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Test planning and operational modal analysis of a wind turbine tower; application to its dynamic behavior

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ABSTRACT

Thorough knowledge of the wind turbine (WT) dynamics is necessary to efficiently improve its design, operation, and maintenance. Due to the wind turbine's large size, there are difficulties in measuring and excitation of full-scale WTs in general modal tests. Because of the issue, the designers may rely on finite elements and numerical models. Nevertheless, by considering the advantages of operational modal analysis relative to the experimental modal analysis, it is an efficient way to understand the dynamics behavior of WT based on the actual operation installed turbine at the site. With regard to performing operational modal analysis and achieving acceptable results, proper test planning has great importance. Initially,in this article, test planning steps will be described for the studied WT's successful operation modal test. Then the modal analysis results will be revealed, and finally, the dynamic behavior of the WT will be discussed based on the modal results.

1. Introduction

For wind turbine (WT) designers, providing economical and reliable WTs is the most significant challenge. However, a full knowing of WT dynamics behavior is needed to meet the requirements. In this regard, the use of operational modal analysis (OMA) as a tool to know the

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WT dynamics based on measured accelerations seems very useful. A wind turbine's practical design needs a precise finite element model or numerical models (i.e., updated model) that correctly show WT dynamic at all performance conditions. Moreover, a successful OMA of WT will closely depend on the quality of logged accelerations data, and it can be achieved by proper test planning.

Generally, there are two primary methods for modal testing industrial structures like WTs, experimental modal analysis (EMA) and OMA. Carne and James [1] and Osgood [2] compared OMA versus EMA of WTs and represent the advantage of OMA to WTs modal tests. The great advantage of the OMA method in application to WT generators is providing the structural dynamics under actual working conditions and real boundary states.

In the last decades, the extraction of modal parameters by experimenting has provided efficient tools for knowing and controlling vibrations, the optimized design, and the condition monitoring of WTs. Shirzadeh, Weijtjens, and Devriendt[3, 4] compared the results from simulations and the OMA test of an offshore WT. They then discussed the turbine's dynamics behavior. Weijtjens, Verbelena [5] analyzed several years of data on vibration levels monitoring at five offshore WTs and had revealed the dynamics behavior of the structures. Camargo and Ulfkjaer[6] investigated the dynamic behavior of a reinforced and post-tensioned concrete structure for applications in the WT towers by considering the obtained modal parameters from the OMA results. Also, since the vibration phenomena originate from the mode shapes, which are natural properties of the structure, exciting the structure at resonant frequencies yields large vibration amplitudes that can result in damage or discomfort. Modal parameters extraction and investigation about their changes can lead to finding out structural performance. Hu and Thöns [7] investigated the resonance of WTs.

Generally, there are two primary methods for modal testing of immense structures like WTs, EMA, and OMA.

WTs are designed for maximum electricity production and safety by the capability of adaptation of the WT structure to the changes. This ability makes WT more challenging to research the dynamic's behavior of structures. Some necessary prerequisites, such as time-invariant and steady-state random excitations, are not easily fulfilled for an operating WT. The violation of these assumptions causes deviations in the extracted modal parameters from OMA. Ozbek, Meng, and Rixen[8] discussed the most crucial challenges in operating modal analysis of WTs. Other studies were done by Lorenzo and Kosova [9] and Tcherniak and Chauhan [10] about the limits of OMA to operating WTs. To solve the problem, considering a careful test planning of the OMA is essential. Planning for accelerations data acquisition and modal analysis should be initiated as soon as possible. Several matters like test objectives, sensor placements, equipment, measurement duration, and FE analysis should be determined. Brincker[11] reviewed the effective test planning for a successful OMA.

The current paper is structured as follows: At first, the studied wind turbine's operational modal test planning, including test purposes, required measurement length, sensors location, finite element modeling, and another requirement, are presented. Then according to the test planning, OMA of the WT tower is performed. Next, the modal parameters will be identified using the state-of-the-art OMA. Finally, based on the extracted modal parameters from the test, the WT's dynamic behavior is discussed.

2. Test Planning

A successful OMA of the WT will closely depend on the quality of the accelerations data logged. So the critical step to get high-quality data from OMA test is test planning. Due to the enormous size of WTs, site location, and risk of working at wind farms, to facilitate the testing process and achieve acceptable results, it is necessary to do proper test planning before starting the operational modal test and data collection. The most critical activities that should take place in the test planning process are the test objectives, number, type of transducers and data logger device, transducers arrangement in the structure, the duration of each data set, sampling frequency, site visits, and necessary coordinating to operator and supply of some required materials.

In this section, test planning of the WT's OMA, which prevents the major causes of problems when conducting vibration tests, will be discussed.

2.1.Test objectives

Because of the time limitations of access to the large operating structures and their complexity and cost of testing, the early establishment of the test objectives is significant. Generally, in the objective test step, the minimum amount of information and useful additional operating system information or adequate resources need to be obtained.

In this study, the OMA aims to extract modal parameters of the WT tower first and second bending pair modes (Fore-Aft (FA) and Side-Side(SS)) installed in the WT research site. The test results were analyzed in two states: 1- An operating condition that rotor is rotating (OP), 2- Parked condition (PA), or idle state.

Also, as we need the WT operating data (like; rotor speed, pitch angle, yaw angle) to select the relevant data for OMA analyses, we should have access to the WT's SCADA† data.

Finally, according to the results obtained from the OMA analysis of logged data, the studied WT's dynamic behavior should be discussed.

2.2.Site visit and preparing the work requirement at the site

Before starting the OMA test procedure, visiting the installed structure at the site can give us many important details that lead to time-saving, good quality of data, and finally, achieving the best test results. Although photos and drawings provide a good view of the structure, a site visit can help prepare a good test plan and reduce the risk of unnecessary delays due to unforeseen circumstances. During a site inspection, the logistics of sensors and data logger placing, cable arrangement, HSE considerations, suitable test schedule, and required coordination should be considered.

In this study, the WT installed at a research site has been visited and inspected. The turbine has three blades, a magnetic generator, a medium speed gearbox, steel tower structure, as shown in Fig (1). The drawings matched to the existing turbine at the site, proper sensors and data logger placement, cables arrangement, required permits, and available operating information from SCADA had been checked and specified in advance.

footnote 1: Supervisory Control and Data Acquisition

In site visits, potential safety hazards that may be exposed to the test personnel should be considered.

2.3.Finite element modeling (FEM)

FEM helps a preliminary understanding of the system's primary modes' structural dynamics, natural frequencies, and mode shapes. So, FEM should be created before the modal test for test planning and specifying the requirements such as measurement duration, sampling frequency, sensor placement.

In this research, as shown in Fig (2), a 3D model of the WT tower was created in ANSYS environment. The FE model was created with changeable design parameters to improve the parameters in the required optimizing or updating process in the project's future stage. In this regard, the studied WT tower is divided into two main parts (because of simplicity in manufacturing and erection); the FE model is created in two pieces with different material properties parameters.

Fig 1: Studied wind turbine installed at the research site

Various types of ANSYS library finite elements were tested to achieve a better numerical result of the WT tower behavior, and finally, “shell 281” was selected. It was also used to model the ANSYS CERIG command, which creates a massless web of rigid bars. The masses of the nacelle, rotor hub, and blades are considered as point masses located at the top of the tower on the wind turbine's height.

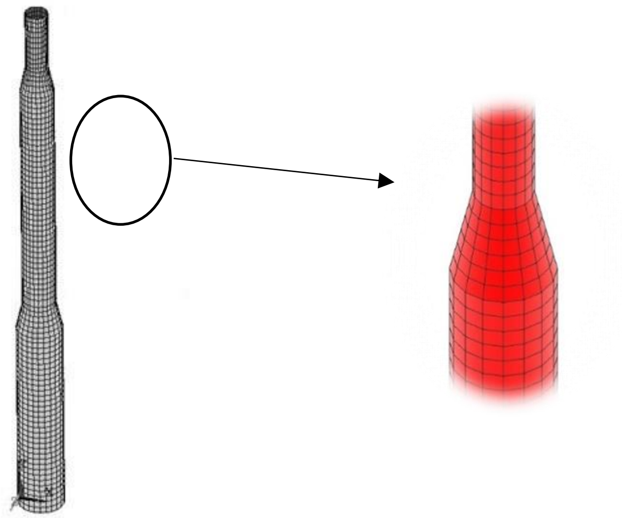

Fig 2. 3D FE model by ANSYS

To access the optimized mesh grid size, many of the mesh sizes were examined in the FE analysis, and the comparison showed that the first frequency has remained fixed approximately for a size smaller than 30 cm.

Based on the FE model and its modal analysis, the natural frequencies and their corresponding mode shapes of the WT tower were computed, and the results are shown in Table (1) and Fig (3).

Table. 1: Natural frequencies and their corresponding modes of the tower obtained from the FE analysis

Tower Bending mode	Natural Frequency (Hz)
1st tower bending mode(FA)	1.565
1st tower bending mode(SS)	1.568
2nd tower bending mode(FA)	9.57
2nd tower bending mode(SS)	9.59

1st tower bending mode(SS) 1st tower bending mode(FA) 2nd tower bending mode(SS) 2nd tower bending mode(FA)

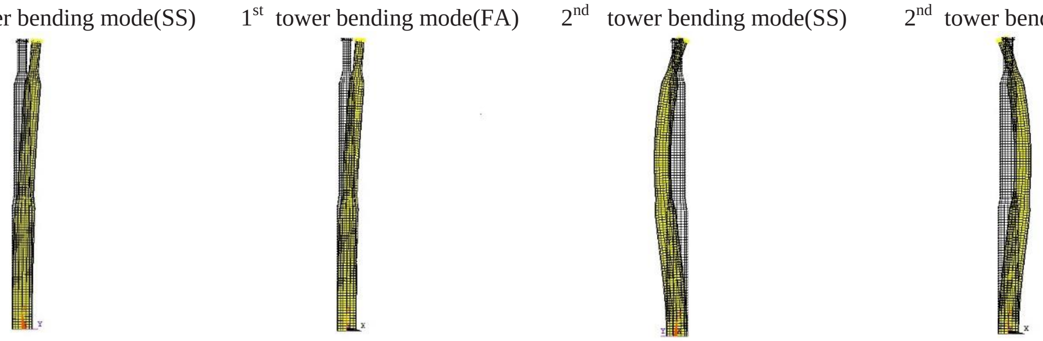

Fig 3. 1st and 2nd SS and FA tower bending mode shapes

2.4 .Time series duration

One of the most critical challenges in the OMA is the measurement length of each dataset. It is always desirable to measure the response of a structure throughout the complete range of specified excitation. So, to have an acceptable analysis, it is imperative to select a sufficient measurement time length to identify the system's lowest natural frequency. Brincker [11] proposed the total measurement time length (T_{tot}) by Eq. (1)

$$T_{tot} > \frac{20}{2\xi f_{min}} = \frac{10}{\xi f_{min}} \quad (1)$$

where f_{min} and ξ are the lowest natural frequency and structural damping, respectively.

Since the first natural frequency of a WT tower was estimated to be about 1.6 Hz based on the results of the initial FEM and a damping ratio of about 0.01, the minimum data collection time for analysis is as follows:

$$T_{tot} = \frac{1000}{1.6} = 625 \text{ s} = 10 \text{ min} \quad (2)$$

2.5. Sampling frequency

The sampling rate determines the upper bound of the frequency range that can be used for analyzing the logged signals. The sampling rate is the number of acquired samples per second and is commonly showed by "samples/second".

The sampling frequency should be twice the maximum standard frequency considered in the study. According to the Nyquist theory, the sampling frequency is because of antialiasing filters which use to prevent signal oversampling by minimizing noise interference in the measurement process. This means that the sampling rate must be chosen large enough such that all of the interest modes are properly detected from the recorded signals.

In practice, by considering the effect of typical antialiasing filters, Brincker [11] recommends the satisfactory sampling frequency by Eq (3):

$$f_s \geq 2.4 f_{max} \quad (3)$$

Since data gathered from the test was required for another study to recognize the higher frequency more than the last interesting mode in this study (2^{nd} tower bending mode), the sampling frequency of 100 Hz was chosen. Then for this study, it re-sampled to the frequency of 24.8 Hz.

2.6.Position of sensors (Sensor placement)

An essential issue in test planning is choosing the best location of the sensors and installing them according to the type and number of sensors available. Finding the installation location of the existing sensors is a kind of optimization problem.

One of the easiest ways to determine the installation location of sensors is using finite element modeling results by considering the interest modes on which the most optimal points are to identify the mode shapes required by the structure correctly. In addition to the results obtained from the software, it is necessary to finalize and determine the selected installation locations of the sensors based on the reality of the structure and accessible locations base on the site visit.

According to the number of available sensors, in this study, the six sensors selected to detect the first and second tower bending mode shapes (FA/SS) of the WT on its tower body, as shown in Fig (4). Also, two additional sensors (No. 3 and 4) were installed on top of the tower for further investigation.

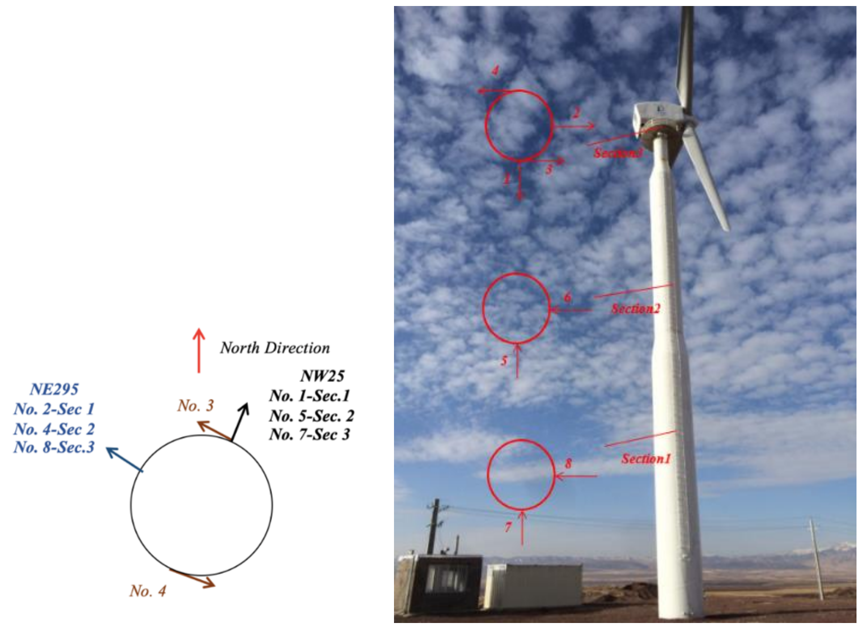

Fig 4. Sensor placement layout on the wind turbine tower

2.7.Test equipment

Leading required equipment to perform the test are: sensors, data logger, cables, laser meter, and sensors mounting bases.

In the test, the data logger with 8-channels and its software was used. MEMS accelerometer sensors have also been provided due to their high sensitivity and low-frequency signals measurement capability. Based on the modal frequency of interest and their expected magnitudes considerations, MEMS sensors ADXL320 are chosen as sensitive enough and have suitable range of measurement frequency. Accordingly, the data logger, with eight channels and its software are located at the bottom of the WT. Aim to collect the most quality signals, the sensors calibrated and equipped with the amplifier by considering the predicted length of cables.

3. Operational modal analysis results

3.1.Data preparation for OMA

After preparing and checking the accuracy of all requirements, operational modal test and data gathering have been started based on the test planning. During two days of the test, data are gathered for several hours while the wind turbine was at operating (OP) or parked (PA) conditions.

As is shown in [8,9,10], some essential assumptions of OMA are not fulfilled when the WT is in the operating state. Approaches to overcome the limitations were investigated by simulation and experimental analysis in[12]. One of the main assumptions of the modal analysis is the time invariance properties of the structure during a test. Indeed, a WT consists of several substructures which move relative to each other during the operation conditions:

the nacelle rotates about the tower axis due to the wind direction (yaw); the main rotor rotates about its axis (rotor speed); Moreover, the angle of the blades against the wind flow changes depending on the wind direction (pitch).

Therefore, any changes in yaw angle, rotor speed, and pitch angle may lead to violating the time invariance assumption.

To select the acceptable datasets that cover the time invariance assumptions, all available ten-minute datasets were checked in this test. Finally, limited acceptable datasets were chosen for OMA of the WT.

Also, the MEMS sensors mounted on the tower measure the tower vibration with respect to the ground (Inertial) coordinate system (GCS) and along its axes. However, because of the nacelle rotation about its axis, analyzing the two subsystems together should be done and it is necessary to describe them in the same coordinate system in advance. Thus, it is required to take into account the yaw angle.

Therefore, the raw data collected from the sensors located on the wind turbine tower were modified by the transformation matrix (Eq. (4)) according to the transmission principle in each dataset:

$$\begin{Bmatrix} x'(t,\theta) \\ y'(t,\theta) \end{Bmatrix} = \boldsymbol{R}(\theta)\begin{Bmatrix} x(t) \\ y(t) \end{Bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix}\begin{Bmatrix} x(t) \\ y(t) \end{Bmatrix} \tag{4}$$

Finally, this transformation leads to the projection of each dataset to a real FA/SS direction at its logged time.

3.2.Preliminary modal results

After preparing and screening the acceptable datasets in the previous section, these time histories were used in the software of structural vibration solutions' operational modal testing named "ARTeMIS" to extract modal parameters.

The data analyzed in this research were grouped into two different cases:

The first case referred to a state in which the WT is in parked or idling condition. The WT is parked with zero rotor speed and large constant values of the blade’s pitch angle. Therefore, in such situations, the wind turbine structure (tower), due to the more excellent resistance of the blades to the wind flow in the SS direction and the possibility of misalignment of the wind's rotor, the tower mainly vibrates in this direction. Fig. 5 presents a sample of a time series of this case.

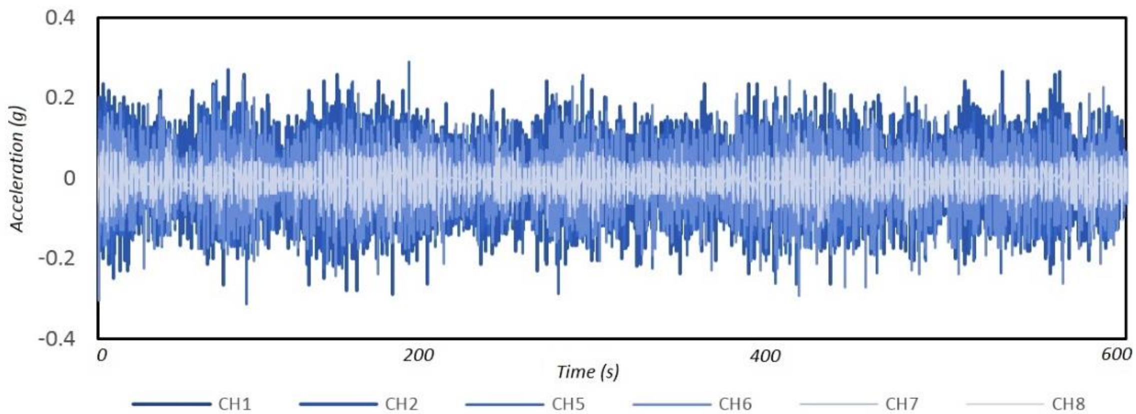

Fig. 5. Time series sample of the WT tower in a parked condition

Since, in this case, the WT blades are in the flag position and so perpendicular to the direction of the nacelle axis, the maximum opposition takes place in the lateral movement of the tower SS, and the minimum resistance is in FA.

In this case, the vibration level of the data recorded by the sensors in the upper sections of the turbine tower (dark blue line/ channel No.1 and 2) is higher than other sensors.

The power spectrum density diagram of the recorded signal in the parked wind turbine state is shown in Fig (6). By considering the FE analysis results, the peaks near the frequencies of 1.5 Hz and 9.5 Hz might be the first two tower bending modes, respectively. Also, the other present peaks in the diagram might be related to the main frequencies of foundations, measuring harmonics, the rotor blades, and noises that will be discussed later. As mentioned before, the objective of the test planning of this study is to find the tower first and second bending pair mode shapes of the WT tower.

The second case is referred to production periods that consist of time series of acceleration data during periods when the turbine rotor is rotating to the near of the rated speed. To some limitations of the power grid at the test period, the wind turbine's operation at rated speed was not available. The recorded dataset under this condition when the rotor is rotating with constant speed, the pitch angle is at minimum, and the nacelle axis is along the wind direction. So, under the operating condition of a wind turbine, the tower's primary vibrations occure in the FA direction.

By considering the achieved spectral density at operating conditions as shown in Fig (7), some peaks are visible around 1.5 Hz and 9 Hz, which may be correlated to the tower bending mode shapes. Also, the rotor harmonic (41 rpm) is shown in the diagram by dashed lines.

The preliminary investigation of data recorded mentioned above, but in the next section, the wind turbine's operational modal analysis will present.

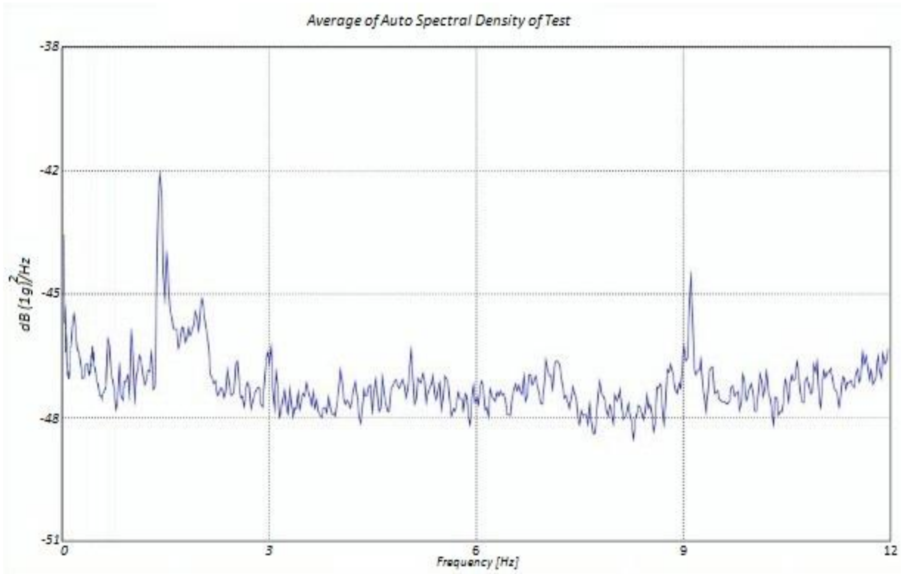

Fig. 6: Power spectrum density diagram of the parked wind turbine (PA)

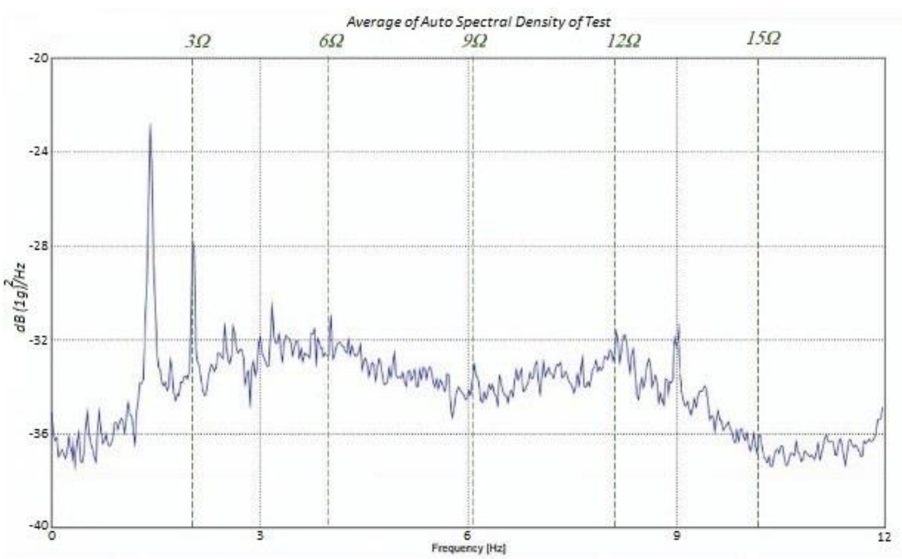

Fig. 7: Power spectrum density diagram of the operating wind turbine (OP)

3.3. Theory of operational modal analysis

The standard algorithms for extracting modal parameters in OMA is stochastic subspace identification (SSI). The SSI method in the time domain estimates the assumed time-invariant matrices of a linear dynamic model of a system. For a linear dynamics model of n degrees of freedom, the following dynamics differential equation can be written[13] [14-18]:

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(t)+\boldsymbol{C}\dot{\boldsymbol{u}}(t)+\boldsymbol{K}\boldsymbol{u}(t)=\boldsymbol{f}(t) \tag{5}$$

where $\boldsymbol{M},\boldsymbol{C},\boldsymbol{K}\in\mathbb{R}^{n\times n}$ are the Mass, Damping and Stiffness matrices of the structure, respectively. $\boldsymbol{f}(t)\in\mathbb{R}^{n}$ is the array of nodal forces, $\boldsymbol{u}(t)\in\mathbb{R}^{n}$ is the array of nodal displacements and t is the time parameter. Eq. (5) can be easily converted into a state space time-continuous form as followed:

$$\dot{\boldsymbol{q}}(t)=\boldsymbol{A}\boldsymbol{q}(t)+\boldsymbol{B}\boldsymbol{f}(t)$$

Where

$$\boldsymbol{q}(t)=\begin{Bmatrix}\boldsymbol{u}(t)\\ \dot{\boldsymbol{u}}(t)\end{Bmatrix},\ \boldsymbol{A}=\begin{bmatrix}\boldsymbol{0} & \boldsymbol{1}\\ -\boldsymbol{M}^{-1}\boldsymbol{K} & -\boldsymbol{M}^{-1}\boldsymbol{C}\end{bmatrix},\ \boldsymbol{B}=\begin{bmatrix}\boldsymbol{0}\\ \boldsymbol{M}^{-1}\end{bmatrix} \tag{6}$$

In a practical case of operational vibration monitoring, all degrees of freedom of the structure cannot be measured. Therefore, the observation equation as follows should be written :

$$\boldsymbol{y}(t)=\boldsymbol{C}_o\boldsymbol{q}(t)+\boldsymbol{D}_o\boldsymbol{f}(t) \tag{7}$$

where $\boldsymbol{y}(t)\in\mathbb{R}^{r\times 1}$ is the output array; r is the number of outputs; $\boldsymbol{C}_o\in\mathbb{R}^{r\times 2n}$ is the output matrix; $\boldsymbol{D}_o\in\mathbb{R}^{r\times n}$ is the direct transmission matrix. Description of this system is denoted by $\sum\left(\boldsymbol{A}_o,\boldsymbol{C}_o\right)$, if there exists a non-singular matrix $\boldsymbol{T}$ whose order is the same with the system matrix $\boldsymbol{A}_o$, and then one of the descriptions of this system is $\sum\left(\boldsymbol{T}^{-1}\boldsymbol{A}_o\boldsymbol{T},\boldsymbol{C}_o\boldsymbol{T}\right)$. After time discretization, the discrete state-space model of the mechanical structure is obtained as followed:

$$\begin{cases}\boldsymbol{q}_{k+1}=\boldsymbol{A}\boldsymbol{q}_k+\boldsymbol{B}\boldsymbol{f}_k\\ \boldsymbol{y}_k=\boldsymbol{C}_o\boldsymbol{q}_k+\boldsymbol{D}_o\boldsymbol{f}_k\end{cases} \tag{8}$$

where a zero-order hold assumption on the inputs $\boldsymbol{f}_k$, $\boldsymbol{A}=e^{A_o(\Delta t)}$, $\boldsymbol{B}=(\boldsymbol{A}-\boldsymbol{I})\boldsymbol{A}_o^{-1}\boldsymbol{B}_o$ and Δt is the discrete-time step.

On the measured outputs, there is some measurement noise that cannot be neglected. To cope with the problems of unmeasured inputs and measurement noise, Eq. (8) is changed into the following:

$$\begin{cases}\boldsymbol{q}_{k+1}=\boldsymbol{A}\boldsymbol{q}_k+\boldsymbol{\omega}_k\\ \boldsymbol{y}_k=\boldsymbol{C}_o\boldsymbol{q}_k+\boldsymbol{\tau}_k\end{cases} \tag{9}$$

where $\boldsymbol{\omega}_k = \boldsymbol{B}\boldsymbol{f}_k$, $\boldsymbol{\tau}_k = \boldsymbol{D}_o\boldsymbol{f}_k + \boldsymbol{\lambda}_{y,k}\mathbb{S}$ and $\boldsymbol{\lambda}_{y,k}$ is the output measurement noise. In Eq. (9), the stochastic terms $\boldsymbol{\omega}_k$ and $\boldsymbol{\tau}_k$ are unknown, but it is assumed that they have a discrete white noise nature with zero expected value (which is equivalent to assuming that $\boldsymbol{f}_k$ and $\boldsymbol{\lambda}_{y,k}$ have a discrete zero mean value white noise nature) and that they have covariance matrices as follows:

$$E\left[\begin{Bmatrix}\boldsymbol{\omega}_p \\ \boldsymbol{\tau}_p\end{Bmatrix}\begin{bmatrix}\boldsymbol{\omega}_p^T & \boldsymbol{\tau}_p^T\end{bmatrix}\right] = \begin{bmatrix}\boldsymbol{Q} & \boldsymbol{S} \\ \boldsymbol{S}^T & \boldsymbol{R}\end{bmatrix}\delta_{pq} \tag{10}$$

where $E[.]$ is the predicted value operator; δ_{pq} is the Kronecker delta.

3.4.OMA Results

Operational modal analysis of the dataset with SSI method was carried out in the ARTeMIS software environment. Accordingly, the stabilization diagrams under parked and operating conditions are presented in Fig. 8 and 9, respectively.

Unstable and noisy poles were removed from the stability diagrams to observe the results and stable poles. Several stable modes and frequencies were obtained from the SSI method analysis and revealed in Table (2) under two operating (OP) and parked (PA) conditions.

Table. 2: Stable modes of the wind turbine under PA and OP Cases.

Stable Modes		1	2	3	4	5	6	7	8	9	10
Frequency (Hz)	PA	1.471	1.495	1.954	2.033	3.541	4.454	5.866	5.934	9.023	9.116
	OP	1.418	1.422	2.05	4.321	6.105	8.213	-	-	8.958	9.041

Based on the above results, natural frequencies and damping ratios of the first and second tower bending pair mode shapes are summarized in Table (3).

Other values of the recognized stable modes obtained from modal analysis in parked and operational conditions may be due to the frequencies of other elements connected to the tower, such as rotor blades, rotation harmonics, excitation due to unbalances of rotor assemblies, generators, or foundation. Regarding the stable frequencies obtained from the analysis of operating (OP) wind turbine, the frequency values of 2.05 Hz, 4.321 Hz, 6.105 Hz, and 8.213 Hz seem to be related to the rotation frequencies 3Ω, 6Ω, 9Ω, and 12Ω, respectively (for rotor speed= 41 rpm).

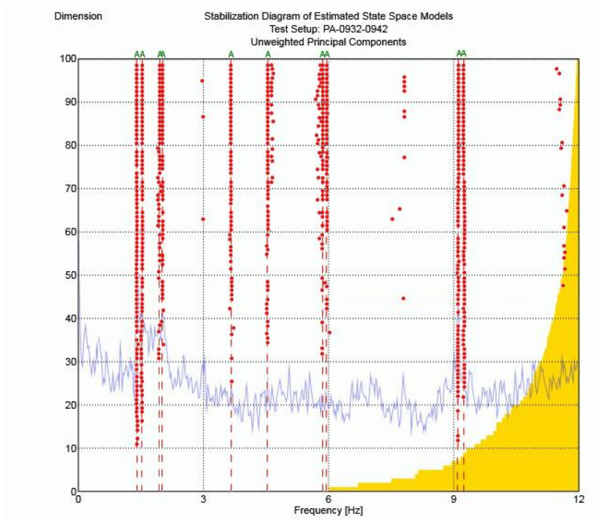

Fig. 8. Stabilization diagram of the wind turbine under the parked status

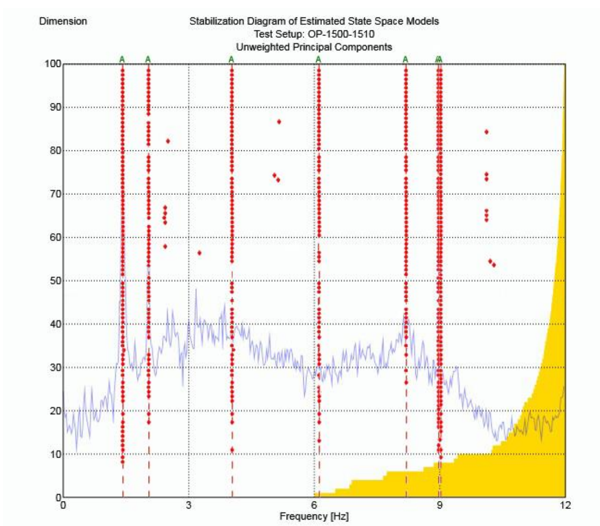

Fig. 9. Stabilization diagram of the wind turbine under the operating status

Table. 3: Frequency and damping ratio of wind turbine tower during the operating and parked state

Tower Bending mode shapes	Parked status		Operating status	
	Frequency (Hz)	Damping ratio (%)	Frequency (Hz)	Damping ratio (%)
First SS	1.471	3.74	1.418	1.543
First FA	1.495	1.352	1.422	8.266
Second FA	9.023	1.134	8.985	4.597
Second SS	9.116	1.416	9.031	2.193

Since, in this study, the sensors were installed only on the wind turbine tower, it is not possible to accurately identify the origin of the other stable modes.

The number of detected stable modes is less than the results in parked conditions in the operating condition. It may lead to the harmonics of rotor excitation and high noise level due to power transfer in these conditions.

4. Discussions

According to the results (Table 3), the first and second tower's bending pair mode shapes around 1.5 Hz and 9 Hz under the parked status stayed approximately constant in spite of operating conditions. So, changing the rotor speed and pitch angles does not change these bending modes. In comparison, the changes in the damping coefficient ratios obtained in these two cases are relatively significant. Also, the damping coefficients of the SS modes of the tower in case 1 (PA) are more than those for FA. Inversely, in case 2 (OP), the damping ratios are higher in direction FA compared to the ones in direction (SS).

In describing this matter, since the blade angle is maximum in case 1 (PA), the blade surface is perpendicular to the SS direction. While a high drag force is taking place in SS direction, SS's damping ratio will be higher than the ones in the FA direction.

On the other hand, in the operating wind turbine status (OP), the blade angle is close to zero, and more resistance occurs in FA direction. Therefore, the damping coefficient ratios in the wind turbine's operating mode in FA modes are more than SS ones. Generally, the damping ratios of the tower's bending mode shapes under the operational cases are higher than those for parked cases (especially for 1st FA mode). This behavior is due to the existing aerodynamics damping in the operation case. Aerodynamics damping has its origin in the wind load acting on the rotor or the interaction between the motion of the structure and the wind flow. Kuhn [15] was described aerodynamics damping and its effect on wind turbine performance.

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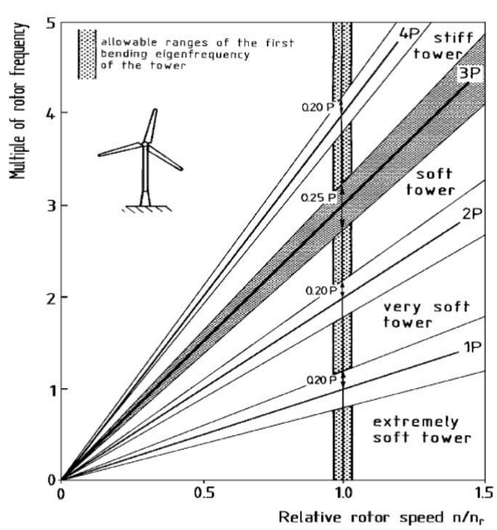

Fig. **10**. Campbell diagram of a wind turbine with a three-bladed rotor-tower stiffness design ranges[17] [

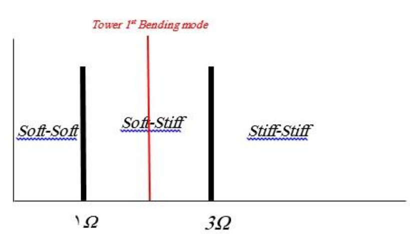

Fig.11: Tower design in point of view of stiffness

Generally, wind turbine vibrations are referred to as vibrations of rotor and tower assemblies. Complete dynamics analysis of tower and rotor turbine assemblies requires OMA of the wind turbine by installing sufficient sensors on its tower, nacelle, and blades by recording acceptable data in different rotor speed ranges.

In reason of the probability of correlating the rotor harmonic' frequencies with the tower's natural frequencies during the wind turbine's operation states, the rotor and tower assembly is always exposed to self-excitation. As a result, the position of the first natural bending frequency of the tower relative to the rotor harmonic excitation frequencies is an essential parameter in the wind turbine's design and operation from a dynamic behavior point of view.

Depending on how the position of the first bending frequency of the tower is chosen relative to the rotor's dominant excitation frequency, the wind turbine tower design is defined as "hard" or "soft."

For a better understanding of the subject, Fig.10 shows a sample of Campbell diagram of a wind turbine with a three-bladed rotor, specifying the range of a soft, very soft, and hard tower. Hau [16] described the tower stiffness design of wind turbine in detail.

According to the studied wind turbine's operational modal analysis, the first frequency of the tower bending mode is around 1.42 Hz. Also, the wind turbine's nominal rotor speed is 50 rpm that accordingly, its rotor harmonics are: 0.83 Hz (**1Ω**) 2.5 Hz (**3Ω**). Therefore, according to the following diagram (Fig. 11), this wind turbine tower is designed in the soft-hard range.

5. Conclusions

This study aimed to investigate the dynamics of the studied wind turbine installed at the research site by operational modal analysis of its tower. Operational modal analysis of wind turbine was carried out to obtain the first and second tower bending pair mode shapes modal parameters. Proper test planning before the operational modal analysis of large structures such as wind turbines will lead to ease of performance, adequacy of the collected data, and finally, achieving acceptable results. The most useful test planning steps are defining test objectives, site visiting, determining suitable sampling frequency and time length, FE modeling, sensor placement, and test equipment. After performing the test, selecting the best dataset by considering the time-invariance assumption is crucial to the operational modal analysis. In the research, the SSI method is used to analyze a widespread and useful method for operational modal analysis. According to the modal test result, first and second bending mode pairs frequencies and damping ratios in FA and SS directions, we can find out some critical dynamics behavior of the wind turbine. The results also showed that the wind turbine tower is designed in the soft-hard range. The modal results are beneficial for getting more knowledge about the structure and achieving the cost-effective design of wind turbine towers that finally lead to a sustainable system. Also, the modal results can be used for finite element model updating in future studies.

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References

[1] T.G. Carne, G.H. James III, The inception of OMA in the development of modal testing technology for wind turbines, Mechanical Systems and Signal Processing, 24 (2010) 1213-1226.
[2] R. Osgood, G. Bir, H. Mutha, B. Peeters, M. Luczak, G. Sablon, Full-scale modal wind turbine tests: comparing shaker excitation with wind excitation, in: Structural Dynamics and Renewable Energy, Volume 1, Springer, 2011, pp. 113-124.
[3] R. Shirzadeh, W. Weijtjens, P. Guillaume, C. Devriendt, The dynamics of an offshore wind turbine in parked conditions: a comparison between simulations and measurements, Wind Energy, 18 (2015) 1685-1702.
[4] R. Shirzadeh, C. Devriendt, M.A. Bidakhvidi, P. Guillaume, Experimental and computational damping estimation of an offshore wind turbine on a monopile foundation, Journal of Wind Engineering and Industrial Aerodynamics, 120 (2013) 96-106.
[5] W. Weijtjens, T. Verbelen, E. Capello, C. Devriendt, Vibration based structural health monitoring of the substructures of five offshore wind turbines, Procedia engineering, 199 (2017) 2294-2299.
[6] E.A. Camargo, J.P. Ulfkjaer, R. Brincker, J. Nøergaard, S.S. Gadegaard, Operational Modal Analysis and Finite-Element Model Updating of Pilot Concrete Wind Turbine Tower, Journal of Structural Engineering, 145 (2019) 05018003.
[7] W.-H. Hu, S. Thöns, R.G. Rohrmann, S. Said, W. Rücker, Vibration-based structural health monitoring of a wind turbine system. Part I: Resonance phenomenon, Engineering Structures, 89 (2015) 260-272.
[8] M. Ozbek, F. Meng, D.J. Rixen, Challenges in testing and monitoring the in-operation vibration characteristics of wind turbines, Mechanical Systems and Signal Processing, 41 (2013) 649-666.
[9] E. Di Lorenzo, G. Kosova, U. Musella, S. Manzato, B. Peeters, F. Marulo, W. Desmet, Structural Health Monitoring challenges on the 10-MW offshore wind turbine model, in: Journal of Physics: Conference Series, IOP Publishing, 2015, pp. 012081.
[10] D. Tcherniak, C. ., S., M.H. Hansen, Limits of Operational Modal Applicability Analysis to Operational Wind Turbines, in: Proc. 28th Int. Modal Analysis Conference (IMAC-XXVIII). 2010.
[11] R. Brincker, C. Ventura, Introduction to operational modal analysis, John Wiley & Sons, 2015.
[12] D. Tcherniak, S. Chauhan, M. Rossetti, I. Font, J. Basurko, O. Salgado, Output-only modal analysis on operating wind turbines: application to simulated data, in: Proceedings of European Wind Energy Conference, 2010, pp. 1-10.
[13] P. Van Overschee, B.L. De Moor, Subspace identification for linear systems: Theory—Implementation—Applications, Springer Science & Business Media, 2012.
[14] V. Boonyapinyo, T. Janesupasaeree, Data-driven stochastic subspace identification of flutter derivatives of bridge decks, Journal of Wind Engineering and Industrial Aerodynamics, 98 (2010) 784-799.
[15] T. Knudsen, Consistency analysis of subspace identification methods based on a linear regression approach, Automatica, 37 (2001) 81-89.
[16] M.J. Kuhn, Dynamics and Design Optimization of Offshore Wind Energy Conversion Systems, in: Delft University of Technology, 2001.
[17] E. Hau, H. von Renouard, The wind resource, Wind Turbines: Fundamentals, Technologies, Application, Economics, (2006) 451-483.
[18] G. Zhang, B. Tang, G. Tang, An improved stochastic subspace identification for operational modal analysis, Measurement, 45 (2012) 1246-1256.