S.R.Z Ilahibaks

An applicability study of the Eigensystem Realization Algorithm on estimating modal parameters from acceleration response measurements of operational offshore wind turbines

TUDelft

Challenge the future

Eneco

An applicability study of the Eigensystem Realization Algorithm on estimating modal parameters from acceleration response measurements of operational offshore wind turbines

By

S.R.Z. Ilahibaks

in partial fulfilment of the requirements for the degree of

Master of Science
in Structural Engineering

at the Delft University of Technology,
to be defended publicly on Thursday September 10, 2020 at 02:00 PM.

Chairman:	Prof. Dr. A. Metrikine	
Thesis committee:	Dr. Ir. K.N van Dalen,	TU Delft
	Ir. D.J.M Fallais,	TU Delft
	Dr. Ir. B.C Ummels	TU Delft
	Ir. W. E. de Vries	Eneco

TU Delft

ABSTRACT

In the design of offshore wind turbine generator (WTG) support structures, a large number of environmental parameters are used. The most important ones include the wind climate (wind speed and wind direction probability distributions), the wave climate (wave height and wave direction as well as peak frequencies of the waves, and water levels) and the soil conditions. These data in combination with the operational data of the wind turbine, such as the rotor speeds, pitch angle and yaw angle are used in dynamic simulations to determine the loads on the structure. Combining all these data correctly ensures that the support structure design, which is subject to large dynamic loads, is fitting for each specific location of the WTG. In particular, the environmental conditions should not coincide too much/often with the support structure natural frequencies, as that may result in resonance, thereby increasing fatigue life consumption. The dynamic behavior of these offshore support structures is of eminent importance.

During the operation of WTGs, the actual dynamical properties of the WTG can be compared to the design. There are several reasons behind the goal of this comparison, for example verifying if the loading assumptions in the design were correct, assessing whether the life time can be extended or even whether the structure can be optimized (e.g. better foundations). Typically, this is done by comparing acceleration measurements of the WTG during idling (e.g. non-operational) conditions and applying Operational Modal Analysis algorithms. Given the high availability of modern wind turbines (e.g. >95% of time in operation) such measurements cannot be done as often as desired for this purpose. Therefore, the question arises to what extent the dynamical properties of WTGs can be estimated using measurement data obtained during operational (operational) conditions.

This research explores the applicability of OMA algorithms in estimating the dynamical properties: the natural frequencies, the mode shapes and modal damping for operational conditions of offshore wind turbines on monopile foundations, using the Luchterduinen offshore wind park as a case study.
The OMA technique explored in this thesis is Eigensystem Realization Algorithm. Test cases were used to confirm the performance of ERA for the estimation of the dynamic parameters. Stability diagrams were used to identify poles for stable modes (frequencies) in the frequency spectrum of data samples and to estimate a correct size of the Hankel matrices.

It is concluded that this preprocessing and pre-analysis of the results is important to confirm the performance of ERA to correctly identify stable modes of support structures of operational offshore WTGs.
Overall, it is concluded that ERA can yield useful results in estimating the natural frequencies for both ON and OFF, provided that an automated analysis is combined with a visual analysis. Even then, the accuracy and the consistency of the identified frequencies is moderate. ERA does not perform well for estimating the mode shapes, yielding inaccurate and inconsistent results.

Based on the results of this work, ERA is found not to be capable of estimating modal damping ratios.

The consistency for the mode shapes is not in all cases good and further study is recommended for both the mode shapes and the modal damping ratio. Another recommendation is to further study the size of Hankel matrices for this application. Furthermore, it is advised to also investigate the use of more advanced Operational Modal Analysis algorithms. The results of this study may be used to explore differences between wind turbines with and without scour protection and also to compare identified dynamic parameters to values used in the design.

ACKNOWLEDGEMENT

To complete your master studies at the TU Delft, the final part of the curriculum consists of doing research and writing your Master thesis.
Almost one and a half year ago I chose to base my research on the dynamics of structures. My love for this topic was inspired by Karel van Dalen and Mr. Metrikine. The company Eneco came onto my path and I was allowed to start an internship there under supervision of Wybren de Vries. My supervisors at the TU Delft were Dominik Fallais and Bart Ummels. The overall supervision was led by Karel van Dalen.

The research process was not one with smooth edges but had its ups and downs, sometimes I really did not know how to continue. But those difficulties were my motivations to go further and try to explore, how to solve the problems. In the end, it led to the expansion of my knowledge.

The appreciation for the support and the critical guidance by Wybren, Bart, Dominik and Karel is very high. I would like to thank the four of you from the bottom of my heart for all the time and effort you put into this. Also, a big thank you to Leon van der Meijden and Ruben Dijkstra for giving me the opportunity to do my research at Eneco. The time at Eneco was not only very educational, it was also a good social experience with colleagues.

I would also like to thank my parents, sisters, and brother-in-law for the believe they always have in me and giving me the opportunity to study in a foreign country by myself. My close friends are not to be forgotten in the moral support I received from them and especially my sparring friend, who was always there to brainstorm with me, if I had difficulties again.

I started this journey on the TU Delft with the saying:
'Wish it, Dream it, Do it'. Today I am proud to say I wished it, I dreamed it and finally I did indeed do it.

Gran tangi,

Shaneeza R Z Ilahibaks

Table of Contents

List of figures

List of tables

List of Abbreviations

DAS	Data Acquisition System
ERA	Eigensystem Realization Algorithm
FA	Fore Aft direction
FDD	Frequency Domain Decomposition
FRF	Frequency Response Function
LAT	Lowest Astronomical Tide
LSCF	Least Square Complex Frequency
OHVS	Offshore High Voltage Station
OMA	Operational Modal Analysis
RPM	Revolutions Per Minute
SCADA	Supervisory Control and Data Acquisition
SS	Side to Side direction
SSI	Stochastic Subspace Identification
TOMA	Transmissibility Operational Modal Analysis
UTC	Universal Time Coordinated
WTG	Wind Turbine Generator

List of Symbols

A	State transition matrix
B	Control influence matrix
C	measurement influence matrix
E	Modulus of Elasticity
EI	stiffness of the beam
f	damped frequency
f_p	Wave peak frequency
H	Hankel matrix
H_{10}	Average water height over the last 10 minutes
H_{m0}	Water level
I	moment of Inertia
m	mass of the beam
T_{h0}	wave direction
V_r	Observability matrix
V_w	Wind speed
W_s	Controllability matrix
Z	eigenvalue matrix
ζ	modal damping factor
θ	angle
λ	eigenvalue
Σ	Singular value matrix
σ	damping ratio
Ψ	eigenvector matrix
ω	eigenfrequency

1. Introduction

In the modern world we live today, renewable resources are becoming more important for several fields, instead of the fossil fuels, mainly because of climate change. This is also the case in the production of electricity, for example by solar energy or wind energy. In this thesis the focus lies on the structures used, wind turbines, for wind energy offshore. In the first chapter the background is given on renewable energy and renewable energy in the Netherlands. Subsequently an overview of previous research is presented, leading to the case description for this thesis. When the case description is formulated and the objective for the research is clear, the research questions are formulated followed by the approach for the study.

1.1 Background

In today's world electricity is one of the main necessities and because of climate change renewable energy becomes more important. Renewable energy is produced in different ways e.g. with wind energy, hydropower or solar panels. In this thesis the focus will be on wind energy, where the mechanical power to turn electric generators is provided by air flow through wind turbines [11]. Wind energy is sustainable, renewable and has a smaller impact on the environment than the traditional ways (using fossil fuels) of producing energy. Wind turbines can be installed on land (onshore) or in the sea (offshore). Because onshore wind turbines need a lot of land space and sometimes are a hinder to the community living in these areas, offshore wind turbines are becoming more popular. Furthermore, offshore wind is steadier and stronger than wind over land. However, the construction and maintenance costs are higher [11].

In the Netherlands the growth of installed offshore wind capacity is also increasing. It is stated in "*Het ontwerp - klimaatakkoord*" [9] that the goal is to produce 49 TWh wind energy by 2030. This is only possible if there are more wind farms. The Netherlands chose the North Sea as new building site for wind farms, such that the most wind farms are outside the territorial sea. The area for the wind parks is split up in sites [29].Figure 1.1 [27] gives an overview of the already existing wind farms and the new wind farms. Wind farm developers are given the chance to compete in tenders given out by the government per site. Sometimes the developers join forces, to form a consortium. The government investigates the conditions of the site, including the soil, the windspeed and information on water depth, current and waves. With this knowledge the wind park developer is considered to be able to design the best possible wind farm.

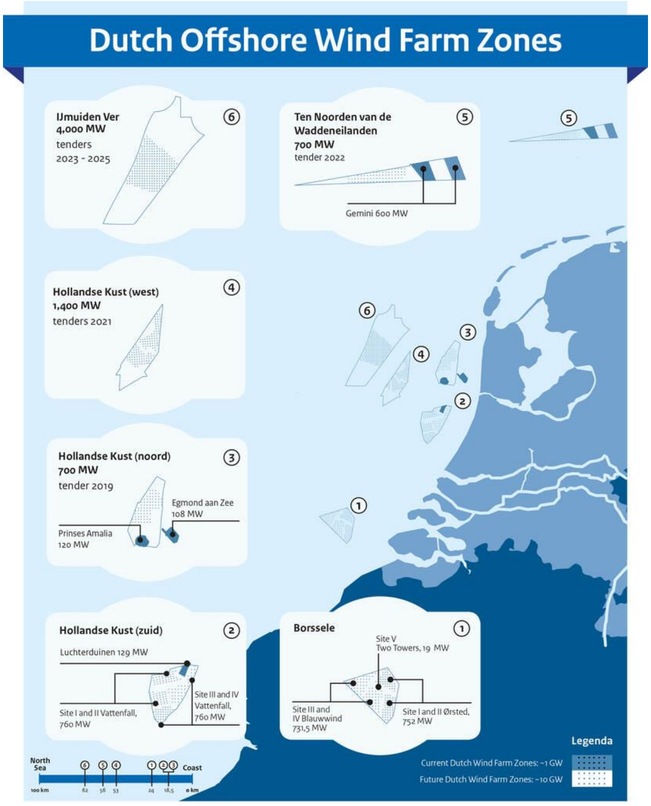

Figure 1.1 Offshore Wind farm zones in the North sea of the Netherlands [27]

In part due to this competitive regime, the Levelized Costs of Energy (LCoE) of the wind turbines needs to be as low as possible. One way of achieving low LCoE is to reduce the costs for construction. In the optimization it is important to still meet the strength, stiffness and stability requirements for determining the dimensions of the structure, which give the lowest costs. An important part of the structure, with high costs is the foundation.

A good way to optimize the foundations is by determining the dynamic response of the structure and design more slender constructions, which will cost less since less steel is needed. Turbines are designed such that the tower fundamental resonance frequency does not coincide with the fundamental rotational (1P) and blade passing (3P) frequencies. System identification is a verification process, which builds mathematical models to estimate dynamical properties of structures from measured data [2]. The focus in this thesis resides in the methodology, with the use of Operational Modal Analysis (OMA) algorithms, to estimate the dynamic properties for the structures using data concerning operational wind turbines.

A company in the Netherlands operating in the field as wind park developer is Eneco. Eneco owns and operates several wind farms, notably Prinses Amalia wind park and Luchterduinen, and more recently, together with Shell, has won the Borssele III+IV and Hollandse Kust (Noord) tenders and will also be competing in new tenders. One of the goals for Eneco is thus to optimize the offshore wind turbine structures in future offshore wind projects. Another goal is to optimize the foundation stiffnesses of these structures. To achieve these goals, identifying the dynamic properties, such as natural frequency, the mode shape and damping ratios, is an essential start.

1.2 Literature review

Over the course of many years researchers in different fields have developed a variety of techniques to determine the dynamic properties: natural frequencies, mode shapes and modal damping of structures. The methodologies on Operational Modal Analysis (OMA) are a few of the possible techniques. OMA which is used for large structures is also researched in many fields and also particularly on wind farms.

The fundamental idea of OMA testing techniques is that the structure to be tested is being excited by some type of excitation that has approximately white noise characteristics [18], that is, it has energy distributed over a wide frequency range that covers the frequency range of the modal characteristics of the structure. Another assumption OMA's rely on, is that the systems are assumed to be linear time – invariant (LTI) and stationary. This allows the systems to be represented as state – space variables. Examples of structures, which are tested with OMA techniques are bridges, high rise buildings and wind turbines (the focus of this thesis). These structures are all very large, making it practically impossible to do experiments on the structures. That's where OMA comes in, because this allows to only know the response of the structure in order to get the dynamical properties of systems.

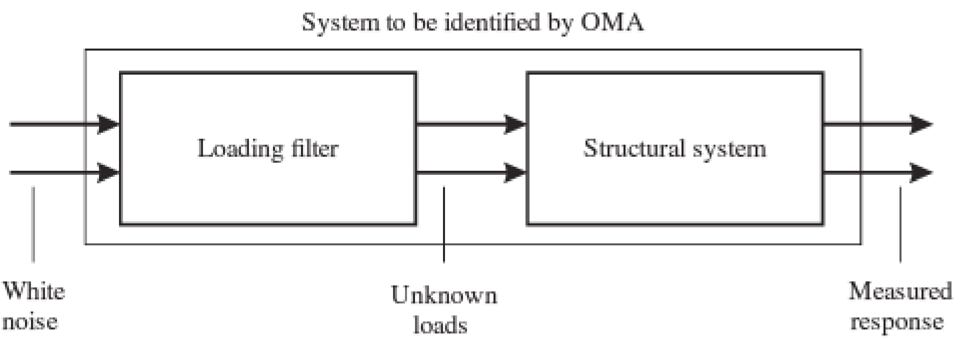

Figure 1.2 System Operational Modal Analysis [18]

When interpreting the modal results, the wide frequency range has to be kept in mind, because some of the estimated modes might be present due to the loading conditions (in the case of offshore WTGs: waves, for example) and some might come from the structural system (resonance frequency of the support structure). Each mode is associated with a specific natural frequency and damping factor, and these two parameters can be identified from vibration data from practically any point on the structure. Sometimes in the identification of the modes there are closely spaced modes visible. These modes must be visible in all data sets in order to classify them as structural true modes [18]. If a mode is a structural mode it is approximately Gaussian (the sum of many independent and identically distributed random variables, will be Gaussian distributed, as the variables go to infinity) and if not, for example a harmonic, the density function should be different.

When using OMA's it is advised to use multiple techniques in order to have a good confidence in the obtained results. Having multiple results can validate the pairs, if they are in a predefined range [18]. In operational testing there are mainly two important aspects, namely there must be multiple loads and the operating response data needs to be of good quality [18].

In this study the main focus is on wind turbines and the use of OMA's for wind turbines. The response of wind turbines to environmental conditions such as wind speed, wind direction and pitch angles is expected to be gaussian distributed [18].

In a study done by Gasparis [1], different OMA techniques are used for system identification to know if structural response data from operating OWT's can be used. Gasparis used simulated data to compare the different techniques and set up two models, a simple MATLAB OWT model and a NREL in FAST, in order to validate the results. With these models Gasparis wanted to analyze if the dynamic properties could be estimated accurately. The addressed techniques, of which the two most basic techniques (1 and 2) will be further discussed, are:

1. Frequency Decomposition Domain (FDD),
2. Eigensystem Realization Algorithm (ERA),
3. Stochastic Subspace Identification (SSI)
4. Least Square Complex Frequency-domain (LSCF)
5. Transmissibility Operational Modal Analysis (TOMA)

FDD is a frequency identification technique based on the peak picking method. In the peak picking method, the modal peaks are displayed by spectral density functions, with the disadvantage that for closely spaced modes it is difficult to select the right peak [3][4]. For the FDD technique the spectral density matrix is decomposed into several auto spectral density functions, each representing its own Single Degree of Freedom (SDOF) system. This is the Singular Value Decomposition (SVD) of the spectral matrix. In the cases other than white noise, lightly damped structures or modes which are geometrically orthogonal, the results are accurate approximations. Otherwise they are exact [3].

ERA uses the time domain but selects the frequencies and modal damping parameters automatically. The smallest state space model among systems which have the same input-output relations with a specified degree of freedoms is equivalent to a problem involving a sequence of matrices, the Markov parameters (impulse responses) [5][6]. ERA is split in 2 parts, the basic formulation of the minimum order realization, where the Hankel matrix is generalized to allow random distribution of Markov parameters and the modal parameter identification. The Hankel matrix is a block matrix formed by the Markov parameters, in which each descending diagonal is constant.

There are many studies done throughout the decades on operating wind turbines. In this chapter we will further review, a study done by OWI-lab, an earlier study done on the wind farm of Eneco and a study on wind turbines of Siemens.

In an earlier study done on the wind farm Eneco Luchterduinen by Middelweerd [25], the researcher used the OMA technique Least Square Complex Frequency-domain estimator (LSCF) to test the sensitivity of the first natural frequencies of wind turbines. The results in this study are compared to a computer simulated calculation and also to automatically obtained natural frequencies by the system of the sensors placed on the wind turbines. Important remarks in this study for the LSCF method are, that the estimation of the natural frequency was influenced by the environmental conditions. The height of the water level for example decreased the natural frequency as the wind conditions did not affect the first natural frequency significantly [25]. On the wave conditions there were no specific conclusions for the influence on the natural frequency, because of contradicting information between the estimation of the sensor and the manually identified natural frequency [25]

In a study done by OWI-lab, turbines in the Belgian North Sea are tested [13]. In this study the main goal is the classification of the resonant frequencies and modal damping for different operational conditions over the course of a year. Also, in this research the LSCF technique is used, but a modified version namely the p-LSCF technique. The measured data comes from 10 accelerometers placed on the wind turbines. The yaw angle is used to transform the data from the accelerometers, which are fixed on the tower structure to the FA-SS coordinate system. The resonance frequencies obtained in the FA and SS differed not very much over the course of one year. An important remark to make, is the sudden drop in the frequency between the idling condition and the cut out. There is structural no difference in the situation, which means that the drop should lie in environmental conditions [13]. A limitation in this study showed to be the estimation of the parameters for fully operational turbines.

A study by Ogno in 2013, had the goal to identify the structural parameters of offshore operational wind turbines [26]. Ogno made use of measurement data of idling turbines, to better satisfy the assumptions of LTI systems. With the use of idling turbines, the influence of rotational harmonics and huge aerodynamic non linearities is avoided [26]. In this study, after testing academic cases between 2 algorithms, the Subspace Stochastic Identification (SSI) algorithm is used. The results obtained for the modal analysis were compared to an earlier done study by Siemens and it showed that SSI improved the obtained results. It was furthermore shown that it was not possible to estimate the mode shape in its total and the modal damping ratios were excessively conservative [26].

As a final remark on the studies taken into consideration, in most of the studies [8][12] challenges occurred in estimating the damping of offshore wind turbines, (OWT), whereas it was possible to estimate the natural frequencies and mode shapes (these are also related to each other). The challenges in estimating the dynamic properties also occurred in ‘operational conditions’, so during the operation of wind turbines with rotating blades. The OMA techniques were successfully applied for idling conditions, so when the rotor was standing still. This led to the recommendations that 1) damping needs to be studied further, 2) the fatigue of structures also needs to be analyzed and 3) the applicability of OMA techniques shall be explored for operational conditions. Mainly the last recommendation will be used as basis for this research/study.

1.3 Case description

An essential step in the use of OMA techniques is the validation of the techniques. The validation is mostly executed by comparing results of different techniques or different tests for the same data (mostly experimental). In this study the measurement data for the Eneco Luchterduinen farm will be evaluated in order to estimate the modal parameters (natural frequencies, modes shapes and modal damping). Mentioned in the literature review, part of the data is already evaluated in the past by Middelweerd [24].
For the validation of the results, it is chosen to use comparable situations as to the cases of Middelweerd. For example, Middelweerd used different environmental conditions to compare and analyze the obtained results. In this study, different environmental conditions will also be used, but the data will be analyzed with another technique, namely the Eigensystem Realization Algorithm (ERA).

Taking a close look at the studies done earlier, it should be possible to identify the natural frequencies for idling or idling states of the wind turbines. Which also leads to the challenge in identifying the natural frequency (or the modal parameters) for operational states. Wind turbines operate at maximum power between wind speeds of 12m/s and 24 m/s, although occasionally the wind turbines can be idling, due to faults or breakdowns or because they are switched off when maintenance is required. These different operational states of the turbines make it possible to compare two different operational states with each other and again, it should be possible to validate the obtained results.

1.4 Research question(s) and Objective

Following from the case description, *the applicability of OMA algorithms in estimating the dynamical properties, the natural frequencies and the mode shapes and the modal damping is yet to be confirmed for operational conditions of offshore wind turbines. The objective for this study is to establish under which conditions the obtained results with ERA can be validated and be classified as reliable.*

The main research question is then:
Is the Operational Modal Analysis algorithm, Eigensystem Realization Algorithm applicable in estimating the natural frequencies, mode shapes and the modal damping for operational offshore wind turbines on monopile foundations?

If the applicability of the OMA algorithm is indeed proved, the next question shall be answered?
What is the assessment on the accuracy and consistency of the results in estimating the natural frequencies, mode shapes and the modal damping for operational offshore wind turbines on monopile foundations?

In order to answer the main research questions the following sub questions are asked:

- Which structural or environmental parameters are relevant (important) in the design of wind turbines?
- What are the operational regions and operational states of operational wind turbines?
- Which environmental conditions apply during these states?
- Which operational regions and environmental conditions should be selected to accurately apply OMA for operational conditions?
- How will the data to use be selected?
- How will the OMA method be implemented in MATLAB?
- How will the verification of the developed model be validated?
- Can the analysis be repeated successfully on other WTG's?
- Can the analysis be used to identify differences between monopiles with and without scour?

1.5 Approach and Structure

The main focus in this thesis is on the applicability and the accuracy/consistency of the chosen OMA, namely ERA. First ERA will be implemented and verified with the toolbox Stabil in MATLAB, to assure the model built is able to identify the dynamic properties for simple cases. After the verification of ERA, the measured data from the Eneco Luchterduinen farm, which is in a local coordinate system, will be preprocessed to the Fore Aft and Side to Side (FA/SS) coordinate system (global coordinate system) of wind turbines. In this preprocessing, the sensitivity of the yaw angle error is also tested. The applicability of ERA with the acceleration response measurement data is split up in two parts. In the first part data sets comparable to the study done by Middelweerd [27] are evaluated manually, for different environmental conditions. After the validation of the results by comparing the outcomes with the results of Middelweerd, an attempt is made to automate the process in establishing the modal parameters. In the second part, the automated approach is used to compare two different operational conditions, namely idling and operational for identical environmental conditions. The environmental conditions of the data sets belonging to idling turbines will be coupled to data sets of the fully operational turbines with approximately the same environmental conditions.

The approach is split up in chapters, resulting in the following overview. In chapter 2 the methodology on ERA is elaborated, followed by the implementation and the verification of the algorithm. In chapter 3 the Eneco Luchterduinen farm and the measurement setup is discussed in detail and the available data for the environmental conditions is also addressed. In this chapter for example the general information and design information is discussed. In chapter 4 the boundary conditions are discussed to select the data, but also the implementation of ERA is discussed. In chapter 5 the selected data samples are evaluated in 2 parts as mentioned in the approach. Chapter 6 will discuss the obtained results and in chapter 7 the conclusions and recommendations following from the results are presented.

2. Methodology and Verification implemented ERA

This research is based on the implementation of the OMA technique ERA. The basis of ERA, such as the theory and the underlying basic assumptions are elaborated in this chapter. Furthermore, the implementation of ERA with the toolbox STABIL will be described.

2.1 ERA

ERA is one of the different OMA techniques that can be used for modal analysis, which is a multiple input, multiple output time domain technique and is a combination of modal identification and system realization, where state space models are the basis [5][6][22]. State space models are used to describe a system of first differential or difference equations with state variables (values which evolve over time). In the ERA the basis of the algorithm is formed by the Markov parameters (impulse responses). With the Markov parameters, a block Hankel Matrix is formed which is the basis for the discrete time state space model. A drawback for the ERA is, that the selection of the size for the Hankel matrix is not addressed enough in research [1][5][22]. This means, that a wrong determination of the Hankel matrix could result in inaccurate results for the modal parameters.

The OMA techniques are all based on assumptions. There are general assumptions (paragraph 1.2) and there are technique specific assumptions. ERA is assumed to be linear time invariant, which can be represented by state – space equations for discrete systems. A system is an LTI system, when the input signals are in a linear relation with the output signals and time does not have an effect on the magnitude. ERA is furthermore applied on force/acceleration impulses or free decays.

The discrete state – variables representation is [5]:

$$x(k+1) = Ax(k) + Bu(k) \qquad 2.1$$

$$y(k) = Cx(k) \qquad 2.2$$

The first step in ERA, is forming the generalized Hankel matrix composed of the Markov parameters, which is used for the singular value decomposition. The Hankel matrix is further built up out of the controllability and observability matrix. Y(k) in the Hankel matrix [5] is the output signal form the measurements for N time series.

$$H(k\text{-}1) = \begin{bmatrix} Y_k & Y_{k+1} & \cdots & Y_{k+\beta-1} \\ Y_{k+1} & Y_{k+2} & & Y_{k+\beta} \\ \vdots & & \ddots & \vdots \\ Y_{k+\alpha-1} & Y_{k+\alpha} & \cdots & Y_{k+\beta+\alpha-1} \end{bmatrix} \qquad 2.3$$

The system is built up using the observability (Vr) and controllability (Ws) matrix for the initial state system H(k). If the realized system is controllable and observable, the row number of both is n, which is also the rank of the realized matrix A. Matrix A is the minimum realization of the state space variables

$$H(k) = V_r\ A^k W_s \tag{2.4}$$

By forming the generalized Hankel Matrix, k = 1 is evaluated for the factorization of H(0).

$$H(0) = U\ \Sigma\ V^T, \tag{2.5}$$

where U and V are orthogonal and Σ is a rectangular matrix. V and U are unitary matrices and Σ is a diagonal matrix, containing the ordered singular values.

The matrix H(0) is built up by time-shifted Y(k) submatrices. In large modal surveys, many of the rows of H(0) below row q (number of measurements) may be deleted without the loss of accuracy. After the decomposition of the H(0) matrix, the realization can be computed [7][22]:

$$A = \Sigma_n^{\frac{1}{2}} U_n^T H(1) V_n \Sigma_n^{-1/2} \tag{2.6}$$

$$B = \Sigma_n^{\frac{1}{2}} V_n^T (:, p) \tag{2.7}$$

$$C = U_n(q, :) \Sigma_n^{1/2} \tag{2.8}$$

In the equations above H(1) is a new matrix and is of the same form of H(0), only with an extra time shift in the data. Now these realizations are transformed to modal coordinates [7][22].

$$A' = \Psi^{-1} A \Psi = Z \tag{2.9}$$

$$B' = \Psi^{-1} B \tag{2.10}$$

$$C' = C \Psi \tag{2.11}$$

Where Z is the eigenvalues matrix and ψ is the eigenvector matrix of A. The modal participation factors are the corresponding rows of B’ and the mode shapes are the corresponding columns of C’.

Now it is possible to estimate the frequencies, modal damping, and the mode shapes. The damped frequencies (ω_i) and modal damping ratios(σ_i) are the imaginary and the real part of the eigenvalues Z [7][22]:

$$s = \sigma_i \pm i\omega_i = \frac{\ln z}{\Delta t} \tag{2.12}$$

With this equation as the basis, the modal damping factor (ζ_i) and the damped frequencies in Hz can be determined by stating the following equations:

$$\zeta_i = -\frac{\sigma_i}{\sqrt{\sigma_i + \omega_i^{\ 2}}} * 100\% \tag{2.13}$$

$$f_i = \frac{\omega_i}{2\pi} \tag{2.14}$$

2.2 Verification model

When ERA is implemented on the measurement data, the analysis will be executed by MATLAB. The next paragraphs verify the use of MATLAB and ERA.

Before ERA is used on the real measurement data, first a test is done with simulated data. The simulated data is accumulated with a toolbox plugged into MATLAB, STaBIL. Based on the stiffness and mass matrices of the structure and the measurement points on the structure, this toolbox is able to simulate acceleration data for the structure and afterwards calculate the modal parameters.

For the wind turbine structure, which has almost the same geometrical properties as the wind turbine structure in Eneco Luchterduinen, the toolbox is used to statically and dynamically verify the structure used. The geometrical properties are chosen in a realistic order Furthermore, the model and script set up for the test model, will be used as basis for the analysis of the Luchterduinen structures. The structure used is modelled as a clamped Euler Bernoulli beam. The dimensions of the structure are almost identical, but the mass on the top of the beam differs from the mass on the top of the wind turbine. For simplicity reasons and to allow the use of prescribed values the mass on the top of the beam is taken to be equal to the mass of the beam. Another simplification made is that the model assumes the foundation to be clamped at the seabed, whereas in reality the foundation has a certain flexibility beneath the seabed. This will lead in differences in the dynamical calculation of the beam model. This clamped beam model is used only to verify the performance of ERA. For the foundation of the wind turbine, there are no assumptions made and some details on the weight of the masses could also differ in reality. Table 2.1 gives an overview of the dimensions of the beam.

Length	100	m
Outer Diameter	5	m
Inner diameter	4.9	m
Density	7850	kg/m^3
Mass topweight	610372	kg
E	210000000000	N/m^2
I	2.38	m^4
EI	500160154570	Nm^2
Modal damping log decrement	5%	
First 3 natural frequencies	0.2244	Hz
	2.3412	
	7.3339	

Table 2.1 Information beam model dimensions

In Figure 2.1 the beam model is given

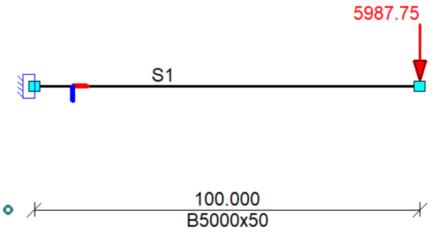

Figure 2.1 Beam model

With known load deformations – relations, called “*the vergeet-me-nietjes*” in Dutch, the beam is statically verified. The results of the beam model in STaBiL were compared to the calculated load deformations. The results for the moments, shear forces and displacements were in both cases identical and it can be concluded, that statically STaBiL is verified. This static verification is done, to verify if Stabil properly implements the stiffness and load.

After the static verification, the beam model is dynamically verified by computing the eigenfrequencies [23] of the beam. These eigenfrequencies are then compared to the results of the testcase model in MATLAB.

The eigenfrequencies can be computed as follows [23]:

$$\omega = \frac{\lambda^2}{l^2} * \sqrt{\frac{EI}{m}}\,,$$

Where
ω, is the natural frequency
λ, is the eigenvalue (root) of the system
l, is the length of the beam
EI, is the bending stiffness of the beam
m, is the mass of the beam ($m = \rho A$)

the frequency equation for a clamped beam is:

$$\frac{1}{\alpha} = \lambda\,\frac{sin\lambda\; cosh\lambda - sinh\lambda\; cos\lambda}{1 + cos\lambda\; cosh\lambda}$$

Table 2.2 gives the calculated results vs the dynamic estimations with Matlab for the beam with and without a mass at the top.

	Without top mass			**With top mass**		
	Calculated	**Matlab**	**Percentage**	**Calculated**	**Matlab**	**Percentage**
ω1 (Hz)	0.5065	0.506558	-0.00011	0.224392	0.224361	0.00014
ω2 (Hz)	3.174413	3.174648	-0.00007	2.341008	2.341201	-0.00008

Table 2.2 Natural frequencies: Calculated vs Matlab

Analyzing the results, it can be said that the frequencies calculated with the frequency equation and the frequencies estimated by the beam model in MATLAB are almost the same in both situations (Table 2.2). The difference is marginal and can be neglected. This means that also the dynamic verification is verified, and the beam model satisfies the conditions.

2.3 Verification Algorithm

For the implementation of ERA an existing script from Mathworks is adapted and modified [30] where needed. The modification made in the script, relates to the modal accuracy indicators used by Al–Rumaithi, which is used in a more advanced modification of ERA. This part of the script was not adapted. In this study, the basis form of Era is used. This script is based on the NASA user's guide for VAX/VMS computers [22]. With this script, the natural frequencies, mode shapes and the modal damping are estimated.

The acceleration data is simulated with STaBiL based on different load cases. The load cases in this model are an impulse load, a harmonic load and a combination of multiple harmonics.

a. An impulse
   With impulses it should be possible to identify all the relevant modes of a structure. Figure 2.2 displays the impulse (a tri pulse of magnitude 7kN) used in the testcases
b. A harmonic load
   In most situations in the field harmonics are observed in the response of functions. These harmonics are often mistaken for to be peaks of the response of the structure. In order to recognize harmonics, these are also implemented in the testcases.
   The harmonic is: $p(t) = 100 * \sin(20 * \pi * t)$
c. Multiple harmonic loads
   Harmonics can also be present in terms of the sum of more harmonics. The following harmonics are also taken into consideration
   $p(t) = 10 * \sin(50 * \pi * t) + 32 * \cos(60 * \pi * t) + 3 * \sin(7 * \pi * t)$

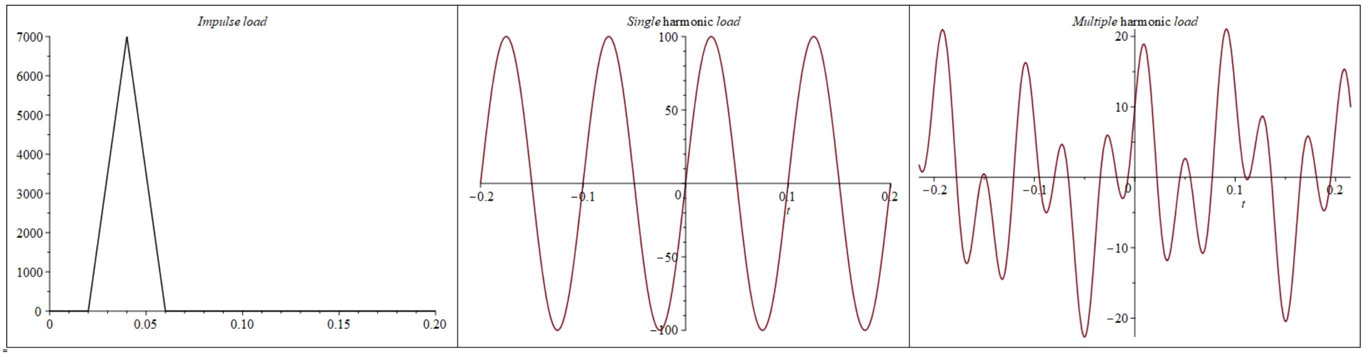

Figure 2.2 Load cases beam model

In order to use the load cases as data input in the model, data needs to be simulated, according to the load case given. The excitation of the given load case is given in the time domain and needs to be converted to the frequency domain and also needs to be differentiated in order to get accelerations. This differentiated excitation in the frequency domain is then converted to displacements in the frequency domain, by using the Frequency Response Function (FRF). This displacement in the frequency domain is differentiated to the acceleration data matrix. This data matrix is then converted back to the time domain,

The simulated data is not totally ready to use in the model. Since in reality the accelerations are measured at several distinct locations, the output from the model will also be given at multiple user-specified elevations at respectively 40m, 60m and 100m.

This process is executed with a selection matrix (S_d matrix). In this selection matrix, the nodes and directions of the sensor positions are defined. This matrix is multiplied with the acceleration results. The obtained matrix is the final acceleration data matrix, which can be used in the analysis of the test case.

For load case c, the multiple harmonic load, the acceleration in the time and frequency domain are displayed in Figure 2.3 and also the force in the frequency domain.

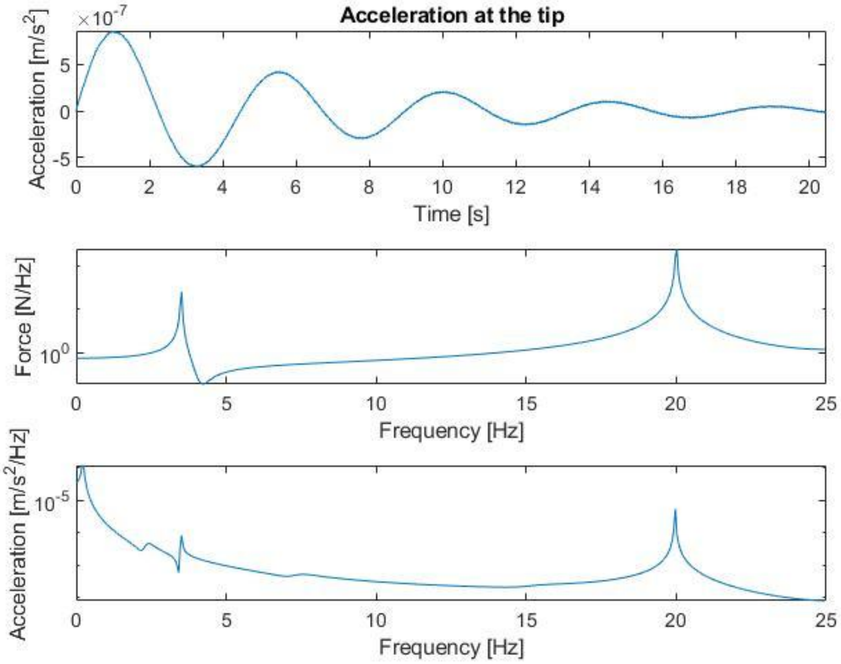

Figure 2.3 Frequency and time response load case c Multiple Harmonics

The data is simulated and the establishment of the modal parameters with the script is possible.
The ERA technique is implemented in the modified fully automated script. The results are known immediately. This script also produces stability diagrams, which is presented in Figure 2.4. The stability diagrams display stable poles for the estimated

natural frequencies. For case c, Table 2.3 presents the obtained results for the frequencies and the modal damping.

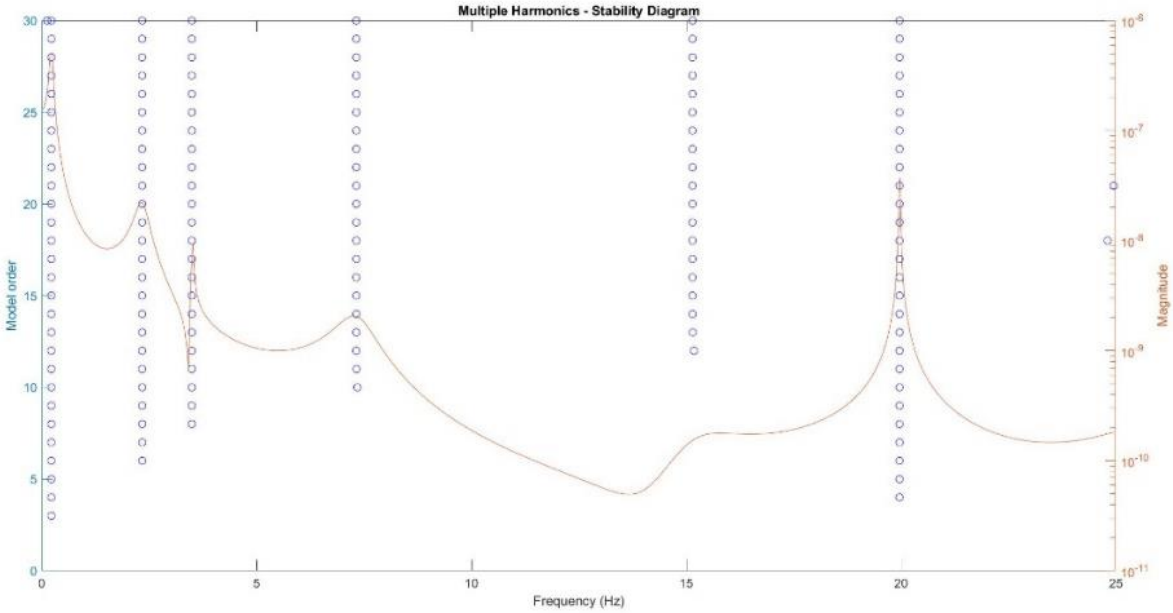

Figure 2.4 Stability diagram load case c

Multiple harmonic		
frequency		damping
Calculated	Identified	
	0	0
0.22	0.22	11.29
2.34	2.34	6.78
	3.49	0.00
7.33	7.32	6.06
	15.14	5.71
	19.96	0.00

Table 2.3 Real Frequency vs Identified frequency and damping

For both cases, the single harmonic and the multiple harmonic stable poles are observed for the structural modes. As expected, stable poles are also observed for the peaks related to the harmonics. Because it is known beforehand what the peaks for the harmonic loading would be and the expected structural frequencies are known, the distinction between the stable modes is made very quick in these load cases. In case of real data, it can be more difficult, so there it is recommended to evaluate multiple stability diagrams for multiple data samples.

For these simple load cases the algorithm proved to work correctly in estimating the modal properties except for the modal damping ratio for the first natural frequency. The modal damping ratio for the other frequencies was indeed in the range close to

5%. For real data the effect of noise in the measurements can have an influence on the estimated frequencies.

3. Offshore wind farm Eneco Luchterduinen and Data sources

In chapter 3 general information on the wind farm Eneco Luchterduinen is given. Some generic information is provided on the locations of the turbines, the properties of the turbine support structures and a description on the measurement setup. Furthermore, chapter 3 gives more detail on the design modal parameters for the Luchterduinen wind farm. In the second part of chapter 3 the available environmental conditions data is discussed, as well as the acceleration measurement data.

3.1 Offshore wind farm Eneco Luchterduinen

In this thesis the focus lies on the applicability of ERA on offshore operational measurement data from wind turbines. The acceleration data for the turbines originates from the offshore wind farm Eneco Luchterduinen.

3.1.1 General information Luchterduinen

The offshore wind farm Eneco Luchterduinen is located in the North Sea of the Netherlands, approximately 23 km off the coast. The water depths in this area vary between 18m and 24m below LAT (Lowest Astronomical Tide). In the wind farm there are 43 Vestas 3.0 MW V112 turbines, of which 41 are installed with scour protection and 2 do not have scour protection. The park is operational since 2015. In Figure 3.1 the positions of the turbines are given. The turbines on position 30 and 42 do not have scour protection.

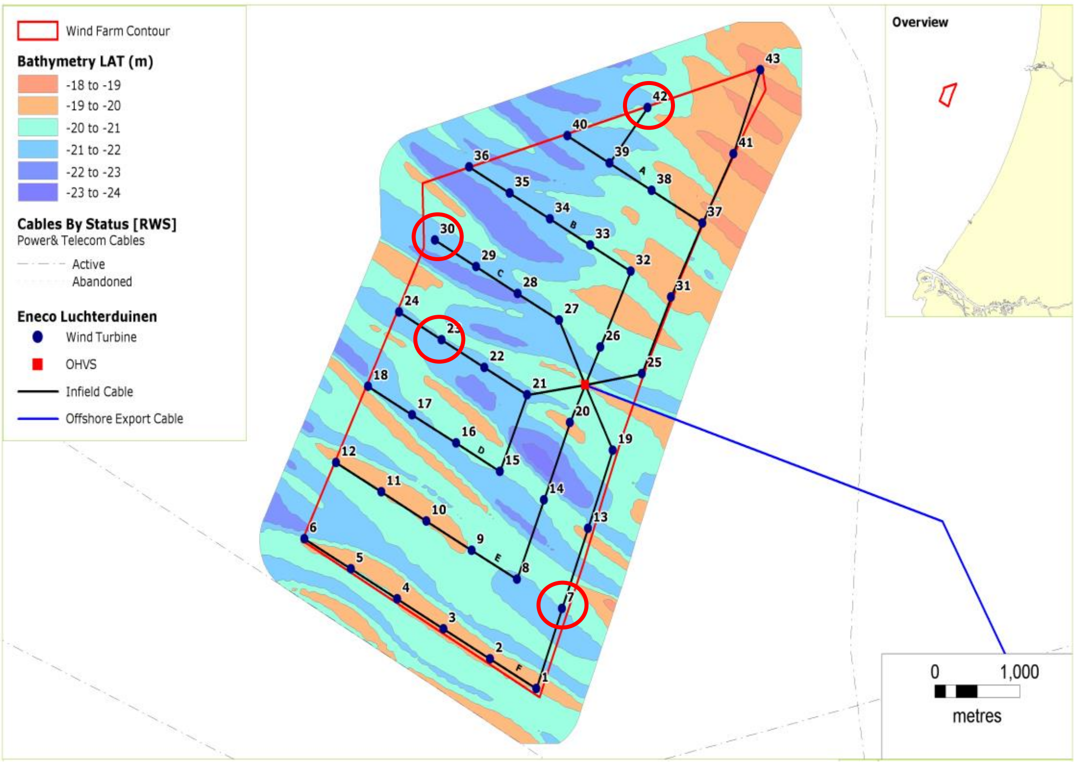

Figure 3.1 Positions Offshore Wind Turbines in Wind park Luchterduinen

The turbines are Vestas 3.0 MW V112. The turbines have a rated power of approximately 3000 kW and have a cut-in wind speed of 3m/s, a rated wind speed of 12 m/s and a cut-out wind speed of 25 m/s [29] (see Figure 3.2).

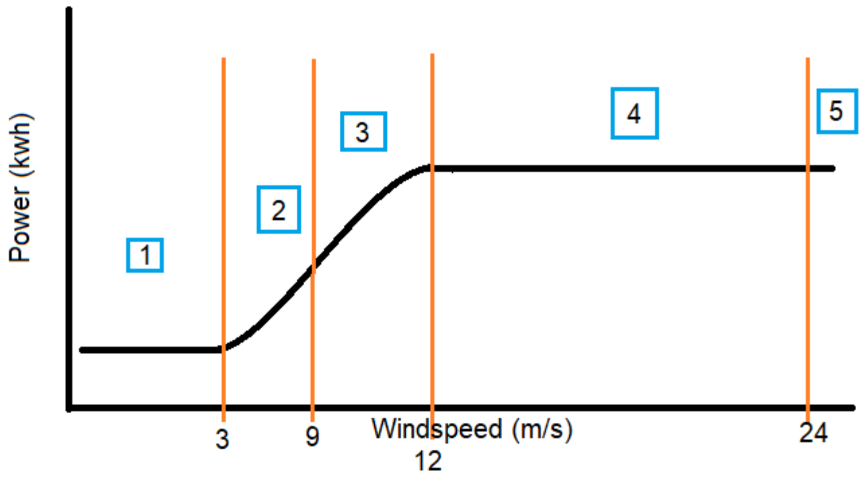

Figure 3.2 Operational regions of a wind turbine

In Figure 3.2 the different regions show the operational states of the wind turbines. In region 1 the turbine is idling and there is no power production. Region 2/3 the turbine is slowly beginning to produce power and it is said that the turbine is in the partial load range. In region 4 the turbine is fully operational, and the power production is maximum. In region 5 the rotors are stopped due to too high wind speeds and the turbine is thus idling.

The wind turbines have a rotor diameter of 112m and 3 blades with a nominal rotor speed of 13.78 rpm. The hub height of each turbine is approximately 80.8m above LAT. The water depth for each turbine differs, depending on the local water depth at each foundation.

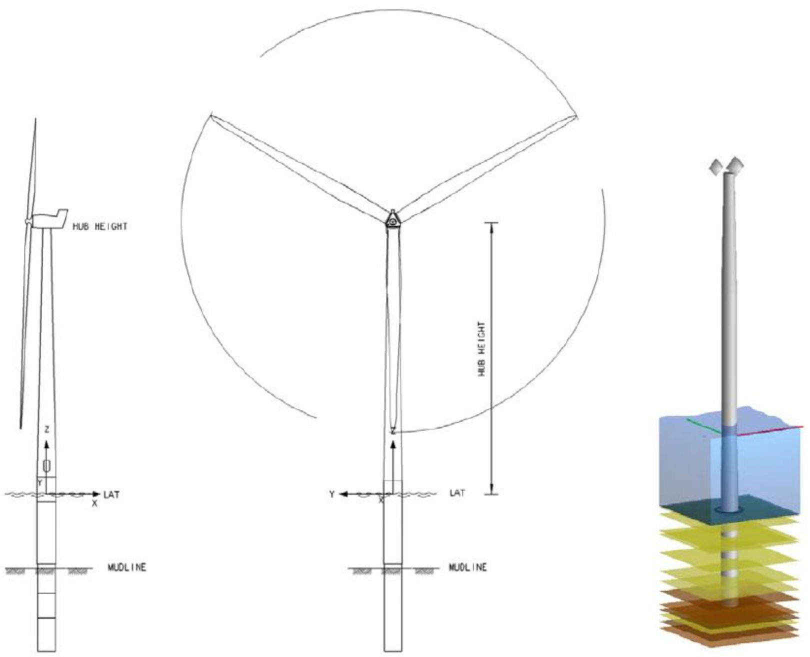

Figure 3.3 Cross section of wind turbines Luchterduinen in general

On 4 of the wind turbines [14], of which 2 have scour protection and 2 don't, dynamic load sensors are placed and a Data Acquisition System (DAS). The DAS records and reports the values of the sensors. The sensors are placed on EL07, EL23, EL30 and EL42 on 3 positions (LAT +18, LAT + 39, LAT +78) and measure vibrations in 2 horizontal directions (X and Y).
Data is thus measured by acceleration sensors placed on 4 wind turbines in x and y direction. Furthermore, data is accumulated by the Supervisory Control and Data Acquisition (SCADA) system implemented in the turbines, such as wind speed and direction, nacelle orientation rotor speed and power. There is also data measured by RADAC. The wave radar, supplied by RADAC, is placed on the Offshore High Voltage Station (OHVS), located in the center of the wind farm. This wave radar measures wave parameters, including, wave heights, periods, and direction as well as water levels. Combining such data allows for analysis of the dynamic properties of the wind turbines during stand-still and operational conditions.

3.1.2 Design information

In the end the goal of this study is to know if ERA is applicable in estimating the dynamic parameters for operational conditions. To help make the assessment of whether ERA provides reliable output, it can be useful to compare against the corresponding values as determined in the design documentation. It should be noted that the reported natural frequencies cover a range of conditions and therefore the frequency results also span a range of values. In Table 3.1 the design values for the first and second natural frequency in the FA direction are given and the corresponding damping factor. This forms the lead in the analysis.
Furthermore, it is expected, that the real values of the natural frequency could be higher in the field. These range values are also given.

	Design Natural frequency (Hz)			
	First	**Second**	**Expected range**	**Damping ratio (%)**
EL07	0.2715	1.144	0.27 - 0.323 Hz	0.71
EL30	0.2637	0.9591	0.26 - 0.323 Hz	0.74

Table 3.1 Design natural frequencies and damping ratios

The design mode shapes for turbine EL30 are known and displayed in Figure 3.4. This turbine is not subjected to scour protection, has a minimum water depth of 21.5 m (the mudline is at 21.5m below LAT). These design mode shapes are used for both turbines, as the design mode shapes for EL07 are not available. It is a random mode shape corresponding to the Luchterduinen design for one of the following positions EL28, EL30 or EL41. The actual conditions for which this mode shape is calculated are not explicitly stated. However, we do see that the difference in mode shape between the three WTGs is small for a first natural frequency ranging between 0.260 Hz and 0.275 Hz. Therefore, we can assume that the actual variation of the mode shape will be limited and may be a reasonable reference for the estimated mode shapes. The reference mode shape is not the absolute truth.

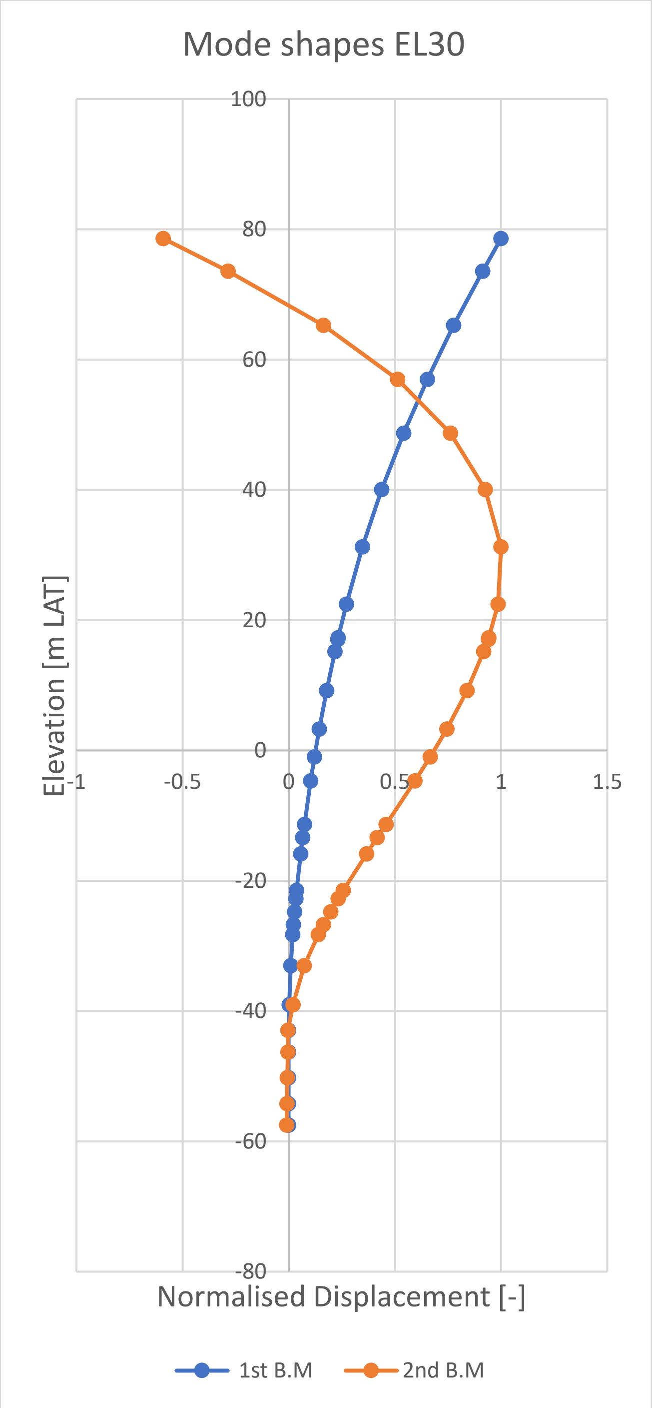

Figure 3.4 Design Mode shapes turbine EL30

The results will also be compared to the study done by Middelweerd. Middelweerd found that the water level significantly had impact on the first natural frequency, whereas the other environmental conditions did not have a huge influence. For the water level Figure 3.5 displays the obtained results.

Wind turbine	<0.3 m above LAT	>1.8 m above LAT	difference
WTG 07	0.306 Hz	0.301 Hz	1.5 %
WTG 23	0.306 Hz	0.303 Hz	1.1 %
WTG 30	0.302 Hz	0.297 Hz	1.7 %
WTG 42	0.305 Hz	0.299 Hz	2.0 %

Figure 3.5 Results obtained by Middelweerd [25] for the difference in water level

3.2 Data

There are 3 sources with data for the Luchterduinen wind farm, where the information of the structural and environmental conditions is stored:

- Sensor data: this is the data consisting the accelerations of the turbines
- SCADA data: this is data regarding the wind, blades, and nacelle
- RADAC data: this is data regarding the waves.

The sensor data (acceleration data) of Luchterduinen is measured for the years 2015 – 2019, but in some cases, data is missing. The SCADA and RADAC data are retrieved for the years 2015 – 2019 in order to couple the 3 resources. Figure 3.6 displays the available resources and examples of the environmental conditions and for the sensor data the available turbines.

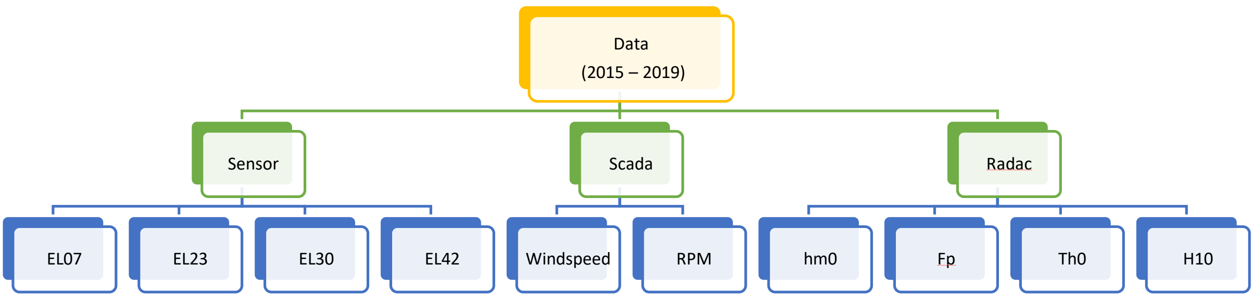

Figure 3.6 Available data resources

3.2.1 SCADA

Data is accumulated by the SCADA system implemented in the turbines. SCADA is a control system, which connects individual turbines, the substation and meteorological stations to a central computer. The SCADA system gathers information from several parts of the wind turbine, but mostly from the nacelle. The SCADA system contains thus information on e.g. the wind direction, nacelle direction, wind speed and the RPM.

In the SCADA system the given (structural and environmental) parameters in Table 3.2 are measured:

Parameters	Unit
Wind speed (Vw)	m/s
Wind direction	degrees
Nacelle position	degrees
Rotor speed	RPM
Blade angle A	degrees
Blade angle B	degrees
Blade angle C	degrees
Operating state	
Tower Acceleration x	m/s^2
Tower Acceleration y	m/s^2

Table 3.2 Parameters measured by the SCADA system

Furthermore, the SCADA data is acquired in time steps of 10 minutes. These time steps are UTC time bases, precisely UTC + 1.

3.2.2 RADAC

Wave data is measured by the RADAC wave radar, which consists of information about the waves e.g. wave height, wave peaks etc. The RADAC system uses an array of three radar sensors to measure the wave parameters, by measuring the instantaneous water elevation at three points on the surface. The RADAC system is located on the Offshore High Voltage Station in the centre of the wind farm. Four of the measured parameters are:

- The peak frequency (f_p)
- The average wave height over the last 10 minutes, water level (H_{10})
- The significant wave height (H_{m0})
- The average mean wave direction (T_{h0})

The RADAC data is measured every minute and is retrieved for the period between July 2015 – September 2019. To make the data time compatible with the SCADA data and the acceleration data, it is converted to 10 minutes time steps. The time steps are converted by repeatedly taking the average per 10 minutes. All the time steps are UTC time based (UTC +1).

3.2.3 Sensor

On the wind turbines of Luchterduinen wind park, acceleration sensors are placed on 3 different elevations (paragraph 3.1). Figure 3.7 illustrates the directions and the number of sensors per location.

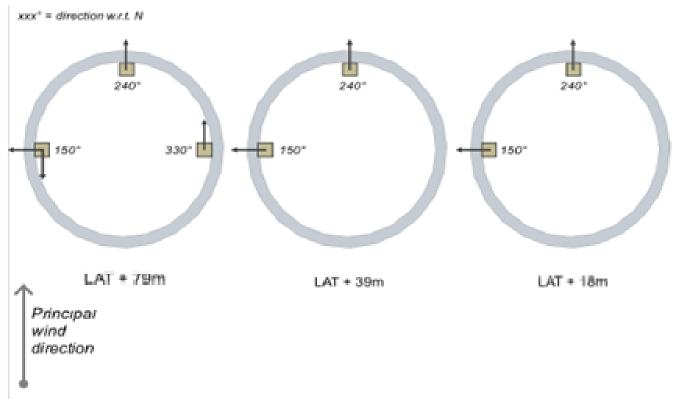

Figure 3.7 Directions and number of sensors per position

The accelerometers are placed on three levels:

- Level 1: LAT +18m. These sensors measure the bending movement of the structure in X and Y direction of a horizontal plane
- Level 2: LAT +39m. These also measure the bending movement of the structure in X and Y direction of a horizontal plane.
- Level 3: LAT +78m. Here 4 sensors are placed. Two are to measure the bending movement of the structure and two sensors are to measure the torsional movements in the horizontal plane.

To ensure the correct orientation of the individual sensors, they are bolted on polyamide blocks.

The sensor data is available from the start of the wind park in 2015 till present. The data sets are samples of 10-minute time steps and are synchronous to the SCADA and RADAC data UTC +1 time based time samples.

3.2.4 Preprocessing data

An important aspect in the analysis of the data samples of the wind turbines is the alignment of the coordinate systems. The orientation of the nacelle and the sensors need to be aligned. With the alignment the data samples consist of data of the FA and the SS. This alignment is done with a transformation matrix. To align the coordinate systems, the global and local coordinate systems are implemented. The nacelle direction fixes the global coordinate system and the sensors of the accelerometers define the local coordinate system. Figure 3.10 gives a representation of the coordinate system of the sensors in relation to the true North[1]. In Figure 3.10 the orientation of the coordinate systems and the angle (theta) between the nacelle and the y sensor is given.

[1] The Nacelle direction for the turbines have a deviation to the north, resp 12°, 12°, 10°, 12°. This is illustrated for EL07 and EL30 in Figure 3.9

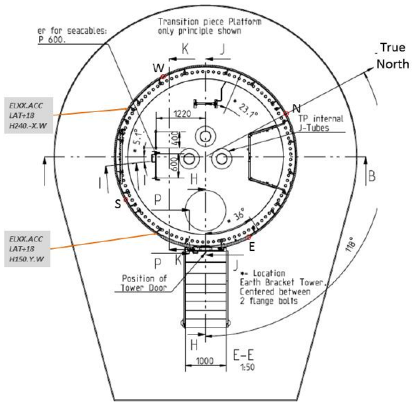

Figure 3.8 Orientation of the sensors

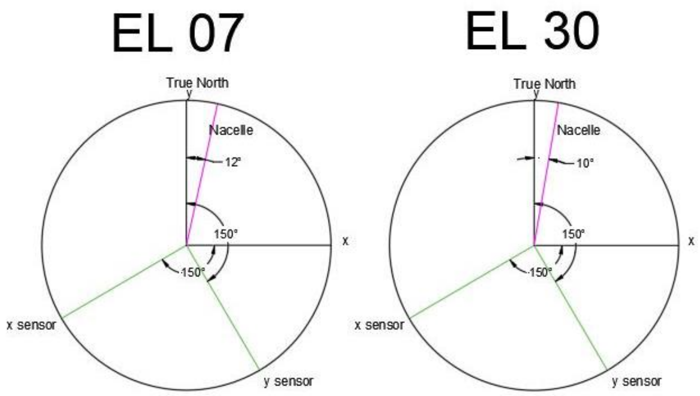

Figure 3.9 Orientation Nacelle and sensors with respect to the true North

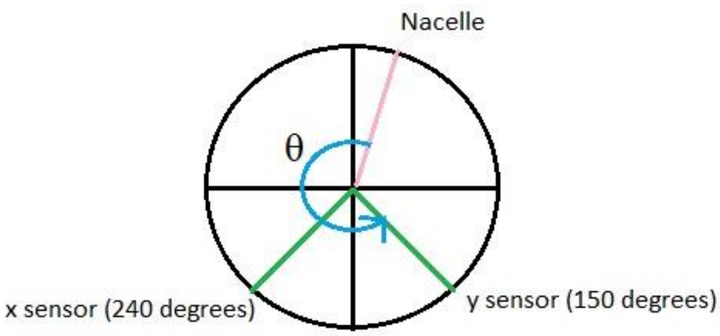

Figure 3.10 Orientation of coordinate systems and the angle theta

Equation 3.1 gives the transformation matrix which holds for rotations counterclockwise with an angle theta:

$$\begin{bmatrix} \tilde{x} \\ \tilde{y} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \tag{3.1}$$

In this equation x and y are the acceleration data corresponding with the x sensor and the y sensor. Theta (θ) is the angle between the nacelle and the y sensor and further $\tilde{x}$ and $\tilde{y}$ are the transformed acceleration data which will be used further in the analysis.

To determine theta the following holds:

$$\theta = 360° - 150° + Nacelle\ orientation \quad 3.2$$

The total acceleration data matrix is of size 6 x 30000. This matrix is split in a matrix for only $\tilde{x}$ and only for $\tilde{y}$ resp in accordance with the Fore Aft and the Side to Side directions of the wind turbines. These matrices then become of size 3 x 30000. The 3 rows of the matrix represent the positions of the sensors (bottom, mid and top) and the 30000 columns represent the time intervals at which the acceleration is measured. In **Error! Reference source not found.** an example is given of the frequency spectrum in the FA and the SS direction of one of the data samples.

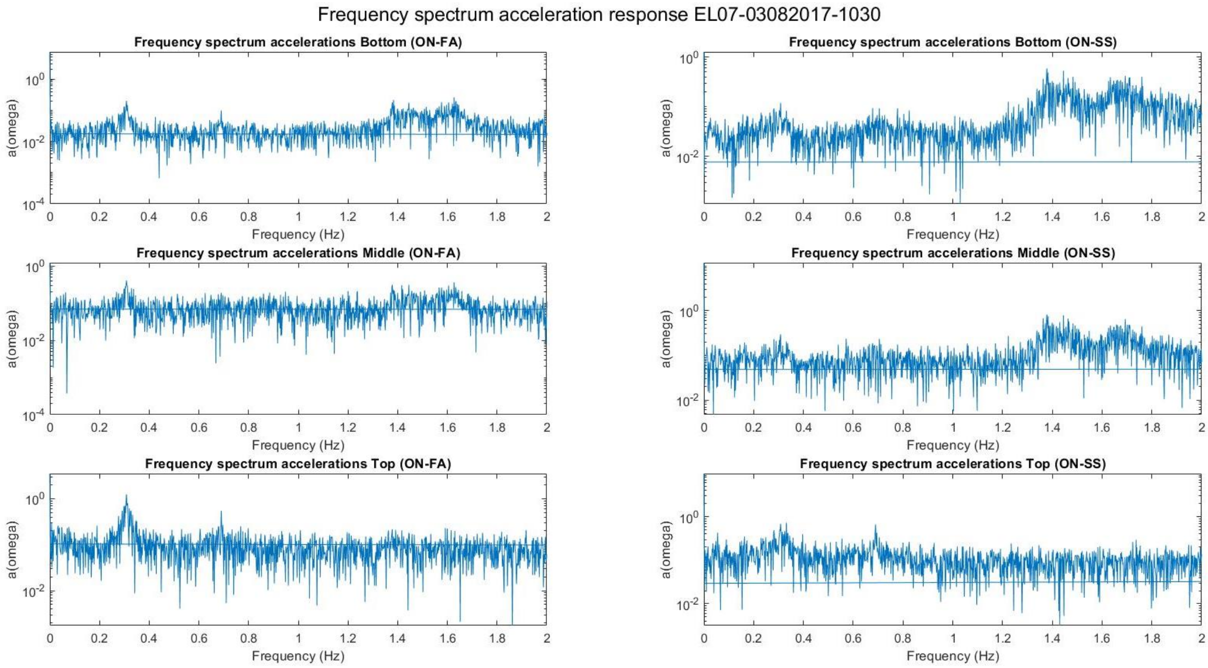

Figure 3.11 Frequency spectra in the FA/SS for EL07

In Figure 3.11 in the figures regarding the FA direction, at the fist peak, the first natural frequency is expected in the frequency response around 0.3Hz, whereas in the graphs representing the SS direction the peak is better visible where the second natural frequency is expected around 1.4 Hz

4. Data selection & implementation ERA

The data samples which will be used to estimate the modal parameters need to be selected carefully. In this selection different conditions play a role, for example the environmental conditions, but also the operational regimes. In this chapter the boundary conditions for the selection of the data samples will be specified after which the selection of the data samples to use is accumulated. The algorithm ERA and its important parameters will be discussed also and the effect of the yaw angle error in the transformation of the data to the FA/SS coordinate system.

4.1 Boundary conditions

In defining the boundary conditions, it is important to define the goals for the case study clearly. The study is split up in two parts, as mentioned in the introduction, and the main goal of this study is the applicability of ERA for estimating the modal parameters for offshore operational wind turbines. The boundary conditions will be specified for each part, but first a general boundary condition is specified.

In the literature review it is mentioned several times, that most of the OMA techniques are indeed able to estimate the modal parameters for idling conditions, whereas for operational conditions operational this is not always the case for all modal parameters. Taking into consideration the different operational regimes of wind turbines Figure 4.1 is presented. In the region where the turbines are fully operational, thus region 4, the governing forces work on the turbine and the power production is maximal, which directly means the blades are at maximum rotational speed also. Sometimes the turbines are also idling or switched off in region 4, due to for example maintenance. For these reasons, it is decided to execute the analysis for the estimation of the modal parameters for different conditions in region 4. An extra modification is made in the use of region 4, to be sure to have the fully operational regime, by using wind speeds between 14 and 22 m/s instead of 12 to 24 m/s (Figure 4.1).

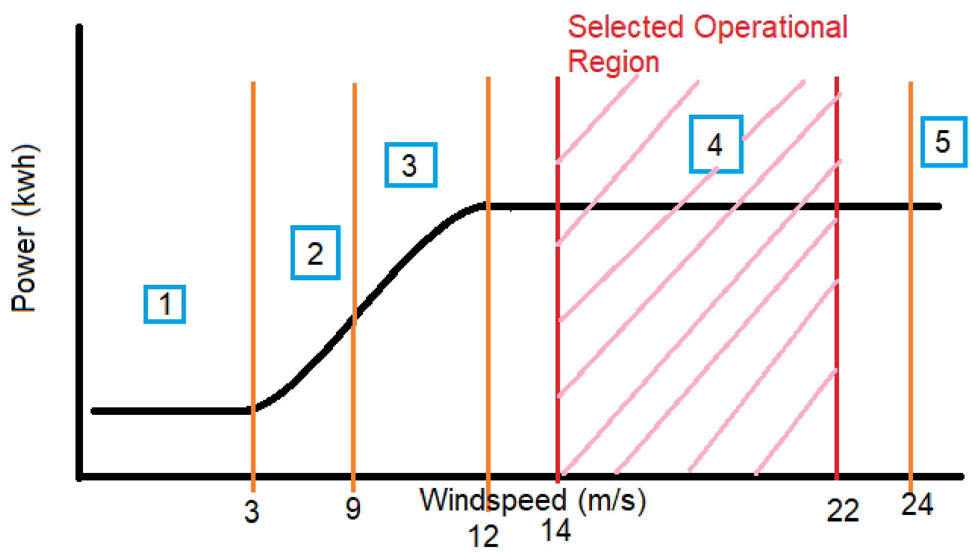

Figure 4.1 Operational regimes wind turbines

Part 1. Different conditions

The goal of part one is to estimate the modal parameters for different operational and environmental conditions. A number of single data sets will be evaluated for each condition. In the end the results will also be compared to the results of Middelweerd. Middelweerd found that the water level was of significant influence on the first natural frequency [25]. This brings us to the first environmental condition to evaluate, namely the water level. Even though Middelweerd suggested the wind conditions did not significantly affect the first natural frequency, this is an important ground to test the applicability of ERA in estimating accurate natural frequencies. The next environmental conditions are thus the windspeed and the wind direction. Most of the time the wind direction is aligned to the direction of the waves, thus the wave directions will be observed simultaneously with the wind directions. Furthermore, Middelweerd did not find a conclusive relation between wave conditions and the natural frequency [25]. In this study the estimation of the modal parameters will be done for the difference in peak frequencies for the waves. The operational conditions taken into consideration are operational and idling. Table 4.1 gives an overview of the chosen conditions

	Operational condition	**Idling/Operational**			
	Environmental condition	**1**	**2**	**3**	**4**
Environmental conditions	**Windspeed**	variable	constant	constant	constant
	Wind direction & wave direction	constant	variable	constant	constant
	Water level	constant	constant	variable	constant
	Peak frequency	constant	constant	constant	variable

Table 4.1 Chosen conditions

Part 2. Idling and Operational conditions

After the execution of the few samples of part 1, in part 2 the goal is whether it is possible or not to use an automated approach for large numbers of data samples, where multiple environmental conditions are not necessarily constant in relation to others. Also, in part 2 the results for the idling conditions will be compared to the results of the operational conditions. To validate the results in the comparison, it is important to have similar samples in both operational conditions. For this reason, a list of tolerances is put up for the environmental conditions. The tolerances allow the values of the environmental condition to be in a certain range. With these tolerances for every sample in the idling situation, a similar sample is selected in the operational situation.

The specified tolerances are given in Table 4.2

Parameter	Tolerances	Unit
Windspeed	1	m/s
Wind direction	15	degrees
Peak frequency	l-m-h	mHz
Water level	25	cm
Significant height	25	cm
Average mean wave direction	30	degrees

Table 4.2 Specified tolerances environmental conditions

4.2 Data assembling

Before the data can be used to analyze different situations, preprocessing of the three different sources is necessary. As stated earlier, the time steps for all the three sources is in the UTC time zone (UTC +1). The goal in the end is to compare similar (environmental) situations with each other in the OFF (idling) and ON (operational in regime IV) states of the turbines.

First the SCADA and RADAC data are coupled to each other, by coupling the same time steps to each other. In this part the time steps with missing data, e.g. if no wave direction data is available, are filtered out.

For the first part of the study the environmental conditions are specified. In regime 4, it showed that there are not enough samples to vary each environmental condition. This could be expected, because in regime 4 the turbines should be preferably in operation for a maximum efficiency of the offshore wind turbines. The parameters for the OFF state are described separately. For each condition 4 to 10 samples are chosen per wind turbine and the values of the environmental conditions on which the selection is based, to evaluate are given in Table 4.3.

	Operational condition	**Operational**			
	Environmental condition	**1**	**2**	**3**	**4**
Environmental conditions	**Windspeed (1)**	variable	240 deg (±5)	250 cm (±5)	0.15 Hz
	Wind direction & wave direction (2)	18 m/s (±0.5)	variable	250 cm (±5)	0.15 Hz
	Water level (3)	18 m/s (±0.5)	240 deg (±5)	variable	0.15 Hz
	Peak frequency (4)	18 m/s (±0.5)	240 deg (±5)	250 cm (±5)	variable
	Idling	14.5 m/s (±0.5)	variable	variable	variable

Table 4.3 Varying environmental conditions

In the second part of the study in finding comparable environmental conditions, the OFF state will be used as reference in identifying similar situations in the ON state. The OFF states are ordered by specifying an RPM smaller than 2.5. For each turbine this delivers a certain number of samples in the selected regime. To couple identical situations of the OFF state to the ON state, tolerances are specified for the selection (Table 4.2 for the parameters specified. Similarly, the ON samples are selected by specifying an RPM larger than 13.6.

For the selected OFF situations based on the samples in the coupling of the SCADA and RADAC data, the availability of all the data samples of the turbines is checked in the sensor data. The dates in accordance with the missing files are removed from the overview of the selected OFF situations for each turbine. Unfortunately, after removing all the missing dates, no samples were left for turbine EL23 and EL30, which means directly that there is no selection for the ON situation to compare with. This new selection (for EL07 and EL30), searches for similar situations in the ON situation with the tolerances specified for each specified OFF sample. Also, in the selected ON situations, for verification it is checked if all the selected samples are available in the database of the sensors.
This order of execution is used for all of the 4 turbines. Table 4.4 gives an overview of the remaining data samples per turbine.

State	EL07	EL23	EL30	EL42
OFF	56	0	67	0
ON	14	0	206	0

Table 4.4 Remaining data samples after tolerance selection

After the remaining selection for the 4 turbines is made for the second part, the choice is made to also only use EL07 and EL30 in the first part of the study.

4.3 Sensitivity analysis for ERA parameters

The OMA technique ERA is used in the analysis of the several data samples of the acceleration response of the offshore wind turbines in the Luchterduinen wind farm. ERA is implemented in MATLAB, according to a script written by Al Rumaithi in Mathworks [28]. This script is adapted and modified where needed, according to the own preferences of this study. The modification of the script used, is able to estimate the natural frequency and the corresponding mode shape and modal damping ratio.

4.3.1 Defining parameters

The ERA script uses several parameters, which are necessary to predefine. These parameters are required in order to estimate the modal parameters. In this part the parameters necessary to predefine are described.

For the estimation of the modal parameters, the measured acceleration data of the sensors is the most important. In the script this data is referred to as the Y component. In this Y component, either the data for the FA direction or the SS direction is used for obtaining corresponding results. The FA and SS data components are obtained by the preprocessing of the acceleration data according to chapter 3.2.4 and consist of 3 rows (three measurement elevations) and 30000 columns (30000 time steps).

Further, the sampling rate of the data is important to clarify, for the appropriate bandwidth of the results in the frequency spectra.

One of the main components of the ERA technique is the use of the Hankel matrices. The size for the Hankel matrices (H(0) and H(1)) should also be specified. With this size of the matrices the realization of the system is defined. Before the realization of the system, the size of the matrix which holds the singular values is defined by the model order. The preferred model order should also be specified.

4.3.2 Hankel matrix

The Hankel matrices are the main feature in the ERA algorithm. The size for the matrices must be predefined, as mentioned in chapter 4.3.1. In this part of the chapter, an appropriate size for the matrices is chosen. The size for the matrix is chosen, after comparing 3 possibilities, namely a small matrix, a middle size matrix and a large size matrix. A matrix is built up out of rows and columns (n x m). For each possible size of the Hankel matrix, the execution on the ERA script is evaluated for one data sample.

Size	Number of Rows	Number of Columns	Number of model orders	Execution time	Difficulties
Small	120	120	27 (3-30)	10 secs	No mode shapes
Medium	1200	15000	27 (3-30)	± 55 min	Several frequencies
Large	2100	30000 – (n_{rows}/3)	1 (3)	± 76 min	Very time consuming

Table 4.5 The possible sizes of the Hankel matrix

In table 4.5 an overview of the possibilities for the size of the Hankel matrix is given. The medium and large sizes of the matrix have a large execution time and it was also observed that more frequencies are estimated below the first natural frequency. These frequencies do not necessarily belong to the response of the structure but could be due to noise in the data. In the literature [1,5,6] it is recommended not to use too large sizes for the matrices. The execution time is less, and the necessary data is available depending on how many frequencies need to be identified at minimum. The choice of a too small matrix leads to not being able to determine the corresponding mode shapes for the possible first frequency. In this study, the aim is to capture the first three frequencies using ERA.

After a trial and error execution for the small sizes the Hankel matrix of a size of 420 by 840 is chosen for the identification of the modal parameters.

4.3.3 Stability diagrams & Model order

Stability diagrams are used in the determination and the classification of the frequencies estimated by OMA algorithms. With the stability diagrams, it is possible to check whether an estimated frequency by the algorithm, returns consequently for different model orders (poles) or not. If the frequency returns consequently for a number of model orders, a stable pole is formed, and the identified frequency could either be a natural frequency, an excitation mode or a bias mode (due to example noise on the structure). The stability diagrams can be used in several ways, for example by using only the estimates for the frequencies or by using a combination of the estimations of the frequencies and the damping ratios. Because it is not sure whether ERA is applicable in estimating the parameters correctly, it is chosen to use the diagrams for the separate estimates of the frequencies and the modal damping ratio. In Figure 4.2 an example is given of a stability diagram obtained for one of the data samples used with model orders from 3 to

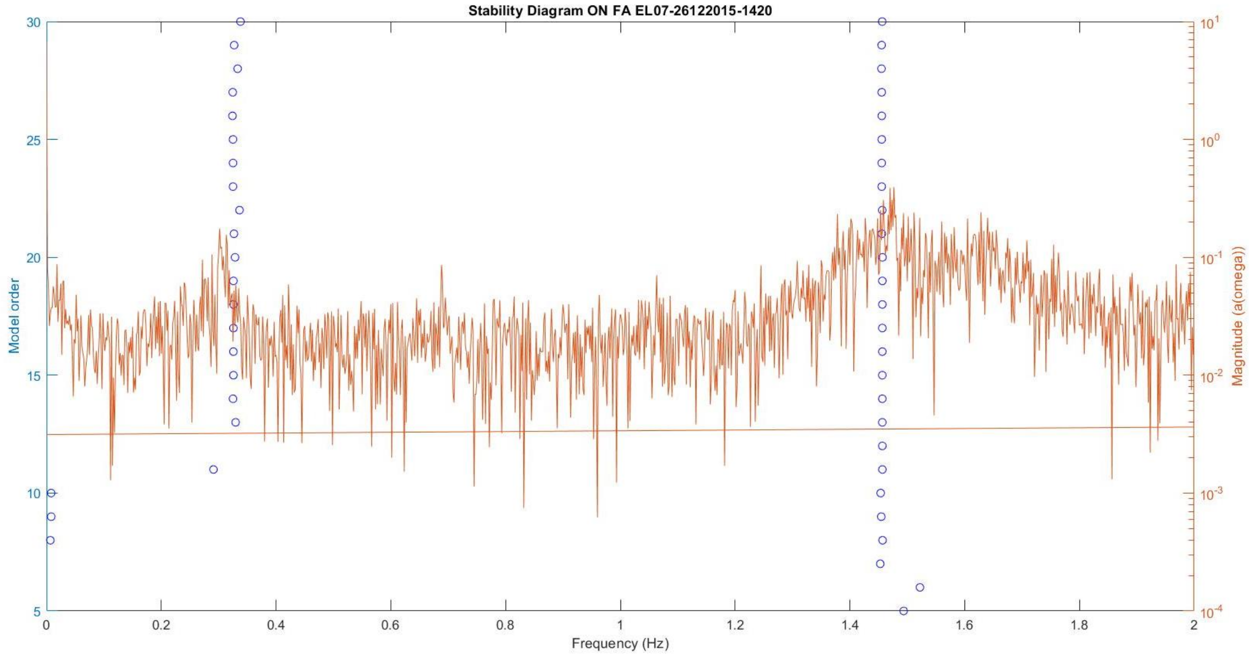

Figure 4.2 Example of a stability diagram for a data sample of EL07

4.3.4 Yaw angle error

The yaw angle of a wind turbine (Figure 4.3), is the angle between the direction of the oncoming windspeed and the rotor axis [29].

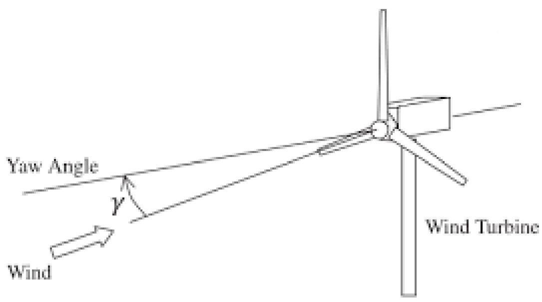

Figure 4.3 Yaw angle definition [29]

The sensitivity of an potential error in the yaw angle in the pre processing of the data is verified by plotting stability diagrams for angle errors of ± 5 degrees and ± 10 degrees. Figure 4.4 shows the results for the 4 cases and it can be concluded, that for angles betweeen -10 and 10 degrees there are no significant differences for a possible error in the yaw angle.

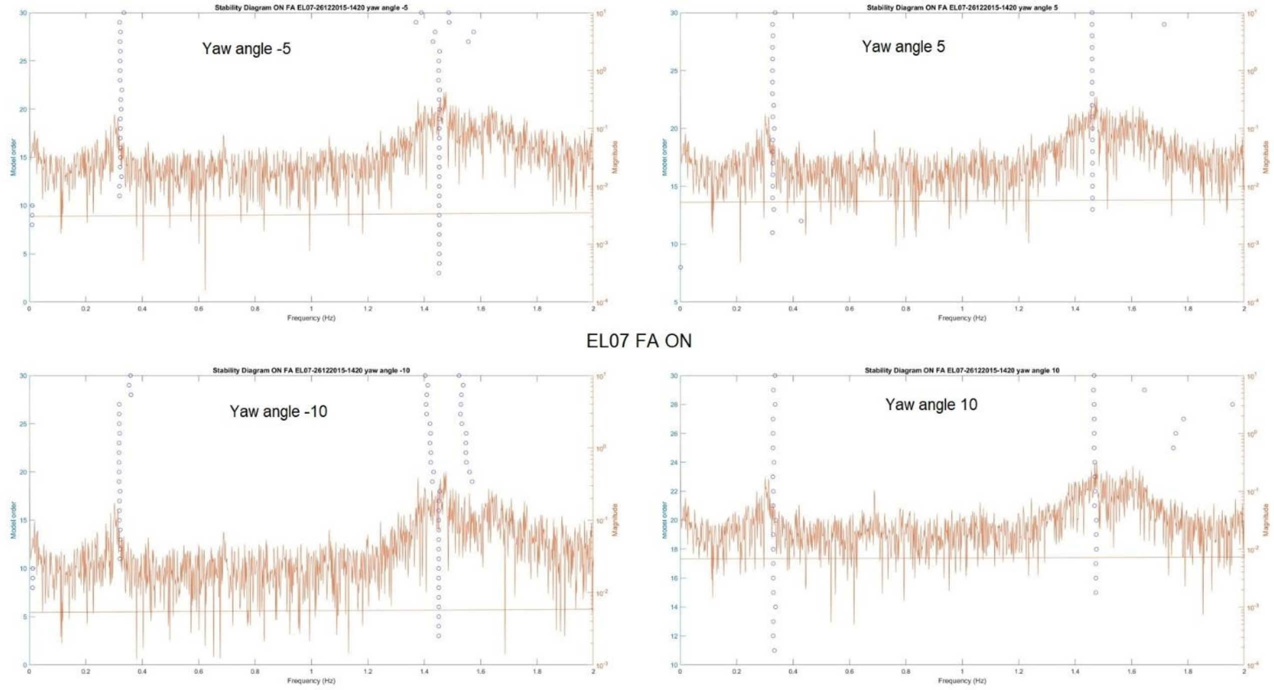

Figure 4.4 Yaw angle error for EL07 ON

5. Identification of Modal Parameters

In chapter 5 the modal parameters are estimated for different environmental and structural conditions. In the first part of the identification process different environmental conditions are evaluated and in the second part different structural conditions are evaluated. In the study of the environmental conditions, samples of the ON state of the turbines are used.

The results for the natural frequencies are analyzed with stability diagrams for model orders from 3 to 30. These diagrams are given in figures, together with the sample specific conditions, time and frequency response of the data sample at use and the orientation of the wind and wave direction with respect to the true north of the nacelle. For each model order, a mode shape and modal damping ratio is estimated by ERA. These results will also be presented in graphs.

5.1 Part One

In the first part of the study different environmental conditions are observed. In the use of different environmental conditions one condition is variable in relation to the others which are relatively constant. The different environmental conditions are evaluated for the operational state of the wind turbines EL07 and EL30, where for each condition 4 to 10 samples are considered. In regime 4 as stated earlier it is not unusual to have situations where the turbines are idling/idling, but these situations are rare. This makes it virtually impossible to find enough samples to vary each environmental condition. For the study of the OFF situation, a selection on its own is used, as mentioned in chapter 4.

5.1.1 Wind and wave direction

Mostly the wind and wave direction are aligned to each other and sometimes it occurs that the directions differ from each other. In this section a closer look on both situations is taken and the identification of the modal parameters for EL07 and EL30. The selection parameters used are:

Windspeed	Wind & wave direction	Water level	Wave peak frequency
18 m/s (±0.5)	Variable	250 cm (± 5)	0.15 Hz

Table 5.1 Definition environmental conditions, varying wind and wave direction

The results and observations for both wind turbines EL07 and EL30 are discussed separately. After the evaluation of several data samples, the first natural frequency is identified in most of the cases, by a visible stable mode at the first peak of the frequency spectrum in either the FA or SS direction. When the wind and wave direction are aligned with each other the first natural frequency is identified by the stability diagrams in the FA direction. Table 5.2 gives an overview of the identified stable modes for EL07 and EL30.

		Natural frequency			
		First		Second	
	Sample	FA	SS	FA	SS
EL07	1	0.316	-	-	1.57
	2	-	0.309	1.64	1.64
	3	0.31	0.268	-	1.406
	4	0.31	0.245	-	1.45
EL30	1	0.295	-	1.38	1.38
	2	0.234	-	-	1.38
	3	-	-	1.38	1.47
	4	0.32	-	1.34	1.38
	5	-	-	1.38	1.31

Table 5.2 Natural frequencies varying wind wave direction

An example is given from one of the evaluated samples for turbine EL07.

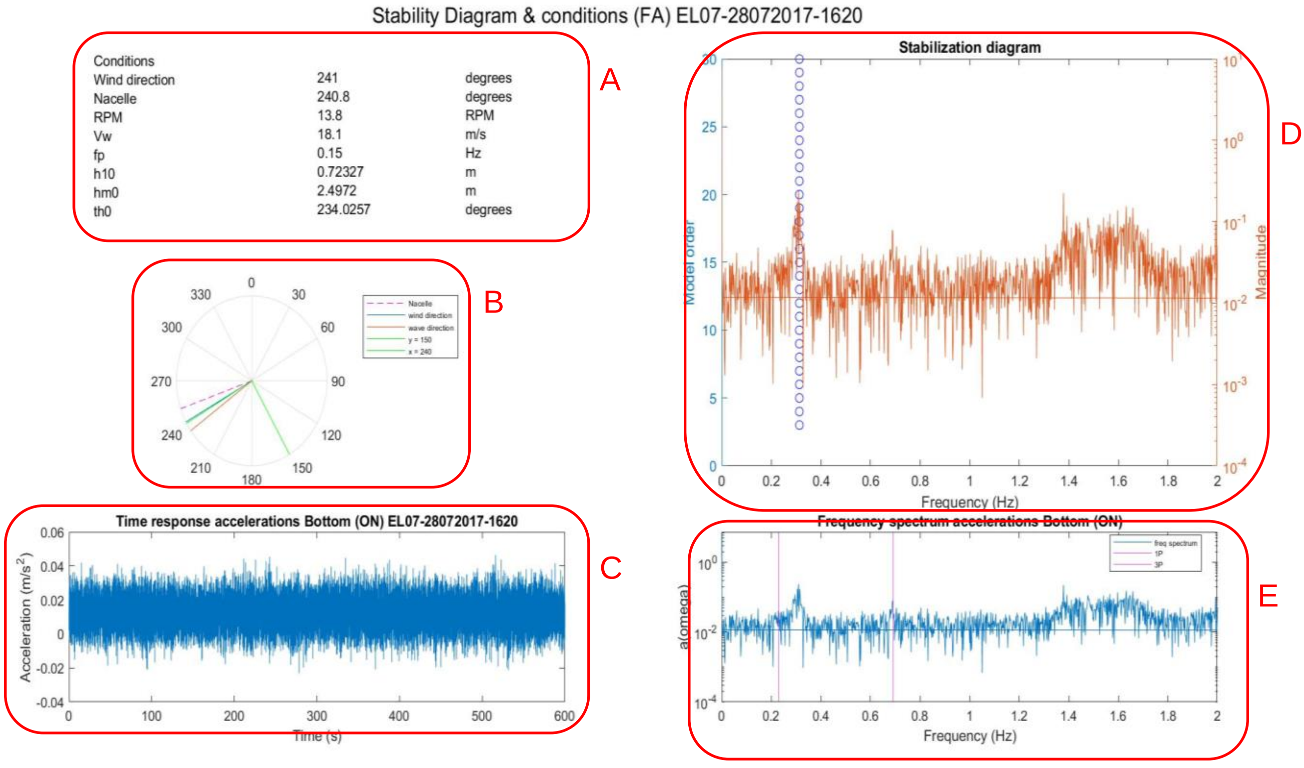

Figure 5.1 Stabilty diagram and conditions EL07 datasample 28072017 16:20h in the FA direction

In Figure 5.1 the stability diagram (D), time (C) and frequency response (E) and the corresponding information (A) on the data sample of the 28th of July 2017 at 16:20h is presented in the FA direction. The orientation of the wave and wind direction in relation to the position of the acceleration sensors and the nacelle direction is also given (B). In the stability diagram (D) at the first peak in the frequency spectrum of the acceleration response, a stable pole (mode) is observed. Out of the frequency response spectrum (E), it is also expected that the first frequency is at this peak. The peak is around 0.305 Hz and it is said that the first observable stable pole is also at 0.305Hz. Up to 2 Hz in the response of the FA direction there are further no other observable poles in this specific situation. In three out of four samples the first observable stable pole was indeed at the first peak, whereas in the fourth sample the first observable pole was at the third peak, where the second natural frequency of the structure is expected. Between the identifications of the FA and the SS directions it could occur at times that there are more observable poles in the SS direction, which could mean that the frequencies are not excited in the FA direction but in the SS direction, or vice versa.

For the first natural frequencies for the several model orders between 3 and 30, the first mode is analyzed, if the correct normalized shape (normalized displacement) given in Figure 3.4 is found by ERA. Figure 5.2 presents the obtained observable 'first' mode shapes found by ERA, over the height of the structure from the first sensor (above LAT) till the top of the structure. In the specified example these found mode shapes all correspond to the expected normalized shape. This is not the case for all evaluated examples, where sometimes a shape of the second mode shape is observed for the first natural frequency.

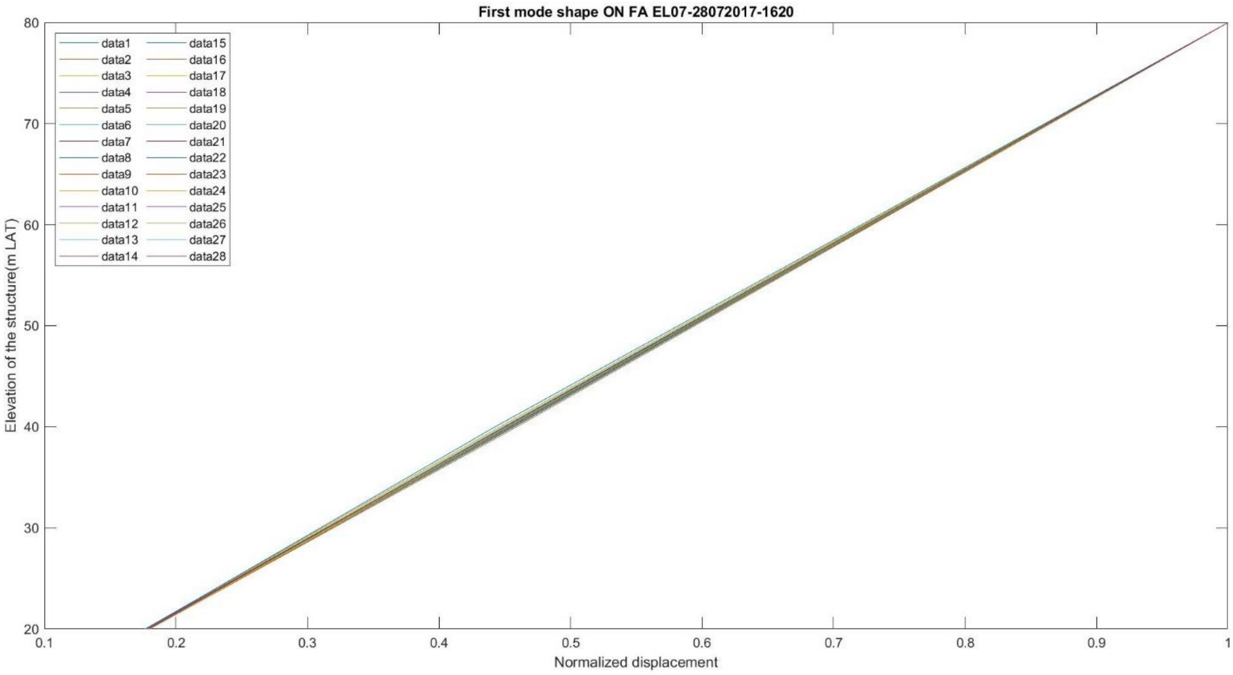

Figure 5.2 First Mode shapes (model order 3 to 30) data sample EL07 28072017 16:20h

To each natural frequency a modal damping ratio can be coupled according to equation 2.13, which is also implemented in the ERA analysis. It is expected that, for a stable mode, the damping ratios would also result in a stable damping ratio. A damping ratio which is relatively in a small range difference. This is however not the case. Figure 5.3 shows the contrary, which is observed in all the data samples evaluated. It is inconclusive what the corresponding modal damping is for these evaluated samples for the varying wind and wave directions.

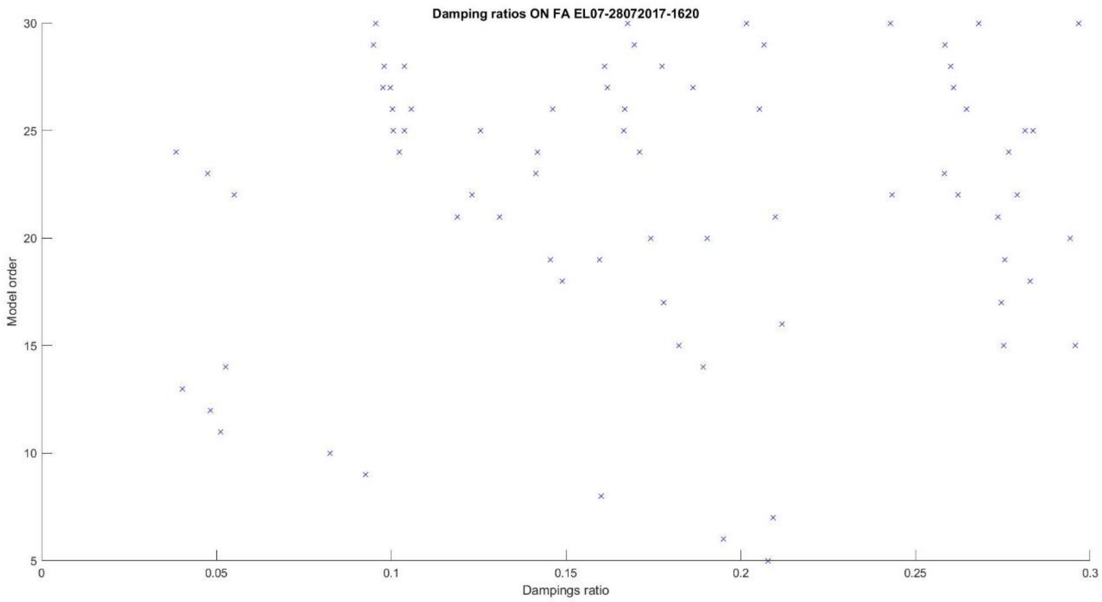

Figure 5.3 Damping ratios data sample EL07 28072017 16:20h

The 4th sample, for which the result differs from the rest for EL07, the wind and wave direction are not aligned with each other (Figure 5.4). The first natural frequency is identified around a 4th visible peak in the frequency spectrum of the acceleration response in the FA direction, whereas in the SS direction the first natural frequency is indeed identified around the first visible peak in the frequency spectrum of the SS direction (Figure 5.5). In this case the first natural frequency is thus better excited in the SS direction, whereas the spectrum of the SS also gives a better visible peak.

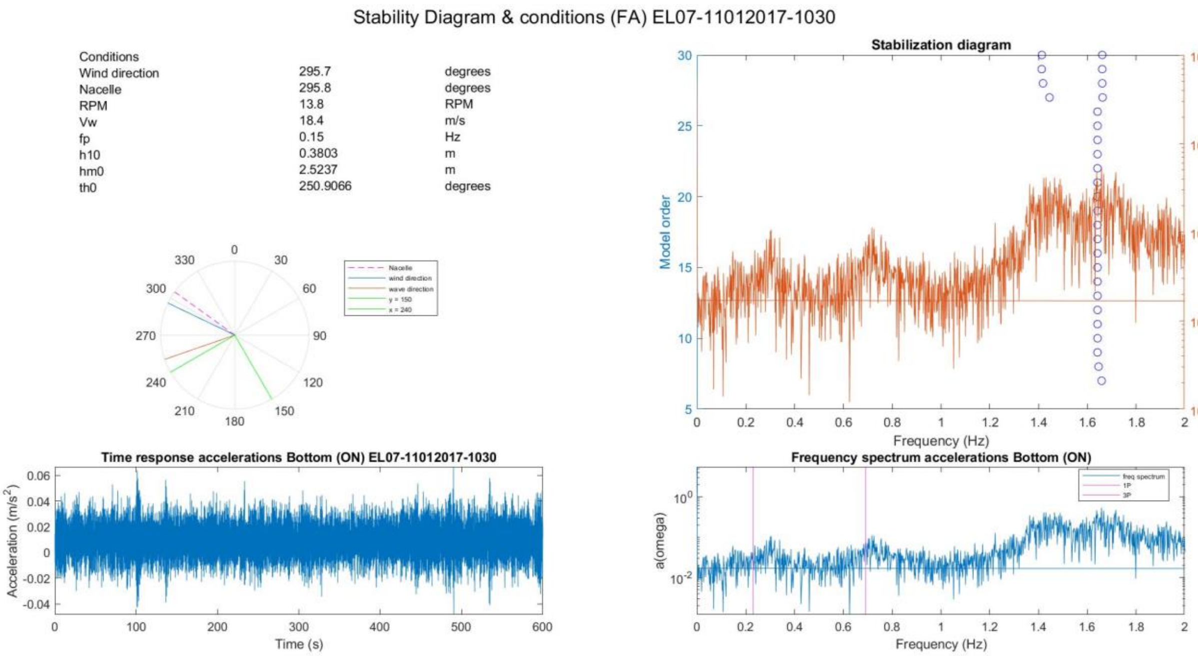

Figure 5.4 Stability diagrams and conditions data sample EL07 for 11012017 at 10:30h in the FA direction

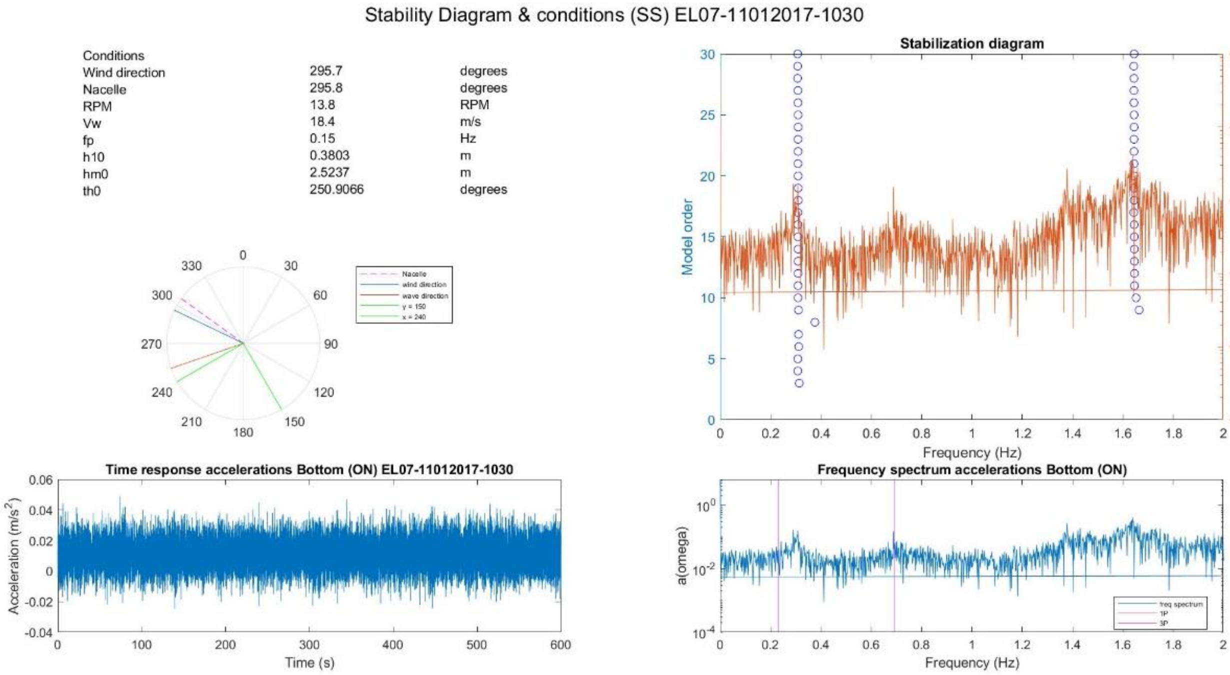

Figure 5.5 Stability diagram and conditions data sample EL07 for 11012017 at 10:30h in the SS direction

Next the results for EL30 on variable wind and wave directions are discussed. In most of the samples evaluated, there are no visible stable poles around the expected first frequency in the FA direction. The first peak for EL30 lies around 0.295 Hz. There are either no visible stable poles or the stable poles are identified before the first peak, around 0.22Hz. No visible stable poles does not mean there are no identifications at all at the peak. In Figure 5.6 the visible pole is identified even before the blade frequency (1P) of the turbine. In the SS direction (not shown) there are more identifications around the first peak, but do not form a stable pole all together.

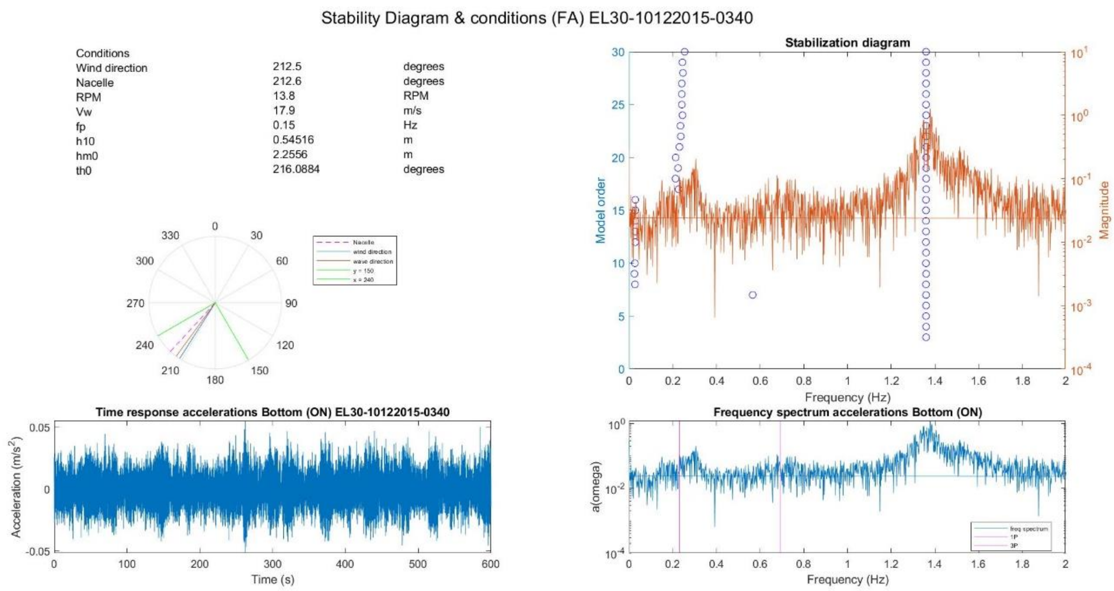

Figure 5.6 Stability diagram and conditions data sample EL30 for 28072017 16:30h in the FA direction

In this specific data sample, the corresponding ‘first’ mode shapes have the mode similar to a second mode shape, which can be seen in Figure 5.7.

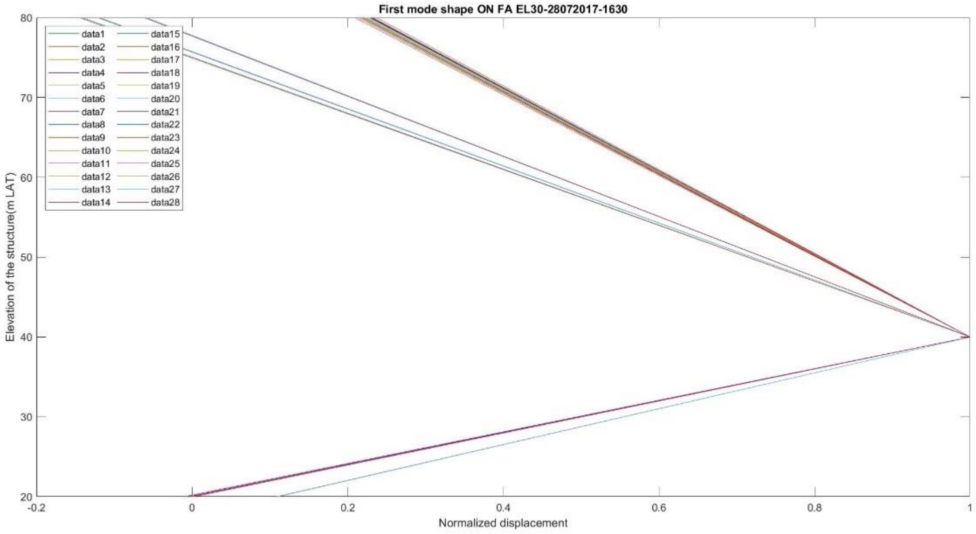

Figure 5.7 ‘First’ Mode shapes (model order 3 to 30) data sample EL30 28072017 16:30h

In other data samples for EL30, there also were correct estimations for the first mode shape and similar results like EL07 occurred.

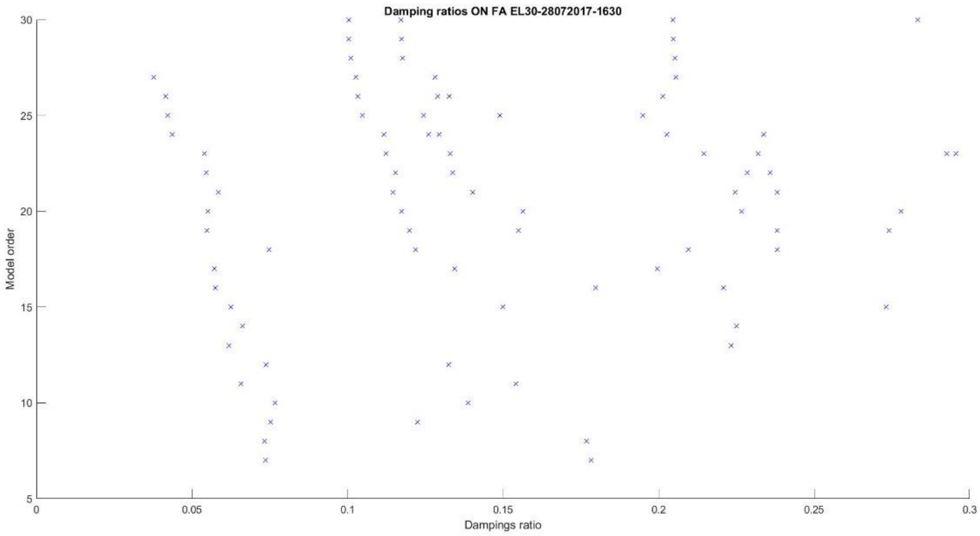

Figure 5.8 Damping ratios data sample EL30 28072017 16:30h

Also, for the estimation of the modal damping ratio for EL30, the results are inconclusive, and it cannot be said that a stable modal damping ratio is obtained for the first natural frequency in the FA direction.

5.1.2 Wind speed

The wind speed in this study is chosen in regime 4 of the power curve for wind turbines. The modal parameters are evaluated for a variable windspeed between 14 and 22 m/s, whereas the other environmental conditions are relatively constant in the operational situation.

Windspeed	Wind & wave direction	Water level	Wave peak frequency
Variable	240 deg (± 5)	250 cm (± 5)	0.15 Hz

Table 5.3 Definition environmental conditions, varying wind speed

For the varying windspeed the results for both turbines will also be discussed separately. First the results for turbine EL07 are discussed, followed by EL30. Table 5.4 gives an overview of the identified stable poles for both turbines in the FA/SS directions.

		Natural frequency			
		First		Second	
	Sample	FA	SS	FA	SS
EL07	1	0.31	0.296	1.45	1.43
	2	-	-	1.51	1.43
	3	-	-	1.57	1.49
	4	0.31	-	-	1.57
	5	0.3	0.33	-	1.61
	6	0.33	0.29	1.63	1.36
	7	0.295	-	-	-
	8	0.309	-	-	1.44
	9	0.31	0.29	-	1.4
	10	0.31	-	-	1.45
EL30	1	-	-	1.38	1.38
	2	-	-	1.38	1.37
	3	0.298	-	1.4	1.38
	4	-	-	1.34	1.37
	5	-	-	1.35	1.4
	6	-	-	1.34	1.38
	7	0.29	-	1.397	1.38
	8	0.27	-	-	1.4
	9	0.31	-	1.38	1.38
	10	-	-	1.38	1.38

Table 5.4 Natural frequencies varying wind speed

The first peak in the frequency spectrum from the acceleration response for EL07 in the operational situation is around 0.31Hz. Also, for the samples evaluated with a variable wind speed, the stable poles in the stability diagrams in the FA direction are around or exactly at 0.31Hz. Figure 5.9.

The cases, where the first peak does not respond with the first stable pole in the spectrum are mostly cases, where the wind and wave direction are not aligned with each other. This phenomenon was also seen in the first part, where the wind and wave direction were variable. A difference for more than 10 degrees exists between the wind and wave direction. The structure seems to be better excited in the SS direction in these situations.

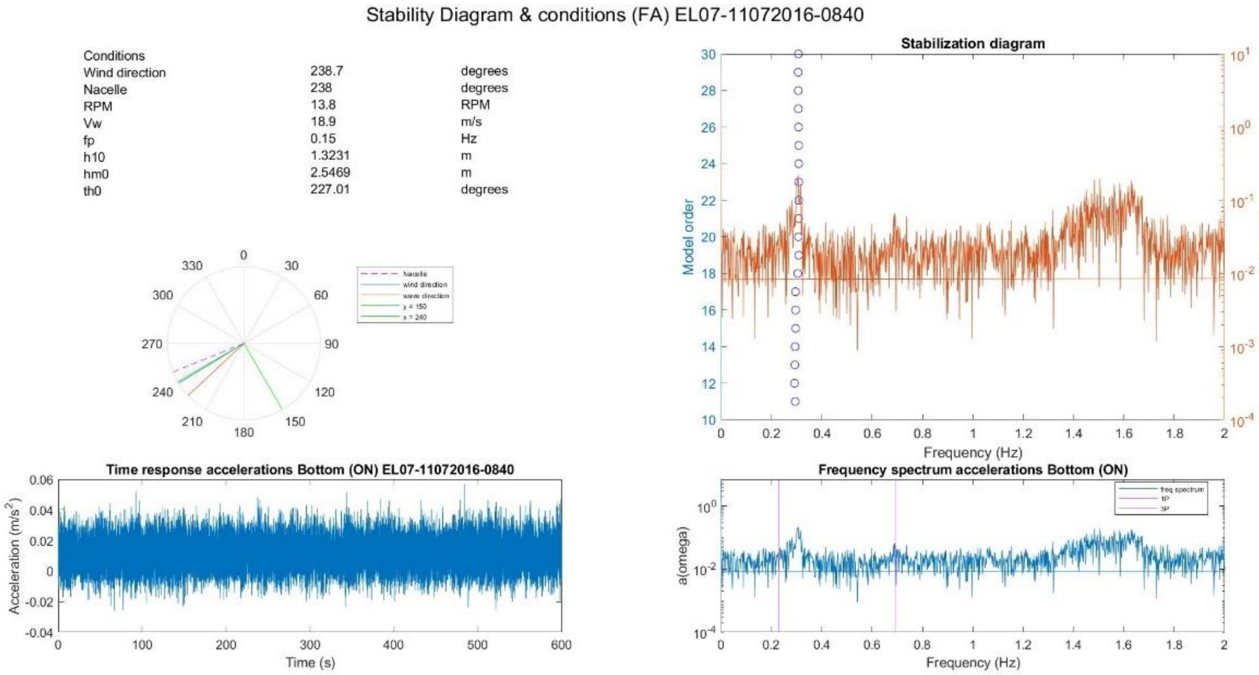

Figure 5.9 Stability diagram and conditions data sample EL07 for 11072016 8:40h in the FA direction

The data samples for EL07 for the varying wind speeds showed similar results for the mode shapes and the modal damping as was seen in the varying wind and wave direction. The ‘first’ mode shape, does not necessarily have the expected shape for all the model orders between 3 and 30. For the modal damping the design modal damping ratio is approximately 0.7%, whereas the identified modal damping ratios start at approximately 0.05%, with no stable identifications. There is a big scatter in the results.

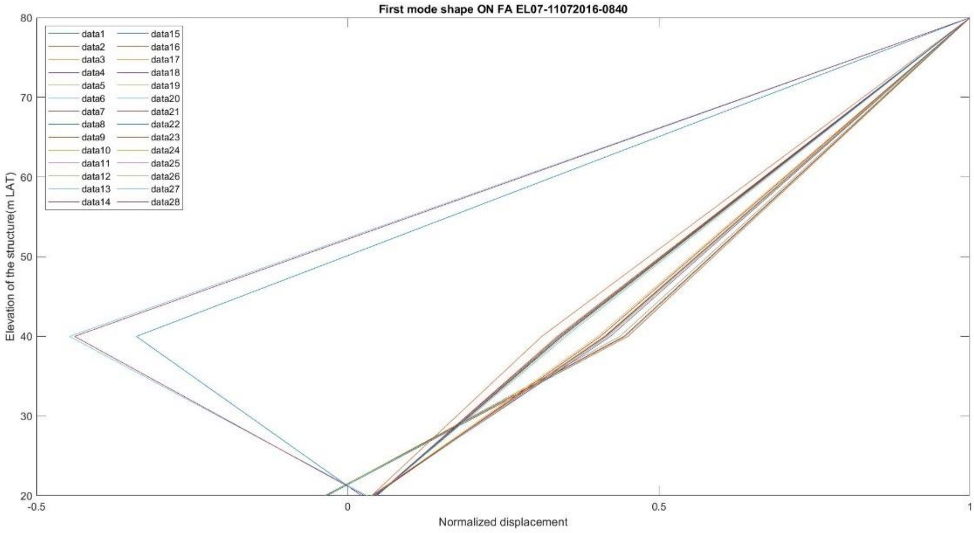

Figure 5.10 'First' Mode shapes (model order 3 to 30) data sample EL07 11012016 8:40h

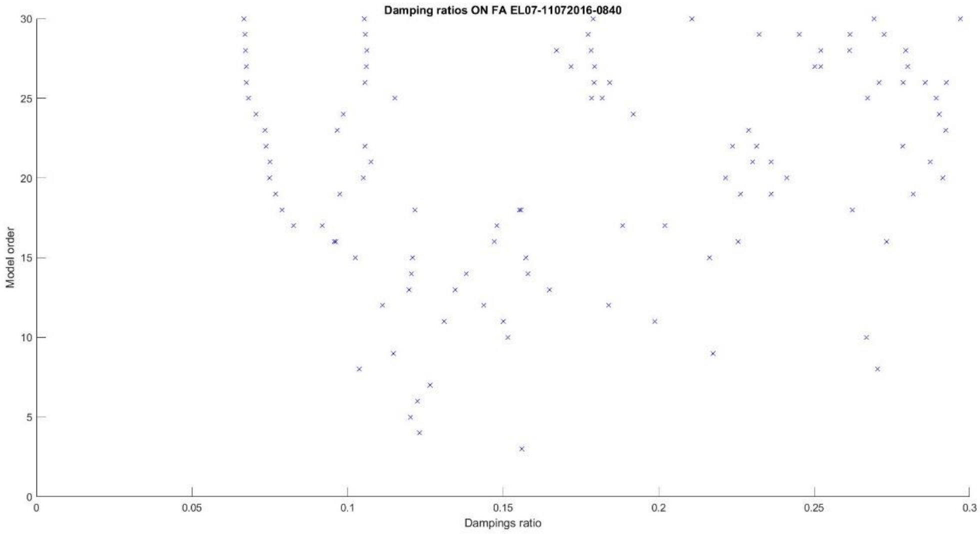

Figure 5.11 Modal damping ratio data sample EL07 11012016 8:40h

In the results for EL30 it is difficult to observe a conclusive first natural frequency in the result of the FA direction as well in the SS direction. In some samples the first stable pole is identified at the expected first frequency of 0.295Hz, according to the peak in the frequency spectrum, whereas in other samples the first stable pole is identified at the third visible peak of the spectrum, where the second frequency is expected. A possibility could be that this phenomenon occurs where the wind and wave directions are not aligned as was seen in the analysis of the varying wind and wave direction. Figure 5.12 shows an example where the first frequency is identified as expected around 0.31Hz.

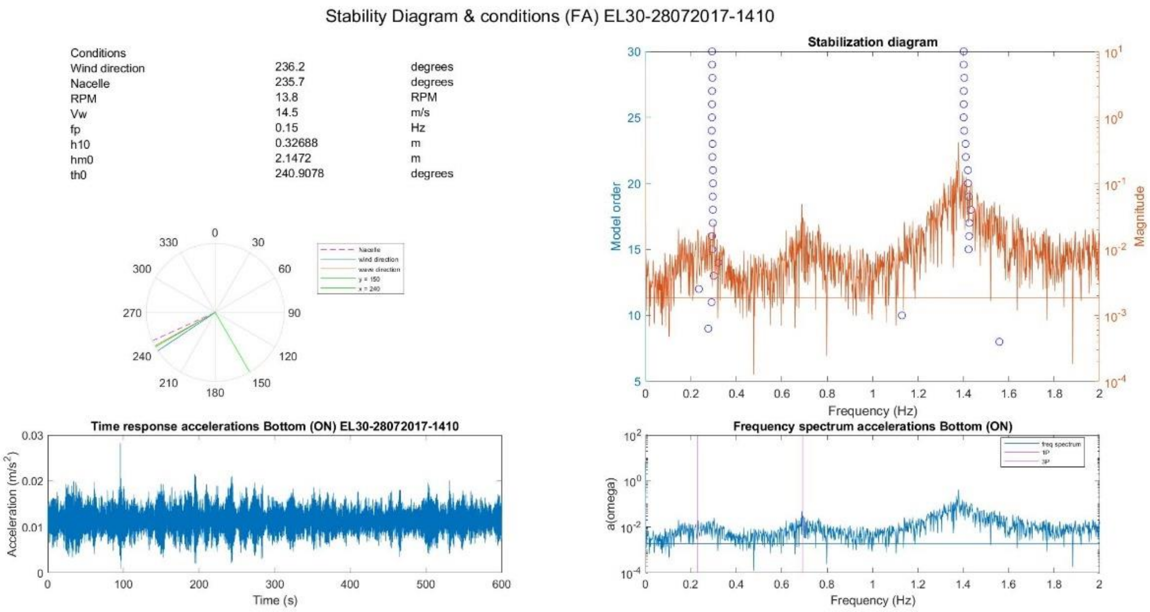

Figure 5.12 Stability diagram and conditions data sample for EL30 28072017 14:10h in the FA direction

For the modal damping and the mode shapes the same phenomena are seen as is seen earlier in the analysis of the varying wind and wave direction. For the first estimated natural frequency, the corresponding mode shape does not necessarily have the shape of a first bending mode and the results for the modal damping ratio are scattered over a wide range.

5.1.3 Water level

In this section of the study the water level is studied for different heights of the water, in comparison to the other relatively constant environmental conditions, to observe the influence of the water level on the identification of the modal parameters in ERA. The parameters used are given in Table 5.5

Windspeed	Wind & wave direction	Water level	Wave peak frequency
18 m/s (± 0.5)	240 deg (± 5)	Variable	0.15 Hz

Table 5.5 Definition environmental conditions, varying water level

The samples evaluated for EL07 and EL30 are just like in the evaluation for the variable wind/wave direction and the wind speed, clear in the obtained results and are given in Table 5.6.

		Natural frequency			
		First		Second	
EL07	Sample	FA	SS	FA	SS
	1	0.31	-	-	1.57
	2	0.31	0.31	-	1.61
	3	0.31	-	-	1.4
	4	-	0.24	-	1.44
EL30	1	0.27	-	1.35	1.32
	2	0.3	-	-	1.31
	3	0.31	-	1.38	-
	4	-	0.29	1.38	1.31

Table 5.6 Natural frequencies varying water level

For turbine EL07 the first stable pole is identified at or around the first peak of approximately 0.31Hz in the frequency spectrum of the acceleration response in the FA direction. In a single case the results differs and also here it could be coupled to the difference in the wind and wave direction and the better excitement of the SS direction with this difference in wind and wave direction. This holds for both turbines EL07 as well as EL30.

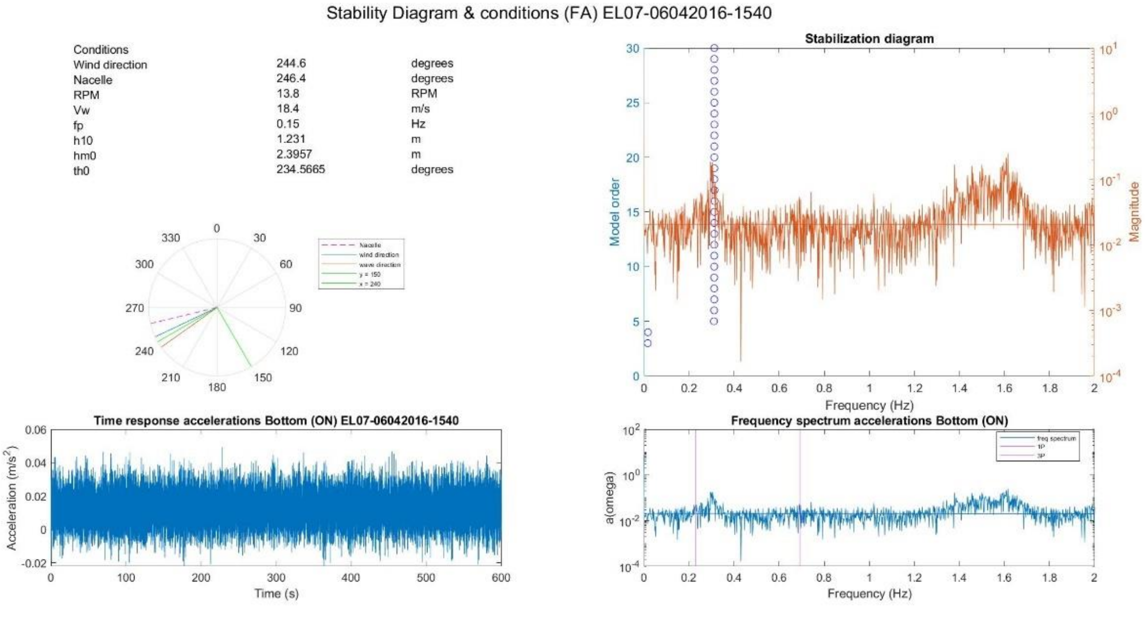

Figure 5.13 Stability diagram and conditions data sample for EL07 06042016 15:40h in the FA direction

In the results of EL30, also the same trend is seen as is seen in the results for the wind/wave direction and the windspeeds. The natural frequency is identified either too early, to late or also around the peak in the frequency spectrum. In the example given in Figure 5.14 the first identified stable pole is around 0.2Hz, which is almost at the first blade frequency and a second stable identified pole, which is at the expected second frequency.

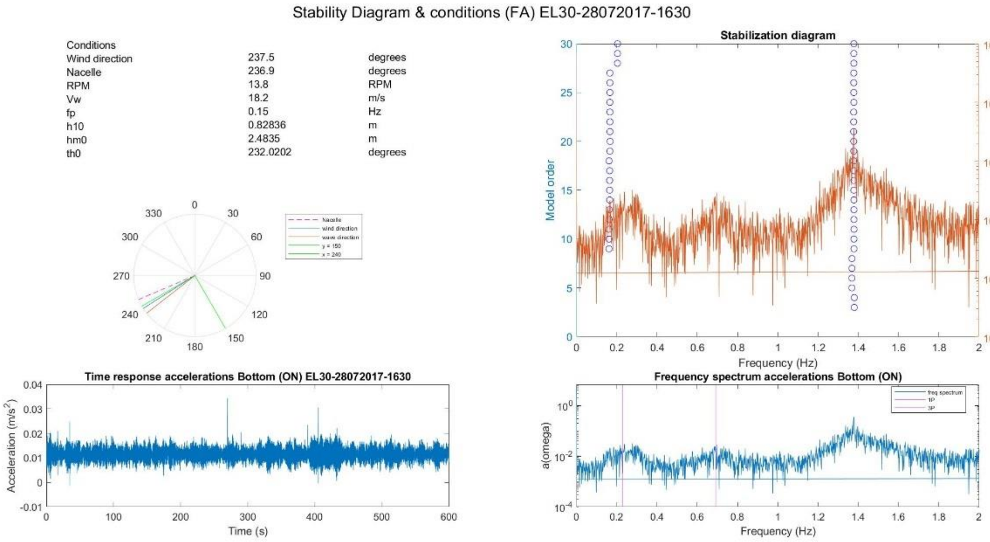

Figure 5.14 Stability diagram and conditions data sample for EL30 28072017 16:30h in the FA direction.

Both wind turbines, EL07 and EL30, show results similar to the earlier obtained results regarding the mode shapes and the modal damping ratios in the cases of the varying wind/wave direction and the varying wind speed.

5.1.4 Wave peak frequency

Finally, the wave peak frequency will be varied (between 0.125Hz and 0.15Hz) for the samples to evaluate and the other environmental conditions are kept constant. The parameters are given in Table 5.7

Windspeed	Wind & wave direction	Water level	Wave peak frequency
18 m/s (± 0.5)	240 deg (± 5)	250 cm (± 5)	Variable

Table 5.7 Definition environmental conditions, varying wave peak frequency

The samples evaluated for both turbines for varying wave peak frequencies result in the stable poles given in

		Natural frequency			
		First		Second	
	Sample	FA	SS	FA	SS
EL07	1	-	-	1.49	1.48
	2	0.305	-		1.44
	3	0.31	-		-
	4	0.3	0.32	1.55	1.44
	5	0.305	0.31		1.45
	6	0.31		1.59	1.5
	7	0.31			1.45
	8	0.26	0.31	1.53	1.47
EL30	1	0.3	-	1.38	1.31
	2	-	0.301	1.34	-
	3	-	-	-	1.38
	4	-	0.295	1.38	1.318

Table 5.8

		Natural frequency			
		First		Second	
	Sample	FA	SS	FA	SS
EL07	1	-	-	1.49	1.48
	2	0.305	-		1.44
	3	0.31	-		-
	4	0.3	0.32	1.55	1.44
	5	0.305	0.31		1.45
	6	0.31		1.59	1.5
	7	0.31			1.45
	8	0.26	0.31	1.53	1.47
EL30	1	0.3	-	1.38	1.31
	2	-	0.301	1.34	-
	3	-	-	-	1.38
	4	-	0.295	1.38	1.318

Table 5.8 Natural frequencies varying wave peak frequencies

The figures 5.15 and 5.16 each show an example of the evaluated data samples for the turbines, respectively EL07 and EL30.

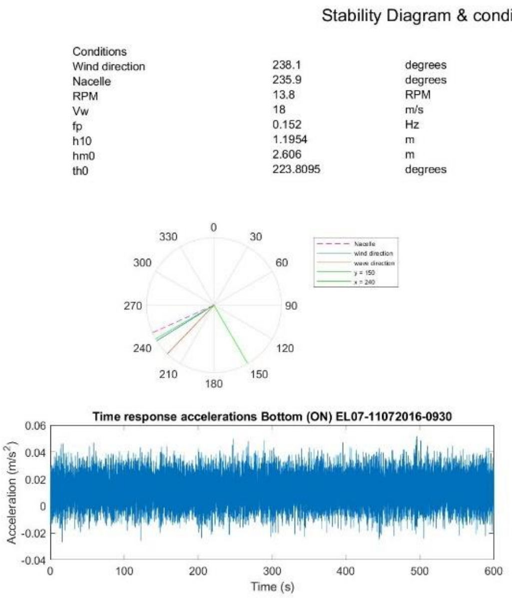

Figure 5.15 Stability diagram and conditions data sample for EL07 11012017 9:30h

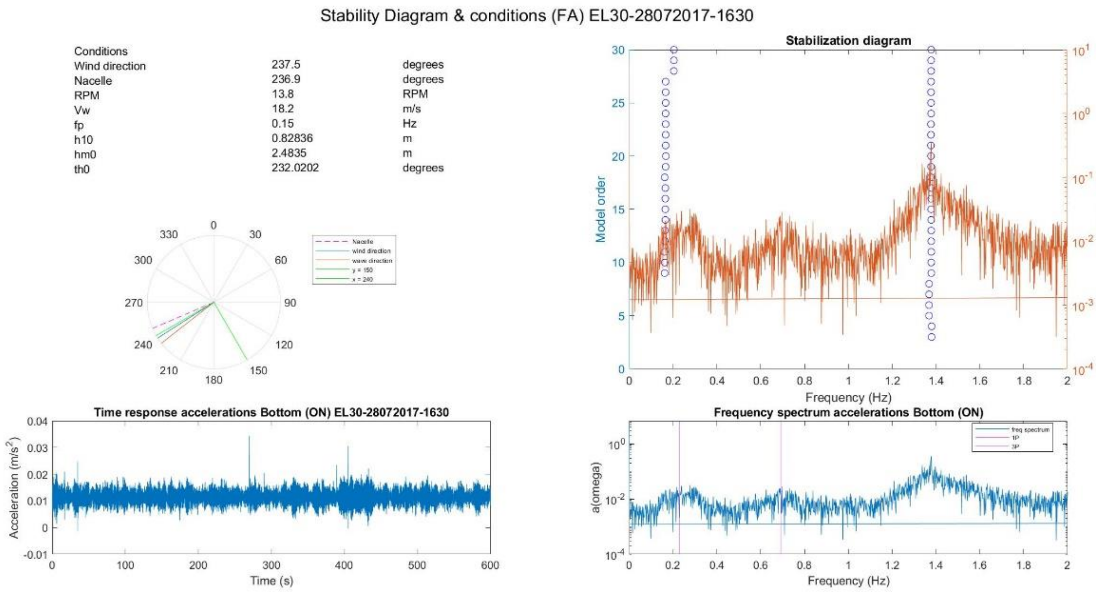

Figure 5.16 Stability diagram and conditions data sample for EL30 28072017 16:30h in the FA direction

In the evaluation of the difference in the wave peak frequency there are no big differences in relation to the earlier obtained results for the varying wind/wave direction, windspeed and the water level. For both turbines, the results show the same phenomena regarding the identification of the natural frequencies and the identification of the mode shapes and the modal damping.

5.1.5 Operational condition OFF

In the introduction of this chapter, it was stated, that due to the number of available samples in the idling state of the turbines, it was not possible to vary each environmental condition separately. Also, most of the samples in the off state were around a wind/wave direction of 150 degrees. The parameters used, to evaluate single data samples with stability diagrams are:

Windspeed	Wind & wave direction	Water level	Wave peak frequency
14.5 m/s (± 0.5)	Variable	Variable	variable

Table 5.9 Definition environmental conditions for Idling conditions

The figures show examples of the results for EL07 and EL30. In both situations relatively the same phenomenon was identified. At the first visible peak in the frequency spectrum of the acceleration response two closely spaced modes are visible. In [18] it is made clear, that a mode is to be classified as a closely spaced mode if the modes are visible in all the data sets (samples). For all samples evaluated in the idling state of both turbines EL07 and EL30 the closely spaced modes are identified in for the first natural frequency. For the second stable pole, the second frequency also closely spaced modes are identified.

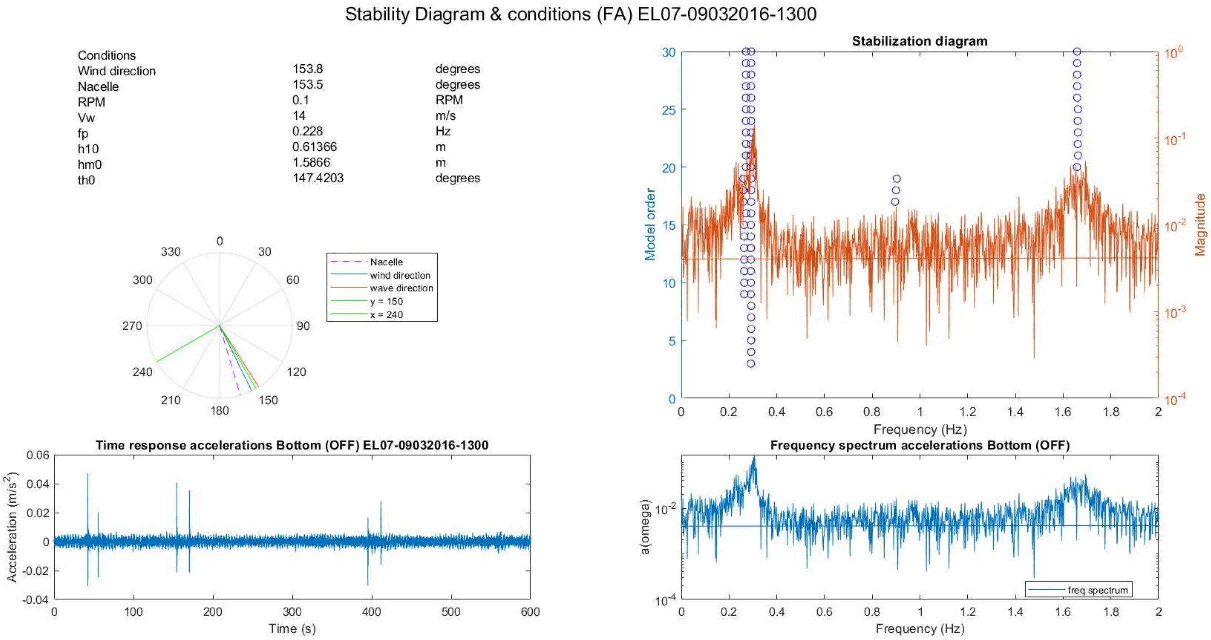

Figure 5.17 Stability diagram and conditions data sample for EL07 09032016 13:00h

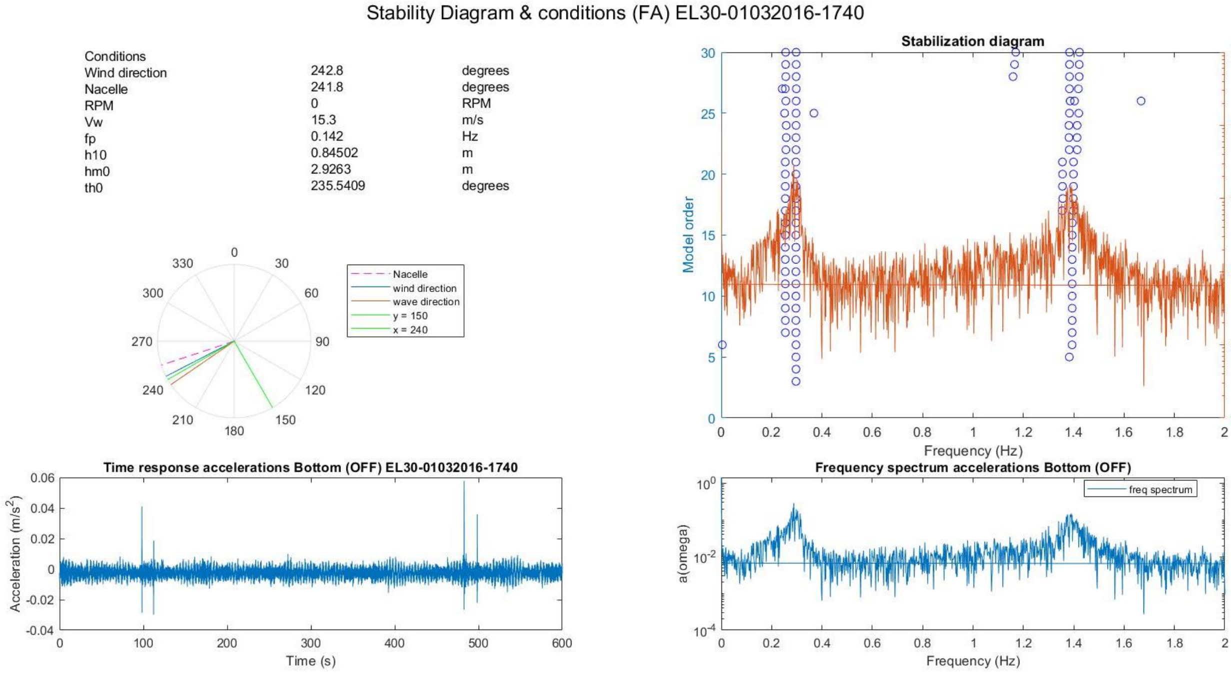

Figure 5.18 Stability diagram and conditions data sample for EL30 01032016 17:40h

5.1.6 Conclusion Part one

In the first part of this study several data samples for different environmental conditions were evaluated to estimate if ERA is applicable in estimating the modal parameters of operational offshore turbines. These evaluated data samples were all for the fully operational turbines. The analysis shows good estimation of the first natural frequency in the FA direction for offshore turbine EL07 at approximately 0.305Hz in the ON state. For most of the cases were there was no visible stable pole at the peak for the first natural frequency in the FA direction, the SS direction did show a visible pole at the frequency at the expected peak of the frequency response. In these situations, the wind and wave direction are mis aligned and it is assumed that the SS direction is better excited due to this phenomenon. The peak in the spectrum for the SS direction is also higher in magnitude.

For offshore turbine EL30, the identification of the first natural frequency was not always very clear for both directions, even though the majority of the results did indeed result in a frequency at the first expected peak around approximately 0.29 Hz. For the second natural frequency around the third peak in the frequency spectra, more or less the same holds. In a combination of the analysis of both the FA and the SS directions the second frequency can be identified. The identification is the best for the direction which is excited better by the environmental conditions. Also, the identification of the natural frequencies for EL30, has less accurate results then EL07.

The results for the mode shapes and the modal damping showed the same observations for both turbines. The identified mode shape belonging to the first natural frequency does not necessarily have the shape corresponding to a first bending mode. The modal damping ratios are inconclusive, due to the large scatter in the results. Stable poles are expected for the modal damping ratios, just like is seen for the natural frequencies.

5.2 Part two

Even though the results from the stability diagrams for the first part of the study were not always conclusive for both turbines in the idling and operational situations, in this part an attempt is made to analyze the data samples by an automatization step. This automatization step holds in, to select one model order in such a way, that it is expected that the most accurate results should be obtained. For each turbine and each state, a model order will be chosen separately, where in the previous part the results were obtained for model orders from 3 to 30.

5.2.1 Operational state: Idling

First the data analysis for the idling state is executed. In this analysis stability diagrams are produced, to identify potential stable modes/poles. The stability diagrams are generated for model orders from 3 to 30 to identify the stable modes just as was done in the first part of this study. To generate the diagrams 5 randomly chosen data samples per wind turbine are used from the selected OFF data samples. This means in total 20 diagrams are produced (10 per turbine, 5 per direction). The results of the stability diagrams obtained with the specified size for the Hankel matrices are presented for the FA direction and Figure 5.19 presents an example for turbine EL30.

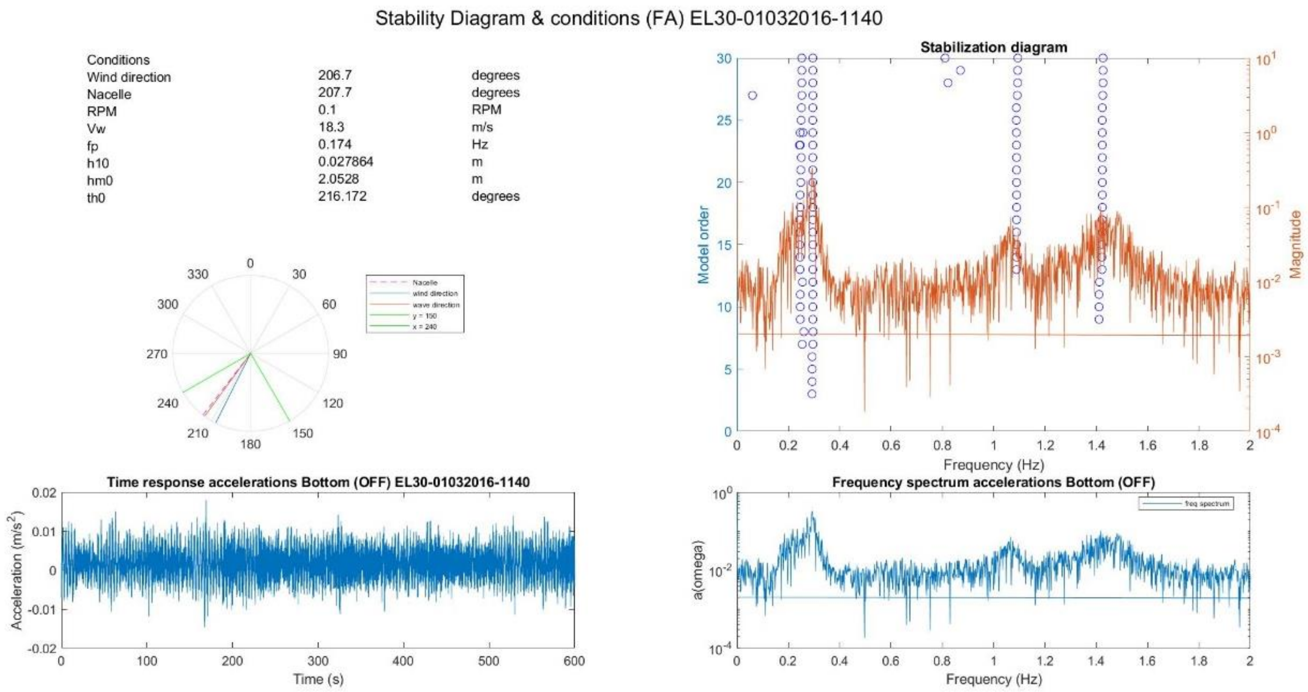

Figure 5.19 Stability Diagram and conditions data sample for EL30 01032016 11:40h

The stability diagram and environmental condition information given in figure 5.5 represents EL30 on the 1st of March 2016 at 11:40h The wind direction and wave direction are in line with the nacelle direction and there is a wave peak of 0.174 Hz, with a wind speed of 18.3 m/s and a water level of approximately 205 cm (above LAT). The spectra represent the responses of the bottom sensor in the FA direction. The stability diagram visualizes 2 stable modes around the first peak of 0.29 Hz. The first stable mode is around 0.24 Hz, which is lower than the expected design frequency and could be classified as a closely spaced mode. At the second and third peak resp 1.065 Hz and 1.42 Hz stable poles are formed.

For the analysis of the whole data set, one model order should be selected to estimate the first frequency for both the turbines. Per model order a different number of frequencies is estimated. These frequencies are accumulated in a matrix next to each other. In this evaluation, a call is made, which model order estimates the first frequency best in relation to the expected natural frequency in comparison with the other modes. For both turbines EL07 and EL30 order 8 is selected. The results obtained in this analysis are discussed.

5.2.1.1 (First) Natural frequency Idling

In table 5.1 the expected range for the first natural frequency is given and has a maximum of 0.323 Hz. The results for the turbines for model order 8 in the FA direction for EL07 and EL30 are presented in boxplots. The median of these boxplots gives an indication of the estimated first frequency. The median is the middle value of all the estimated values for the first natural frequency.

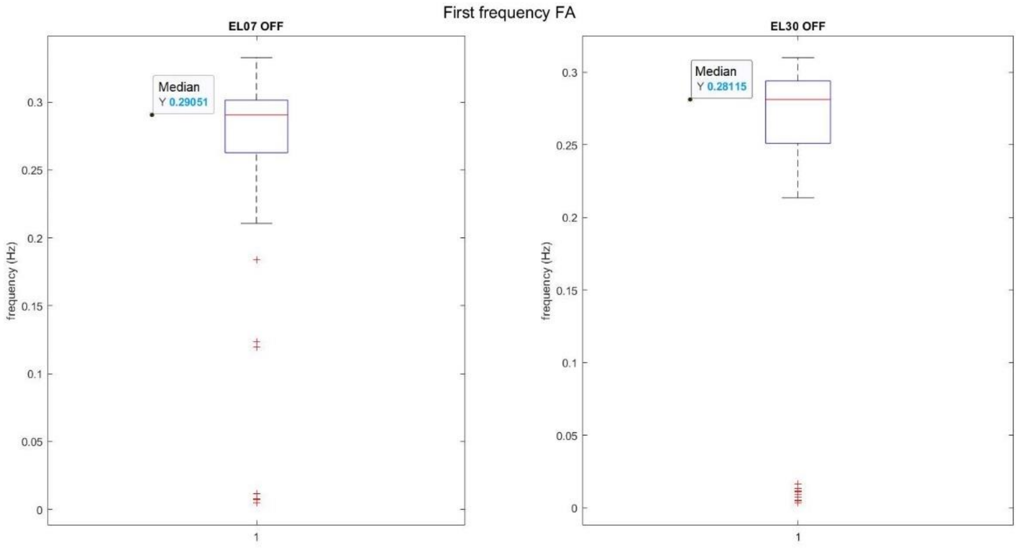

Figure 5.20 First natural frequency OFF

For EL07 the median is 0.29 Hz and for EL30 0.28Hz. Taking the lower bound in consideration and having in mind the design value for both EL07 and EL30 resp 0.2715 and 0.2637Hz, the estimated frequency is indeed in the design range of the wind turbines.

	frequency	**Expected**	
	Median	**Lower**	**Upper**

EL07	0.29051	0.27	0.323
EL30	0.28115	0.26	0.323

Table 5.10 Error estimation of the frequency

The first frequencies were estimated in the correct range of the expectations for EL07 and EL30 in respectively 37 and 44 cases. For more than half of the cases this was thus the case, which leads to the estimation of the natural frequency in the design range of the turbines, whereas the peaks in the frequency spectra lie around respectively 0.305 Hz and 0.29Hz for the majority of the data samples.

	Samples	**Good estimate**	**Repeat**
EL07	56	37	66.07%
EL30	67	44	65.67%

Table 5.11 Repetition factor

5.2.1.2 Mode shapes Idling

The shape of the first mode is given in Figure 3.4 as reference, which shape is expected for the corresponding first modes of the estimated first natural frequencies. The mode shapes will be checked for the data samples with a correct estimation of the first frequency (table 5.3). The results of the normalized mode shapes for turbine EL07 are presented in (figure 5.8). It can be observed that still approximately 3 mode shapes do not have the form for the first mode but rather a shape similar to a second mode shape.

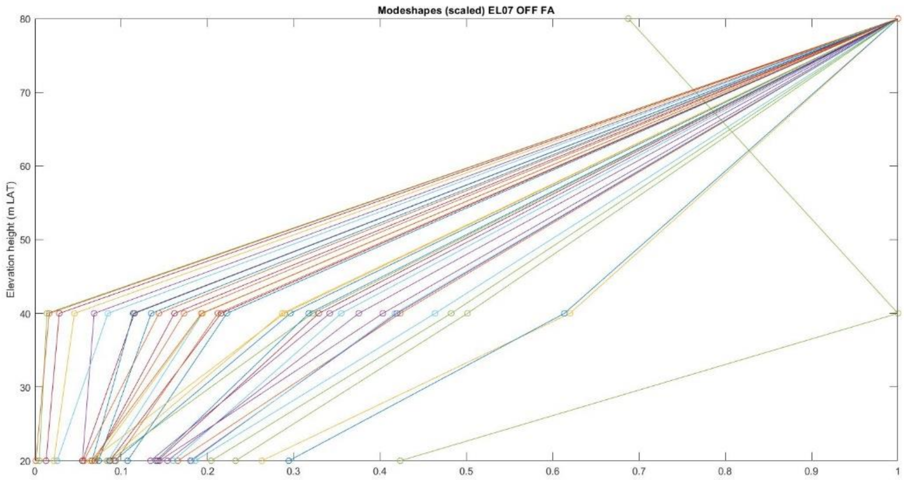

Figure 5.21 Mode shapes EL07 OFF

For both the turbines boxplots are accumulated and plotted over the expected mode shape of turbine EL30 (**Error! Reference source not found.**. For both cases, the box plots show that, after filtering out the ‘bad’ estimations of the first natural frequencies, the normalized mode shapes do correspond to the reference shape of EL30. In combination with the inspection of the plots of the normalized mode shapes and the boxplots, it is concluded that the majority of the mode shapes have the correct form after eliminating the ‘wrongly’ estimated frequencies.

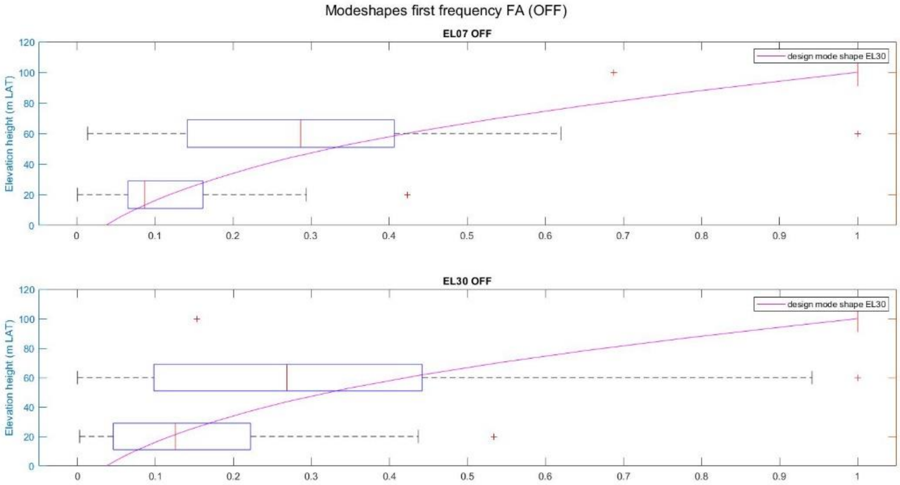

Figure 5.22 Boxplots mode shapes EL07 & EL30 OFF

5.2.1.3 Modal damping ratios Idling

The last verification for the OFF state is the estimation of the modal damping ratio. For the modal damping boxplots are also used in the evaluation of the results. The modal damping ratio is expected to be around resp 0.71 and 0.74 (table 5.1). Identical to the mode shapes, the modal damping ratio is checked for the data samples with a presumably correctly estimated frequency.

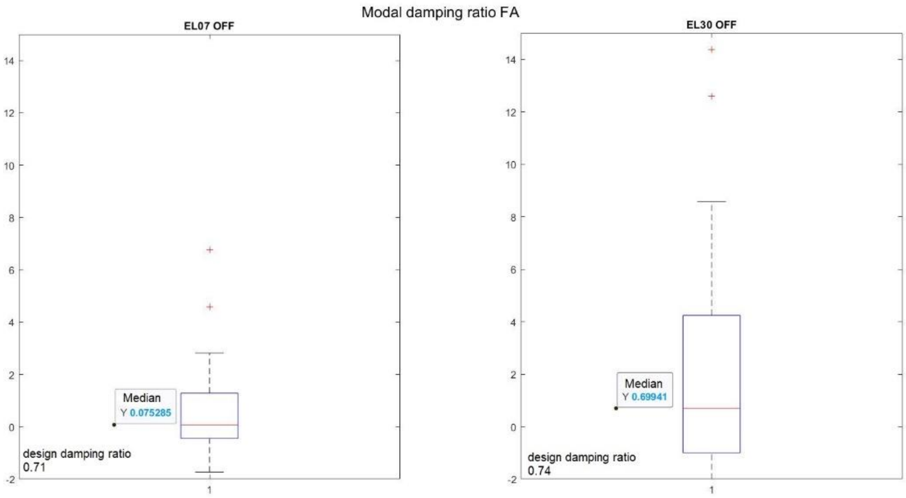

Figure 5.23 Modal damping ratio OFF turbine EL07 and EL30

The median for EL07 is 0.07% and the median for EL30 is 0.699%. Comparing the results to the design damping ratios, the modal damping ratio for EL07 is very low and the ratio for EL30 is approximately in the expected range (with an error of 5.49%). Estimating the modal damping turns out to be more challenging and doesn’t seem to be consistent in the results. It is neither clear if the result for turbine EL30 is in this case correctly determined by accident.

Two out of three dynamic properties, namely the first natural frequency and the mode shapes gave relatively good results for the selected data samples and after eliminating the data samples where the natural frequencies differed significantly.

5.2.2 Operational state: Operational

The same automation procedure followed in the previous chapter will be followed for the fully operational state of the offshore wind turbines.

Identical to the OFF state the data analysis for the operational conditions starts with the producing of stability diagrams to identify stable modes/poles. The chosen size of the Hankel matrices for the idling conditions is also used for the operational conditions. Orders from 3 to 30 are selected for the identification of stable modes for the 5 randomly chosen data samples. Also, in the ON state 20 diagrams are evaluated (5 per direction, 10 per turbine). An example of the results for the FA direction for turbine EL30 is presented in Figure 5.24.

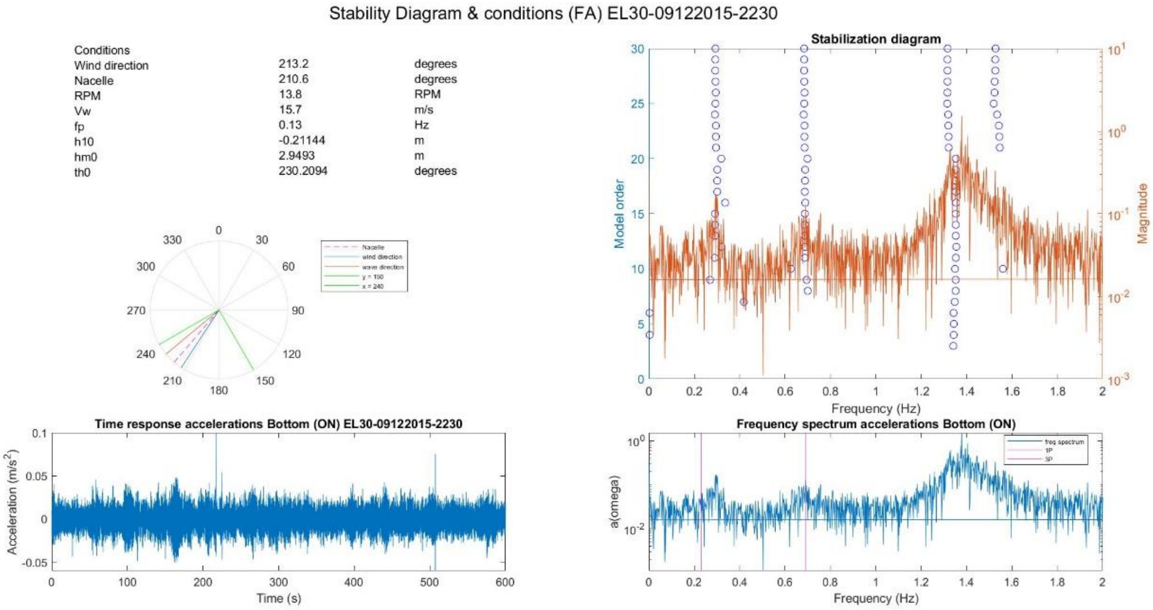

Figure 5.24 Stability diagram and conditions for EL30 09122015 22:30h

The figure presented displays the stability diagram and condition information regarded EL30 on the 9th of December 2015 at 22:30h in the FA direction. The wave direction differs approximately 15 degrees to the wind and nacelle direction. A peak frequency of 0.13 Hz is noted and a wind speed of 15.7 m/s. In the presented frequency spectrum 3 peaks are visible, whereas the second peak corresponds with the 3P frequency. In the stability diagram it is observed, that a pole forms at the first peak around 0.29Hz. Also, at the second peak a pole appears, even though this pole should be classified as an excitation mode, because it coincides with the 3P frequency of the wind turbine. The third pole forms around the frequency 1.33Hz, which is expected to be the second natural frequency.

In the ON state the visual inspection is a little bit more challenging. The stable modes are more difficult to identify. But when the modes are identified it is in some cases even possible to observe the second natural frequency and as the example shows, the 3P frequency is also visible in the results. In the end after examining all the stability diagrams for EL07 and EL30 it is known which order could best be chosen for the analysis.

For the evaluation of all the selected data samples for the operational conditions of EL07 (14 samples) and EL30 (206 samples) a model order must be chosen. After evaluation of the matrices, which are put next to each other the order 24 is chosen for EL07 and the order 21 is chosen for EL30, based on engineering judgement on what order will result in the best estimates.

5.2.2.1 (First) Natural frequency for Operational conditions

The first natural frequency lies in a range between resp 0.27 - 0.323 Hz and 0.26 - 0.323 Hz (table 5.1). For both turbines boxplots with the median are produced (figure 5.15).

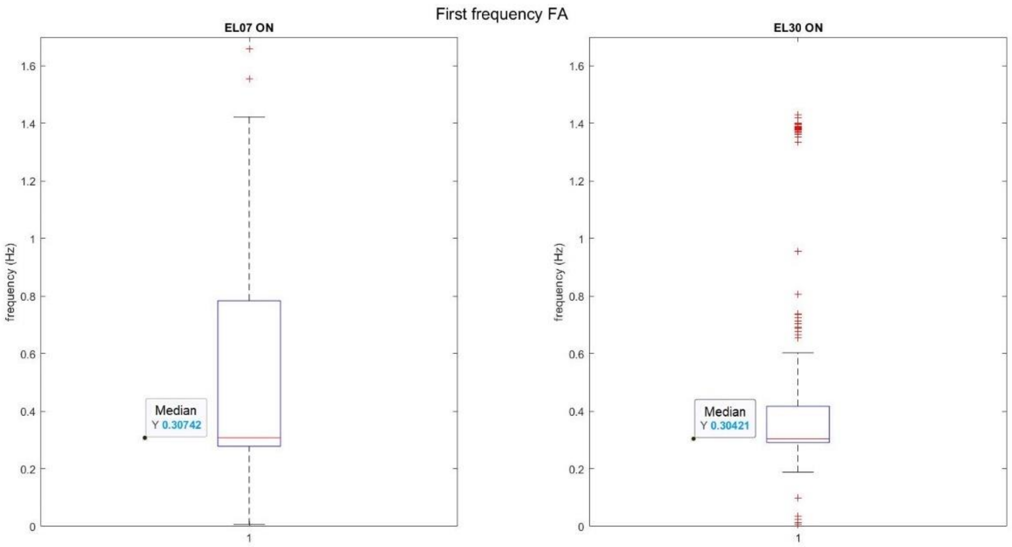

Figure 5.25 First natural frequency ON

The median for resp EL07 and EL30, are 0.31 Hz and 0.30 Hz. In comparison to the upper and lower bound (Table 5.12 this is an estimation in the design frequency range for both turbines. For the ON state, the expectation in the field is that the frequencies are a little higher, than for the OFF state.

	frequency	**Expected**	
	Median	**Lower**	**Upper**
EL07	0.30742	0.27	0.323
EL30	0.30421	0.26	0.323

Table 5.12 Error estimation of the frequency

Similar to the analysis of the data samples in the idling condition, the mean or the median of the results is the middle value of the estimations. This means if more or less of the half of the estimates are good estimates the mean result will be in the expected range. For only half of the samples turbine EL07 has a good frequency estimate and EL30 has a good frequency estimate for 115 out of 206 data samples. The percentage of the samples with a good estimate is much lower, than in the OFF state, but still enough to find a mean value in the expected design range.

	Samples	**Good estimate**	**Repeat**
EL07	14	7	50.00%
EL30	206	115	55.83%

Table 5.13 Repetition factor

5.2.2.2 Mode shapes Operational

Equal to the determining of the mode shapes for the idling conditions of the turbines, the mode shapes will only be checked for the frequencies with a good estimate. In this analysis the mode shapes are observed on their correct form for a first mode with refence Figure 3.4. The mode shapes for turbine EL07 are plotted and displayed in figure 5.16.

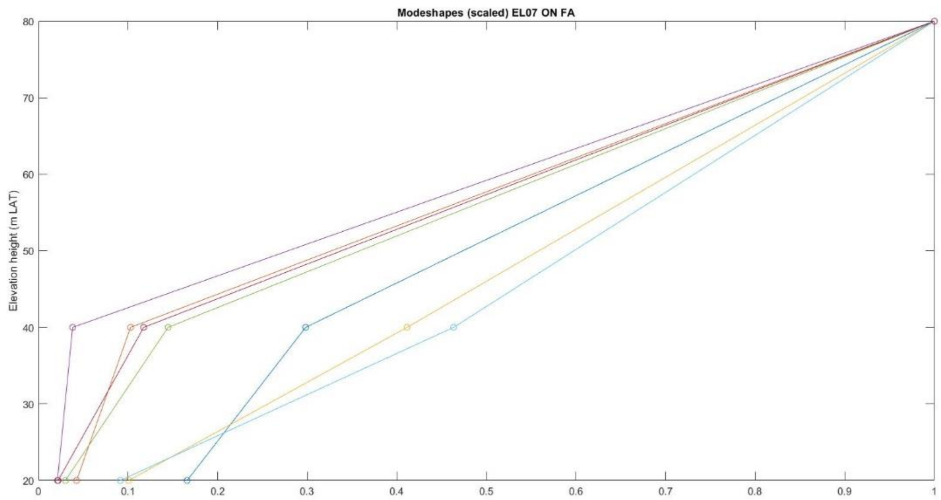

Figure 5.26 Mode shapes EL07 ON

The normalized mode shapes in figure 5.16 have the expected mode shape. The mode shapes for turbine EL30 are also evaluated, where it is clear that there are still samples between the good estimates, which do not correspond to a first mode shape, but to a second mode. The results of EL07 and EL30 are gathered in boxplots and plotted over the design reference mode shape of EL30 (figure 5.17).

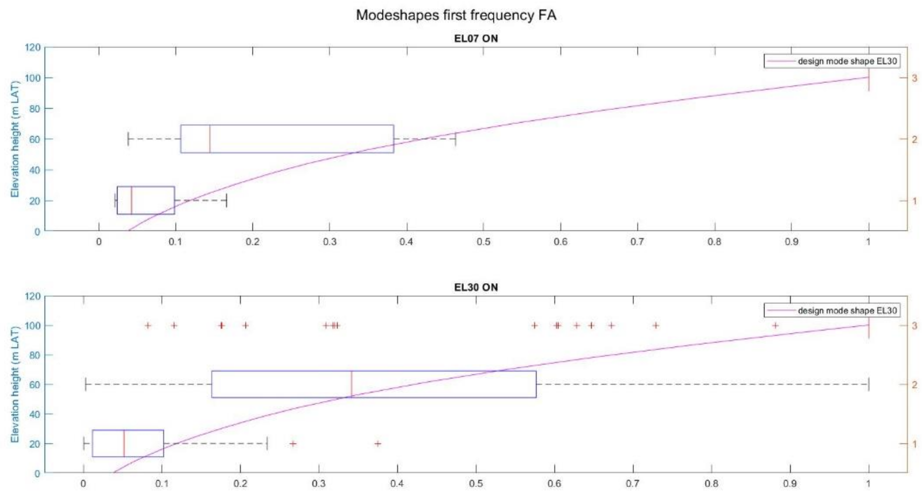

Figure 5.27 Boxplots mode shapes EL07 and EL30 ON

The boxplots for EL07 do not fit precisely above the design mode shape, but the shapes are of an expected first bending mode. This also holds for the EL30. The conclusion is drawn, that the estimate of the mode shapes for the first natural frequency in the FA direction becomes better after the ‘wrong’ first natural frequency estimates are eliminated out the data samples.

5.2.2.3 Modal damping ratio Operational

In 5.2.1.3 the conclusion resulted, that it was difficult to estimate the modal damping ratio. The results were not consistent. This could mean, that also for the ON state, it would be difficult or maybe impossible to estimate the modal damping ratios. An attempt is made in the estimation of the modal damping ratios. The results are displayed in figure 5.18 in boxplots.

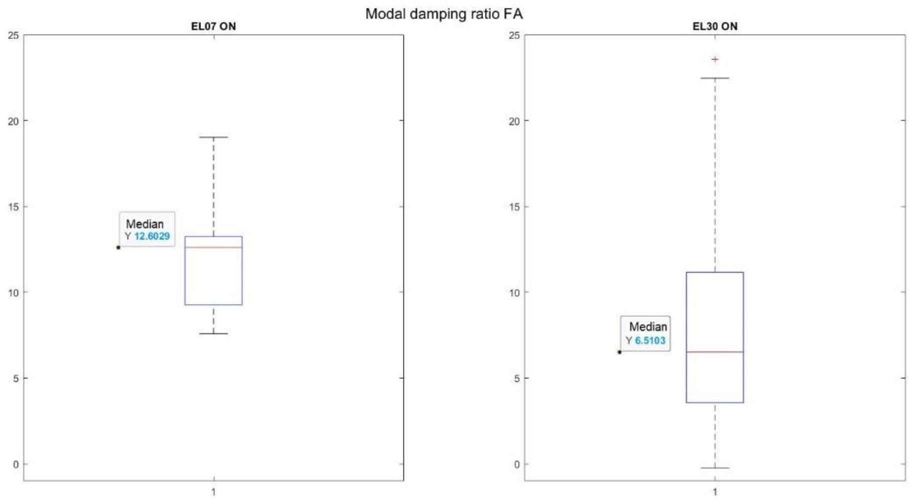

Figure 5.28 Modal damping ratio

The median for EL07 is 12.60% and the median for EL30 is 6.51%. These modal damping ratios are much higher than the design damping of 0.71%. Estimating the modal damping ratios in the ON situation with ERA looks difficult, even though it was expected because of the already challenging results for the OFF state and the scatter plots of the different varying environmental conditions.

5.2.3 Conclusion Part two

In the second part of the study similar environmental conditions are evaluated for the turbines fully operational and turned off. In this part, the automatization of ERA is tested, by selecting one model order for the execution of the selected data set. In the off situation for both turbines EL07 and EL30 a model order 8 was used and in the ON state respectively 24 and 21.

In both operational conditions of the turbines the mean value for the first natural frequency lay in between the design range of the natural frequencies for the turbines and the mean values did not differ significantly to the results of the frequencies in the first part. After eliminating the ‘wrongly’ estimated frequencies the corresponding mode shapes and modal damping ratios were determined. For these first frequencies the majority of the mode shapes showed a correct form in reference to the design mode shape. The modal damping ratios, however, were estimated to be very low or very high. The very high estimates of the damping ratio occurred in the fully operational state of the turbines.

6. Results: Identified vs Design

In this chapter the results obtained with the algorithm ERA from the analysis of the selected data samples for different varying environmental conditions and idling and operational conditions are discussed. These results are compared to the design and to the results obtained by the earlier study done on Luchterduinen by Middelweerd. Further it will be concluded if ERA is applicable for estimating the dynamic parameters for offshore operational wind turbines and an assessment on the accuracy and consistency is also given.

6.1 Part one vs Design

In the first part of this section the obtained results for the modal parameters for varying environmental conditions are compared to the results obtained by Middelweerd . Also, a comparison to the design of the wind turbines is made.

In the study on Luchterduinen by Middelweerd , the main and most important conclusion was the influence of the water level on the frequency. The other environmental conditions did not have a significant influence [27]. According to the results of Middelweerd (Figure 3.5) the first natural frequency for EL07 and EL30 are approximately 0.31Hz and 0.30 Hz.

Due to the limited number of samples studied in this research, the water level phenomenon stated by Middelweerd, could not be confirmed by this study. The obtained frequencies did correspond to the results of Middelweerd.

Furthermore, in the first part of the study the first and second natural frequencies could be identified in combining the results for both the FA and the SS directions, depending on the better excitement of the direction. It is assumed for the first natural frequency that in some cases, the SS direction is better excited, when the wind and wave direction are not aligned to each other. The obtained first natural frequencies for the turbines are respectively 0.305Hz for EL07 and 0.295 Hz for EL30. In Comparison to the design range (Table 6.1), which is used as refence the frequencies are indeed in this given range. The design values are given in a range, because over time due to example corrosion, marine growth, seabed and water level changes, the conditions of the turbines and the frequencies could change over time. Also, the second frequencies are at a higher value, than the design values.

	Design values		Middelweerd		Varying environmental		Idling state	
	EL07	EL30	EL07	EL30	EL07	EL30	EL07	EL30
First	0.27 - 0.323	0.26 - 0.323	0.306	0.302	0.305	0.295	0.31	0.29
Second	1.144	0.9591			1.53	1.36	1.65	1.41

Table 6.1 Natural frequencies for EL07 and EL30

For the idling conditions of the turbines, a similarity is recognized between the identification of the frequencies. The remark must be made, that in the idling state, closely spaced modes are visible.

Further, in the identification of the modal parameters, the estimation of the first mode shape is observed for the corresponding first natural frequency for the model orders between 3 and 30. Not for every mode a shape in correspondence with the reference normalized mode shape (Figure 3.4) is found. Some of the mode shapes correspond with other normalized bending modes.

For the modal damping ratio, the results were not clear, to couple a specific modal damping ratio to the corresponding natural frequencies. It was expected, that similar to frequency, stable damping ratio poles would occur. It was thus inconclusive if the ratios matched the design ratio of respective 0.71% and 0.74%.

6.2 Idling vs Operational

In this part of the section the results obtained for the idling and operational conditions of the turbines are discussed and compared to the design values. In the discussion on the results, the findings of the varying environmental conditions are also considered.

In both the situations OFF and ON, ERA was able to estimate the first natural frequencies in the expected range (Table 6.1). In the idling conditions the frequencies are more towards the lower bound reference of the design frequency and in the operational conditions the frequencies are more to the upper bound frequency of the range, which is used as reference. Figure 6.1 and 6.2 illustrates the results for both situations.

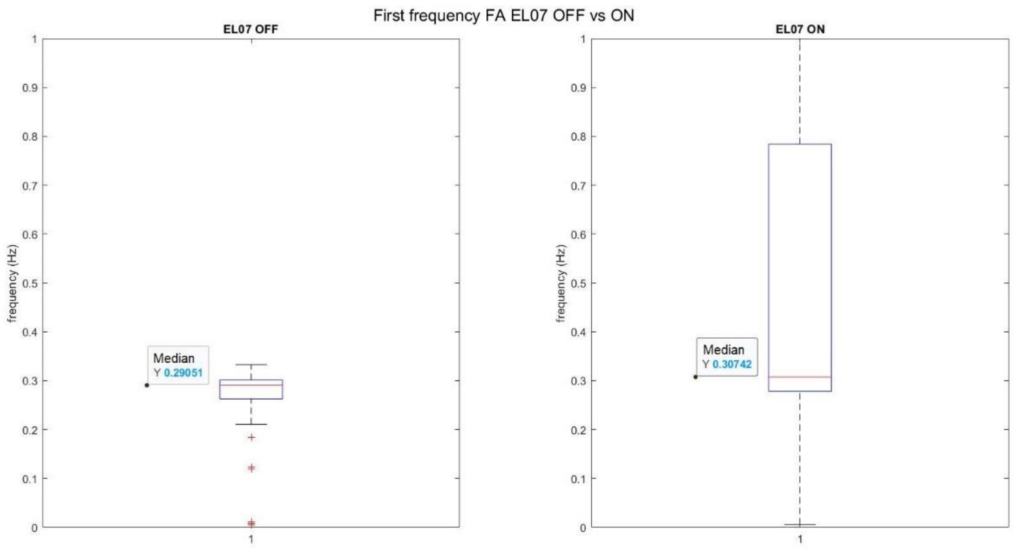

Figure 6.1 First natural frequency OFF vs ON

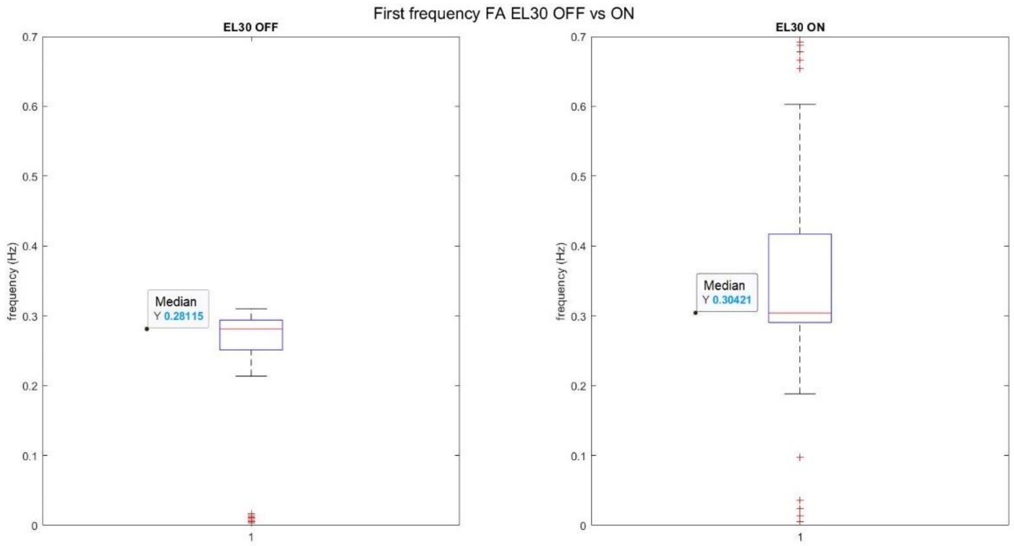

Figure 6.2 First natural frequency OFF vs ON EL30

After the estimation of the first natural frequency, the frequencies with good estimates were used in the compilation of corresponding mode shapes. For the majority of the estimations, the shapes corresponded with the expected shape for a first mode shape. Even though the shape corresponds, the mode shape does not necessarily fit one on one with the given reference design first mode shape (figure 6.8 and 6.9), because the identified corresponding natural frequency is not the exact design natural frequency and also for EL07 the conditions of the structure for example the foundation stiffness differ from the conditions of EL30.

To compare the results with the OFF situation, the mode shapes for EL07 in the idling condition are plotted together with the operational condition (figure 6.7), in relation to the elevation of the structure (above LAT).

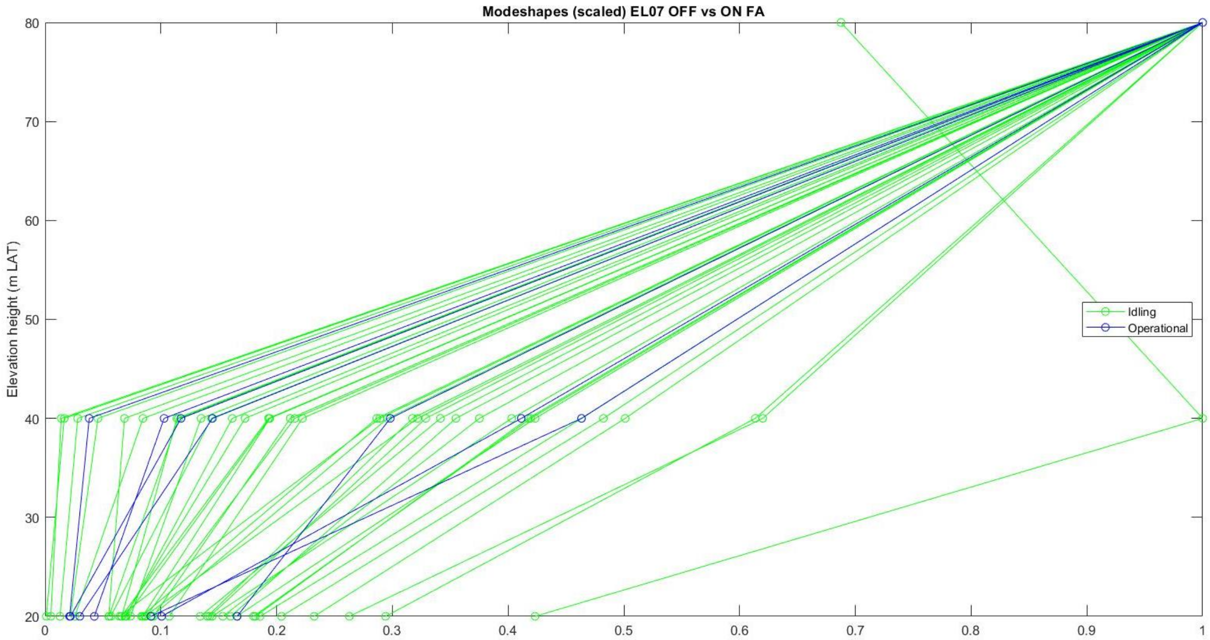

Figure 6.3 Mode shapes EL07 OFF vs ON

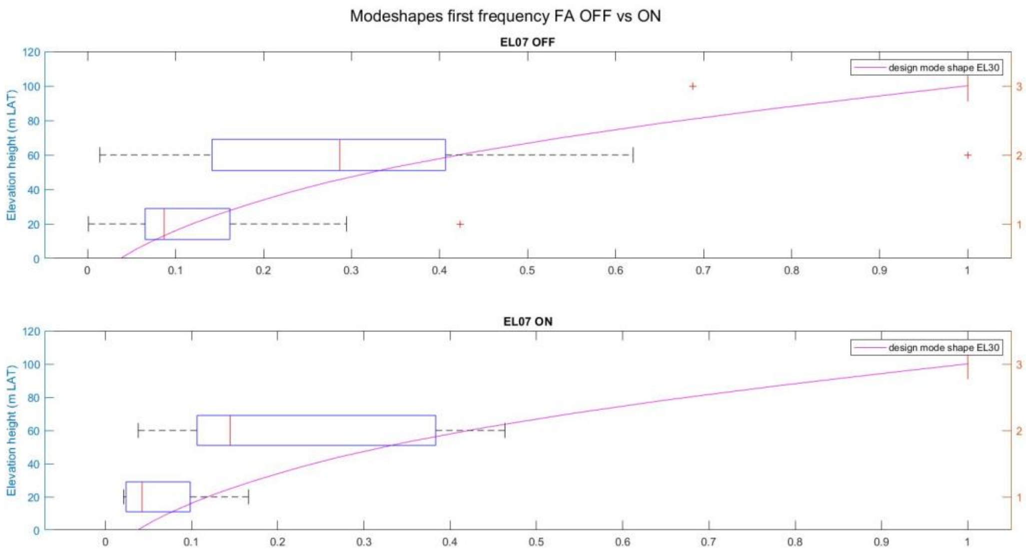

Figure 6.4 Mode shapes OFF vs ON EL07 (vs design)

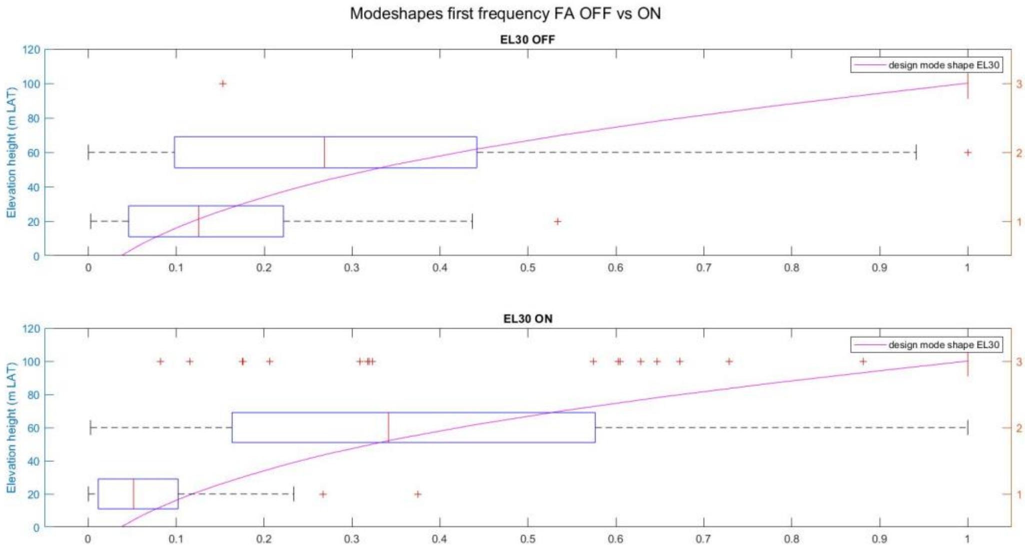

Figure 6.5 Mode shapes OFF vs ON EL30 (vs design)

The estimation of the modal damping ratio seems in the correct range for EL30 in idling conditions (figure 6.6). For EL07 in idling conditions and both the turbines in operational conditions the estimation of the modal damping is far from the expected value (figure 6.6 and 6.7).

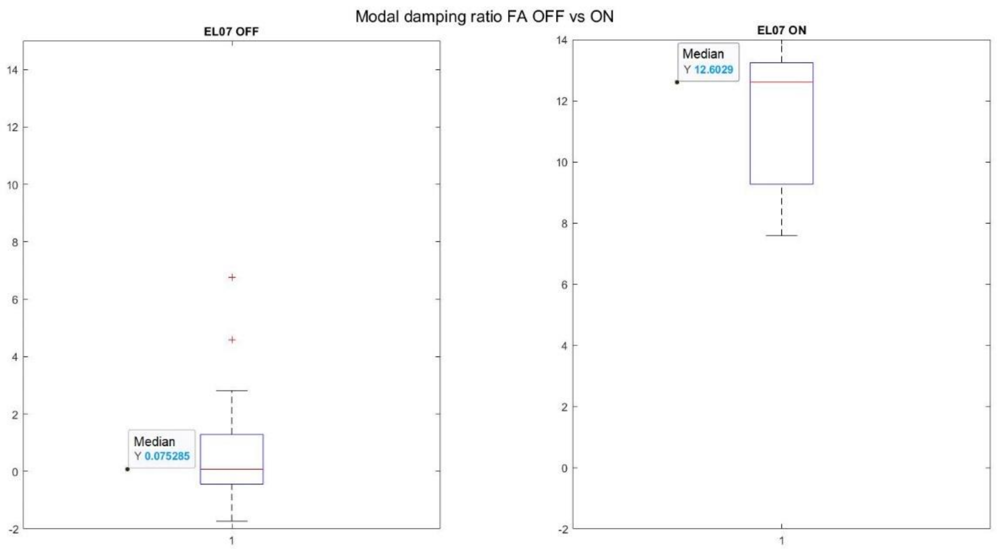

Figure 6.6 Modal damping ratio OFF vs ON EL07

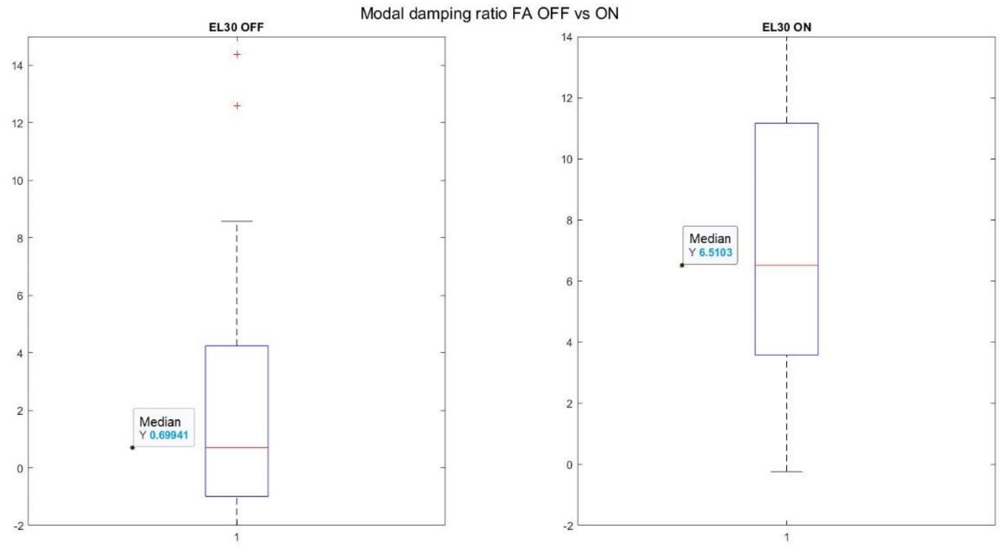

Figure 6.7 Modal damping ratio OFF vs ON EL30

The discussion on the results for the identification of the modal parameters for different variable environmental conditions and the discussion for the attempt to automate the ERA script in the identification for the modal parameters in the idling and fully operational conditions of the turbines, clarifies the applicability of the OMA algorithm ERA for operational offshore wind turbines. In both steps of the study the outcome for the natural frequency resulted in a positive outcome. In the visual part of the study, the frequencies in combining the results for both the FA and the SS direction, were good approximates in correspondence with the frequency response spectra of the measured acceleration data of the sensors. In the automatization attempt for the FA direction the estimates of the first natural frequencies were in the design range as included in the design documentation and did not differ much from the results obtained by the visual inspection.

In both parts of the analysis of the study, the mode shape for the first natural frequency did not always correspond with the expected shape for a first mode shape. Sometimes shapes for the second mode shape occurred. In the second part of the study, the identification of the mode shapes was improved, by removing the wrongly made estimates of the frequencies.

The modal damping ratio did not result in stable poles for the damping ratio in the first part of the study. The results differed much between the order 3 and 30 and it was not possible to estimate one specific damping ratio for the turbines. In the second part of the study, where one model order was chosen, the modal damping ratio was very high in the fully operational situations. This leads to say, that after analysis of both methods, there are no reliable modal damping ratios obtained.

7. Conclusions and Recommendation

Offshore wind turbine generators (WTGs) have support structures, typically monopiles, that are designed specifically for the WTG location based on wind, wave and soil data. During the operation of WTGs, the actual dynamical properties of the WTG can be compared to the design, with the goal to optimize WTG structures in future offshore farms. Typically, this is done using operational data obtained during standstill/idling conditions only (‘OFF’). This research explores the applicability of the Operational Modal Analysis (OMA) algorithm ERA (Eigensystem Realization Algorithm) in estimating the dynamical properties, the natural frequencies and the mode shapes for *operational* conditions of offshore wind turbines on monopile foundations (‘ON’). For this, a large amount of operational data from the Luchterduinen offshore wind park has been selected, reviewed, processed and analyzed.

7.1 Conclusions

The environmental conditions of relevance for this research are found to be the wind speed, the wind and wave direction, the peak frequency of the waves and wave height, and the water level. Tolerances must be specified in order to select similar/same environmental conditions for the operational states ON and OFF to allow a clear comparison of the performance of ERA for both situations. For operational conditions for wind turbines, the relevant operational region is State IV, full operation, where the rotor speed is nominal at 13.78 rpm. Given that the data used for selection are 10 min. averages, only datasets for wind speeds of 14-22 m/s were selected to ensure a ‘clean’ dataset.

The performance of the algorithm in MATLAB is confirmed using dynamic test cases, for which the accelerations were generated by using a Stabil Model. Before analyzing the selected data sample set as a whole, randomly chosen data samples are analyzed by producing stability diagrams and visual inspection. Poles for stable modes (frequencies) in the frequency spectrum of the data sample are identified, allowing model order selection for the whole data set in the automatization part of the study.

It is concluded that pre-processing and pre-analysis of the results is important to confirm the performance of ERA to correctly identify stable modes of support structures during the operation of offshore WTGs. In the visual analysis of ERA a combination of the analysis of both the fore-aft and the side-side directions leads to the possible identification of the first and the second frequency of the structures. The identification is confirmed to be best for the direction which is excited most by the environmental conditions. Visual inspection is however found not to be a practical method for analyzing the full data set. When applying ERA for operational data for OFF, the first natural frequencies and the first mode shape can be identified correctly after eliminating the wrong estimates. The identification of modal damping is however found to be a challenge: the results are spread over a wide range.

In the ON situation it is also concluded that the first natural frequency and also the first mode shape of the offshore wind turbines can be correctly identified for turbine EL07. It is noted that some pre-processing is required for this by terminating (clearly) wrong estimates of the frequencies. For the majority of the data samples analyzed for turbine EL07, the natural frequencies identified in the visual analysis closely correspond to the peaks in the frequency response. For EL30, the identification did not yield similar results and the reason for the differences is unclear. Visual analysis of results for the mode shapes and the modal damping showed similar observations. It is found that the first identified mode shape does not necessarily correspond to a first mode. For both EL07 and EL30, the modal damping ratios are inconclusive with a large scatter in the results and outside the expected range, while stable poles would have been be expected.

Overall, it is concluded that ERA can yield useful results in estimating the natural frequencies for both ON and OFF, provided that an automated analysis is combined with a visual analysis. Even then, the accuracy and the consistency of the identified frequencies is moderate. ERA does not perform well for estimating the mode shapes, yielding inaccurate and inconsistent results. Based on the results of this work, ERA, as it has been applied in this study, is found not to be capable of estimating modal damping ratios.

7.2 Recommendations

When comparing the results between OFF and ON states of the WTGs, it is concluded that ERA can estimate the first natural frequency and the first mode shape, but the modal damping ratio is more difficult during ON. It is recommended to further study the consistency of the mode shapes. Also, the impact of the misalignment of the wind and wave direction on the identification of the first natural frequency by ERA should be studied further.

The natural frequencies of EL07 identified in the visual analysis for ON correspond almost exactly with the peaks in the frequency response for the majority of the data samples. This is not the case for EL30. This difference should be studied further to determine the possible causes. It is recommended to focus in particular on the estimation of the frequency in relation to the frequency response.

It is noted that turbine EL07 has scour protection and EL30 does not. A comparison on the influence of scour protection, as planned, could not be made due to the lack of meaningful results for EL30. The results of this study may be used to explore potential differences and influences in the results between turbines with and without scour protection. Also, it is recommended to evaluate data samples of EL42 (which does not have scour protection either) and study if there are similarities in the behaviour response to EL30.

In this thesis situations were compared with each other, with similar environmental conditions, to validate the results. It is suggested to compare data samples of situations where the environmental conditions are not necessarily similar to each other and not necessarily in State IV and to further verify the results. With this analysis, the influences of the environmental conditions may be identified separately to better understand the observed differences in the results obtained in this research.

A general recommendation is the further study of the size of Hankel matrices for this application of ERA for a better defining of the correct size of the Hankel matrices. It is known from literature that this has a large impact on the results in general and it is expected this also holds for the application as explored in this thesis.

Furthermore, the estimation of the modal damping ratios needs more study. The source of the error in estimating the damping ratio shall be investigated. Specific attention should be given to rule out possible sources such as errors in the algorithm, violations of the assumptions and the impact of the environmental conditions.

Finally, it is noted that ERA is a rather basic OMA technique and the identification was found to be not optimal for all modal parameters. After establishing a better identification based on the recommendations above, it would be recommended to also apply a more advanced algorithm to estimate the dynamic parameters. For example, a modification of ERA with Natural Excitation Technique (NExT) or SSI or TOMA, may yield more accurate results and a higher consistency.

References

[1] G. Gasparis, A benchmark Study on Operational Modal Analysis System Identification Algorithms for Operating Offshore Wind Turbines

[2] E. Lourens, Course OE44055 Load Identification and Monitoring Structures

[3] R. Brincker, L. Zhang, P. Andersen, Modal Identification from Ambient Responses using Frequency Domain Decomposition, Proceedings of the International Modal Analysis Conference (IMAC) 18, 6 (2000)

[4] R. Brincker, C.E. Ventura, P. Andersen, Damping estimation by Frequency Domain Decomposition, Proceedings of IMAC 19: A Conference on Structural Dynamics 19, 6 (2001)

[5] P. Li, S.L.J. Hu, H.J. Li, Noise Issues of Modal Identification using Eigensystem Realization Algorithm, The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction, 9 (2011)

[6] J.N. Juang, H. Suzuki, An Eigensystem Realization Algorithm in Frequency Domain for Modal Parameter Identification, Astrodynamics conference, 6 (1986)

[7] R.S. Pappa, K.B. Elliot, A. Schenkt, Consistent – Mode Indicator for the Eigensystem Realization Algorithm, JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS Vol. 16, No. *5,* 7 (1993)

[8] P. Guillaume, C Devriendt, G de Sitter, Identification of modal parameters from Transmissibility Measurements, Journal of Sound and Vibration Vol 314, 7 (2008)

[9] Staatscourant, Nr. 20060, 11 april 2019

[10] J.N. Juang, R.S. Pappa, An Eigensystem Realization Algorithm for Modal Parameter Identification and Model Reduction, Journal of Guidance, Vol 8 No 5, 6 (1985)

[11] Wind power, https://en.wikipedia.org/wiki/Wind_power visited on 02082019

[12] C. Devriendt, P.J. Jordaens, G. de Sitter, P. Guillaume, Damping estimation of an Offshore Wind Turbine on a Monopile Foundation, IET Renewable Power Generation 7, 10 (2013)

[13] W. Weijtjens, R. Shirzadeh, G. de Sitter, C. Devriendt, Classifying resonant frequencies and damping values of an offshore wind turbine on a monopile

foundation for different operational conditions, Proceedings of EWEA, 9 (2014)

[14] G. Nieubourg, Y. van Ingelem, Eneco Luchterduinen integrity monitoring: As-built documentation, 03 November 2016

[15] System Identification, https://en.wikipedia.org/wiki/System_identification (14-06-2020)

[16] Operational Modal Analysis, https://en.wikipedia.org/wiki/Operational_Modal_Analysis

[17] K.J Keesman, System Identification An Introduction ISBN 978-0-85729-521-7

[18] R. Brincker, C. Ventura, Introduction to Operational Modal Analysis SBN 978-1-119-96315-8

[19] B. Peeters, G. de Roeck Reference based Stochastic Subspace Identification in Civil Engineering, Inverse problems in Engineering Vol 00, (28) 1999

[20] M.El-kafafy, P. Guillame, T. De Troyer, B. Peeters, A Frequency-Domain Maximum Likelihood Implementation using the modal model formulation, (1998)

[21] https://nl.mathworks.com/help/ident/gs/about-system-identification.html#:~:text=System%20identification%20is%20a%20methodology,Select%20a%20model%20structure. (visited on 20-06-2020)

[22] R.S. Pappa, Eigensystem Realization Algorithm User Guide for VAX/VMS computers

[23] Vestas 3MW brochure

[24] J.N. Juang, R.S. Pappa, Effects of Noise on Modal Parameters Identified by the Eigensystem Realization Algorithm, Journal of Guidance Vol 9 No 3, 14 (1986)

[25] L.H.P Middelweerd, Sensitivity analysis of the first natural frequency of the offshore wind turbines in the Eneco Luchterduinen wind farm

[26] M.G.L Ogno, Identifying structural parameters of an Offshore Wind Turbine using Operational Modal Analysis

[27] Offshore wind energy, https://www.government.nl/topics/renewable-energy/offshore-wind-energy (visited on 27-07-2020)

[28] ERA algorithm script, Ayad Al-Rumaithi, https://nl.mathworks.com/matlabcentral/fileexchange/69494-eigensystem-realization-algorithm-era

[29] S. de Zutter, J.D.M. de Kooning, A.E.Samani, J.Baetens, L. Vandevelde, Modeling of active yaw systems for small and medium wind turbines, 52nd International Universities Power Engineering Conference (UPEC), 6 (2017)