtained with a least squares estimator in the frequency domain, using polynomials with orders between 1 and 32 [8]. The fitting was performed in the frequency range 0.01 –1.5Hz. In the corresponding stabilization diagram with increasing model orders one can clearly identify several stable poles.

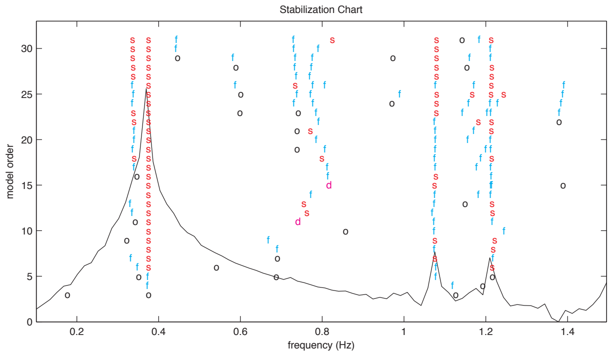

Figure 16: Stabilization diagram after applying the least squares frequency domain estimator to the Fast Fourier Transformations of the overspeed responses

In the stabilization diagram algorithm used in this paper we evaluate for every pole, the distance to the nearest pole calculated with the previous model order and we plot:

- a red s, if distance is smaller than 1%,
- a blue f, if only frequency variation is smaller than 1%,
- a purple d, if only damping variation is smaller than 5%,
- a black o, if neither the pole, nor the frequency, nor the damping ratio stabilizes

The damping ratio of the dominant mode was found to be **1.05%.**

Damping ratio FA-Mode
1.05%

The peak below the dominant mode was identified with a much higher damping and has a frequency of 0.29Hz. This perfectly coincides with the wave period of the waves with a wave direction almost in line with the nacelle. During the overspeed stop the wave period was around 3.4 seconds. Note that this confirms that waves can induce significant oscillation and accelerations in the turbine as was stated in [3]. The wave frequency is close enough to the resonance frequency of the fundamental mode of the wind turbine to have a dynamic amplification. Therefore, waves can have a significant effect on the lifetime of the wind turbine and should definitely be taken into account when performing fatigue calculations.

The higher stable modes are due to the contributions of higher tower modes and blades modes in the overall vibration of the wind turbine during an overspeed stop. Note that this approach fits a polynomial function with multiple modes and therefore overcomes the limitations of the traditional procedure of fitting an exponential decaying function to the measured accelerations in the time domain. The frequency domain technique uses a model that starts from the knowledge that the overall vibration consists out of different modes. Therefore, the results are not affected by the fact that multiple modes are present in the measurements. The obtained result therefore corresponds closely with the previous results when we applied a narrow band-pass filter around the FA-mode.

4.3. Ambient Excitation

Ambient vibration tests have the strong advantage of being very practical and economical, as they use the freely available ambient wind wave excitation. Furthermore, the data is collected during the normal use of the structure and consequently the identified modal parameters are associated with realistic vibration levels.

An operational modal analysis was performed with the rotor slowly rotating (0.2 rpm). In the 40 minutes of recorded data (just before the overspeed stop was performed) the wind had an average speed of around 4.5m/s. The nacelle was put into the direction of the wind. Figure 17 shows the movement of the tower in the FA and SS direction during 2 successive time segments.

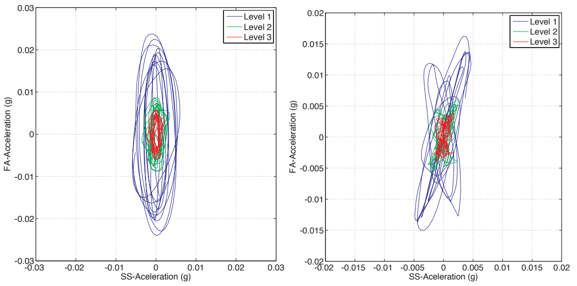

Figure 17: Movement seen from above on 3 levels in FA and SS direction during ambient excitation at 2 different moments in time

One can observe that the movement is mainly in the FA direction, i.e. the direction of the wind, but there is also a small contribution of the SS movement. The tower does not vibrate purely in the wind direction, both the FA mode as the SS mode are present, resulting in an additional movement perpendicular to the wind.

Correlation driven analysis in the time domain

When using the vibrations measured during the ambient vibrations one can calculate the correlation function of the measured accelerations. It has been shown that the output correlation of a dynamic system excited by white noise is proportional to its impulse response [24]. Therefore it is possible to estimate the modal damping ratio of the modes under analysis from the obtained correlation in a similar way as from the decaying time series obtained during an overspeed stop.

By fitting again an exponential function to the relative maxima of the auto-correlation functions the damping ratio can be extracted from the parameters of the fitted expression. Figure 18 shows the normalized auto-correlation function of a sensor in the SS direction and the FA direction together with their exponential fit.

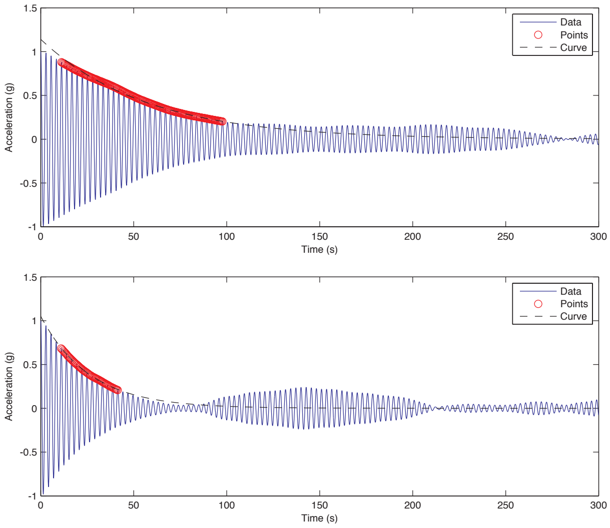

Figure 18: Exponential fitting of an autocorrelation function of a sensor in the FA direction (top) and SS direction (bottom)

As mentioned above this approach can only provide good estimates for the damping when the decay consists of 1 mode. When this is not the case and there is strong coupling between 2 modes, e.g. between the FA and SS mode, one will not be able to see a nice decay.

Band	0.01-1.5Hz	0.1- 0.8Hz	0.3-0.5Hz
Level 1 FA	**0.89**	**0.89**	**0.84**
Level 2 FA	**0.90**	**0.90**	**0.84**
Level 3 FA	**0.90**	**0.90**	**0.84**
Level 1 SS	**1.81**	**1.79**	**1.59**
Level 2 SS	**1.80**	**1.78**	**1.61**
Level 3 SS	**1.74**	**1.79**	**1.65**

Table 1: Estimated damping ratios on the 3 levels both in FA and SS direction using different band-pass filters

The auto-correlation of the FA movement still seems to have a nice decay in the beginning, but some small coupling can be noticed in the tail of the decay. This coupling prevents the auto-correlation to fully decay and therefore tends to give a small underestimate of the damping of the FA mode. In the auto-correlation of the SS movement the coupling between 2 modes is strongly present and therefore the estimate of the modal damping using this signal is not correct.

Correlation driven analysis in the frequency domain

In a similar way as with the decaying functions obtained during the overspeed stop, the Fast Fourier Transformation of the decaying auto-correlations can directly be used as input for the analysis methods in the frequency domain. The Least Squares estimator in the frequency domain can be applied to a matrix with a single column containing the Fast Fourier Transformation of the auto-correlations. During this analysis we used the data from the first 300 seconds of the auto-correlation resulting in a frequency resolution of 0.0033Hz. The transformation of the correlation function into spectra is preceded by the application of an exponential window to reduce leakage and the effect of the noise terms in the tails of the correlation functions. The damping ratios can be corrected for this window. The fitting was performed in the frequency range 0.01 –1.5 Hz. In the corresponding stabilization diagram one can clearly identify several stable modes.

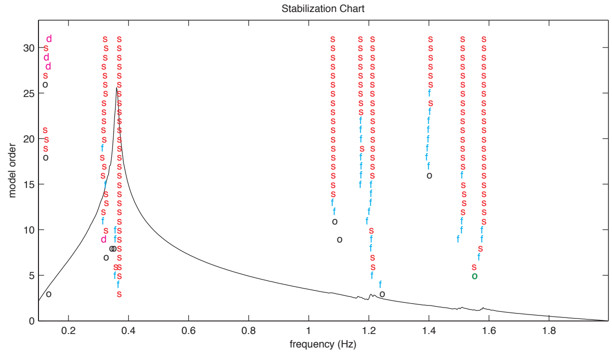

Figure 19: Stabilization diagram after applying the least squares frequency domain estimator to the Fast Fourier transformations of the auto-correlations

The damping ratio of the dominant modes was found to be **1.07%.**

Damping ratio FA-Mode
1.07%

Note that this approach fits again a polynomial function with multiple modes and therefore the results are not affected by the fact that multiple modes are present in the measurements as was the case for the previous correlation driven analysis in the time domain.

The stable pole below the dominant mode has a frequency of 0.31Hz. This corresponds again with the wave period during the ambient test which is now slightly lower in comparison with the overspeed test.

Periodogram driven analysis in the frequency domain

The periodogram driven analysis is the traditional approach for performing operational modal analysis in the frequency domain [8][9]. The first step of this method is the calculation of the power spectrum matrix from the measured accelerations. The different columns contain the cross-spectra between the accelerations at all measurement points with the corresponding acceleration of each chosen reference point. The elements of these matrices have been estimated using the Welch method by dividing the available time series in segments of a certain length, with an overlap between segments of 50%. In order to reduce the leakage a Hanning window was applied [8].

Considering again the 40 minutes of ambient data, we can calculate the spectra. Figure 20 shows 6 cross-power-spectra using the sensor in the FA direction on the top level as reference sensor with 40 blocks, 50% overlap and a Hanning window. The frequency resolution in this case was 0.0086Hz.

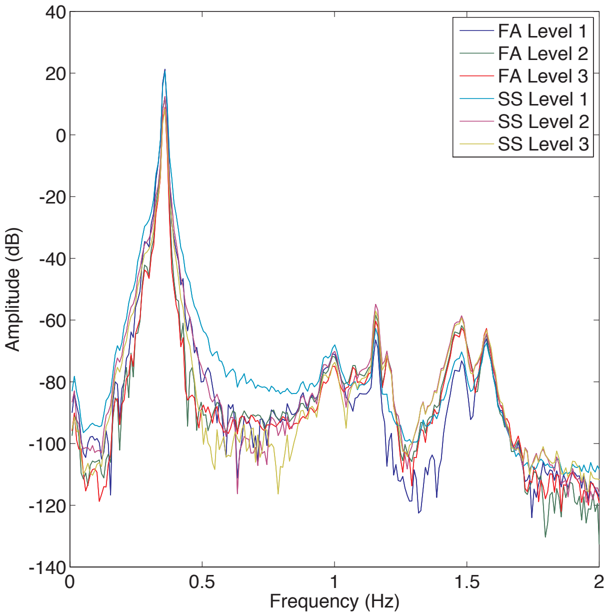

Figure 20: Auto and cross spectra with reference sensor 1 in FA direction

We can now apply the Least Squares estimator to the power spectra matrix with both the sensor in the SS and FA direction of the top level as reference (6x2 matrix) in the frequency domain 0.1-2Hz. Figure 21 shows the stabilization diagram where we can identify several stable modes.

Note that this approach results in 2 stable modes around the dominant peak corresponding respectively with the FA mode (0.358Hz) and SS (0.345Hz) mode.

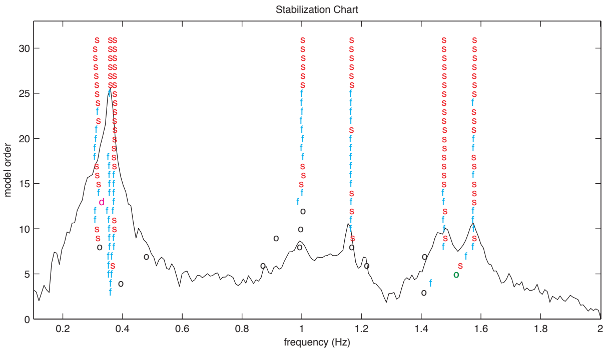

Figure 21: Stabilization diagram after applying the least squares frequency domain estimator to the spectrum matrix

Damping ratio FA-Mode
1.05%

Damping ratio SS-Mode
1.27%

We find a slightly higher damping in the SS direction. This is as expected due to the presence of aerodynamic effects in this direction considering the pitch angle of 80.5 degrees [12]. According to [19] the aerodynamic forces are present even at standstill due to the larger blade surface that interacts with surrounding air when the tower vibrates in the SS direction.

5. Conclusions and future work

The analysis of the measured data showed that the ambient vibration tests together with the application of state-of-the-art output-only identification techniques can provide good estimates of the modal damping ratios of offshore wind turbines.

However, care should be taken when analyzing such data. High scatter is to be expected when the analysis is not carefully done. For the methods in the frequency domain results can depend e.g. on the measured time, on the number of blocks and number of frequency lines. A detailed discussion can be found in [8][9][23][26]. In general we can say we achieve a scatter on the damping of around 10%. The results in this paper are obtained after a careful optimization of above parameters by minimizing the standard deviations on the results. As such, the obtained 68% confidence bounds that could be found, vary from 0.05 to 0.07 [25].

Using the exponential fitting approach one can encounter difficulties when several modes, e.g. first FA and SS mode, are present with close frequencies or when colored ambient force contributions are present, e.g. waves. Proper filtering is required in order to obtain good estimates of the damping. The techniques presented in the frequency domain estimate the correct damping ratios even when several modes are present in the overall vibration and their natural frequencies are close. Furthermore the operational modal analysis approach also allows to extract the higher modes.

The approaches for dealing with ambient data presented in this paper require long time-series. When we will perform in the near future the data analysis of the long term monitoring campaign of the wind turbine in operation we will be required to work with short time segments in order to comply with the time-invariant assumption of the system under analysis. The elimination of errors on the damping estimates due to transient phenomena, when using short time segments, will be needed. Therefore we can use estimators that can take into account these possible leakage errors [26]. These techniques preferably work directly with the measured Fourier data instead of using the averaged spectra, which become inapplicable when only short data records are measured. A further optimization of the results can be expected from using the maximum likelihood estimators and taking the noise information into account [27].

For future work we can say that a detailed investigation of the possibilities and limitations of several existing OMA techniques and new OMA techniques, such as the transmissibility based OMA approach, for testing wind turbines is needed.

It is therefore the objective to provide in the near future reliable guidelines to identify the modal parameters (more specifically the damping ratios of the fundamental tower/foundation modes) from operational measurements on an offshore wind turbine. This will help us to get a better understanding in the damping-effects in offshore wind turbines and to better estimate the real lifetime of wind turbines.

So far we can conclude that the results obtained in this short term measurement campaign are in good agreement with GL recommendations for additional offshore damping for piled support-structures [28]. Taking into account a possible scatter of the results we can state that the additional offshore damping of the fundamental mode is between 0.9% and 1.2%.

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