Detailed point-by-point response to all referee comments

Title: Development of new strategies for optimized structural monitoring of wind farms: description of the experimental field

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Introduction

First of all, the authors would like to acknowledge the work of the reviewers, which raised very pertinent questions and suggested corrections that have contributed to significantly improve the quality of the paper.

In order to allow an easier re-review, all the introduced modifications are explained in this document and are highlighted in the revised manuscript.

Interactive Comment 1

Dmitri Tcherniak

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Table 1 - Comment 1: page 2, line 47

Comment from Referee	p.2, l.47: "a few number of easy to install sensors" - " a few number" does not read good.
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	“In the project a very extensive instrumentation will be deployed in order evaluate different monitoring layout alternatives, but the final goal it to propose a minimal optimized monitoring layout based on ***reduced number of sensors that can be easily installed***.”

Table 2 - Comment 2: page 4, line 68

Comment from Referee	p.4 l.68: the phrase "of variable height in section" is unclear same sentence; p.4 l.68: "boltedconnections" – mistype
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	“The hub is placed at a height of 95 m and is supported by a steel tower, ***with a hollow circular cross-section with variable diameter and thickness, composed of four segments that are linked on site with bolted connections***.”

Table 3 - Comment 3: page 4

Comment from Referee	p.4: Please check the consistency using a space between the value and the unit: "12m/s" but "20 m/s", also "100 m diameter rotor" but "height of 95m"
Author's response	In the revised document, it is now consistently used a space between the value and the unit.
Author's changes in manuscript	For example: 12 m/s, 95 m.

Table 4 - Comment 4: page 4, line 83

Comment from Referee	p.4, l.83: "since the main purpose is to simulate the dynamic behaviour of the tower". The main purpose of what? Of the entire project or of the numerical model? If the authors mean the entire project, it would be necessary to reflect this somewhere in the introduction.
Author's response	The main purpose of the numerical model is to simulate the dynamic behaviour of the tower.
Author's changes in manuscript	Section 3.1 was rewritten in the revised manuscript (see Table 9).

Table 5 - Comment 5: page 7, line 124

Comment from Referee	p.7, l.124 "the harmonic frequencies associated with to rotor operation" -> two rotor operations?
Author's response	The harmonic frequencies associated with the rotor operation ($\Omega, 3\Omega, 6\Omega, \ldots$).
Author's changes in manuscript	"The dashed vertical lines represent the harmonic frequencies associated with ***the*** rotor operation ***($\Omega, 3\Omega, 6\Omega, \ldots$)***."

Table 6 - Comment 6: page 7, figure 8a

Comment from Referee	p.7, fig.8a: It is hard to see if there are "blue" peaks behind the red ones for the 1st and 2nd tower modes
Author's response	There is a blue peak for the 1st tower mode, but for the 2nd one there isn´t. Under non-operating conditions, the peak pairs associated with the first two tower mode pairs clearly stand out. In operating conditions, additional peaks associated with the rotor rotation frequency appear. The peaks associated with the second pair of bending modes become much more diffuse, which makes their tracking over time quite challenging.
Author's changes in manuscript	Paragraph included in the revised manuscript: "For the first tower bending modes there are two very pronounced peaks for the two considered operating conditions. For the second pair of tower bending modes only in non-operating conditions there is a clear peak in ANPSD. In figure 11 this comparison will be addressed again"

Table 7 - Comment 7: page 8, line 150

Comment from Referee	p.8, l.150: what is a MEM accelerometer? Do you mean MEMS accelerometers?
Author's response	It is a typo that was repeated several times, we meant MEMS (micro electromechanical systems). This is corrected in the revised manuscript.
Author's changes in manuscript	"Two alternative systems to characterize accelerations at the tower: a commercial system based on a set of very low noise accelerometers and a customized low-cost system based on MEMS ***(micro electromechanical systems)*** accelerometers designed and assembled in FEUP (Moutinho and Cunha, 2019);"

Table 8 - Comment 8: page 16, figure 20

Comment from Referee	p.16, fig.20. What are the units of the vertical axes?
Author's response	These are normalized power spectra, so without units.
Author's changes in manuscript	No changes have be made in the revised manuscript.

Interactive Comment 2

Anonymous Referee #1

Received and published: 29 April 2020

Referee general comment:

> *"This paper presents the Tocha wind farm as well as the sensors installed and some initial results from those sensors. The paper is interesting, and it is useful to see the different types of results from different types of sensor. The purpose is as a precursor to future work, but I think the paper is interesting enough on its own merit. The paper is generally well structured and well put together, however I have several observations."*

Table 9 - Comment 1: page 4, section 3.1

Comment from Referee	Section 3.1 needs more detail on the simple model as results are presented later. Some more specifics on thing such as how elements are modelled, what boundary conditions are used and what assumptions are made would be useful.
Author's response	In order to better interpret the experimental results, a numerical model of the wind turbine was developed using ROBOT STRUCTURAL ANALYSIS software (Autodesk, 2016), following the technical drawings provided by the manufacturer. It is a simplified model, in which the operation of the turbine is not modelled. Rotational movement of the rotor and all control systems are disregarded, being the main purpose the simulation of the dynamic behaviour of the tower under the test conditions presented in the following section. It is considered that the foundation does not allow any kind of relative movements and is not considered the opening of the door (a specific numerical model for this detail has shown that it has a reduced influence on global behaviour). Thus, for the modelling of the tower was based on 3D bar elements to which the corresponding cross sections were assigned. Regarding blade modelling, at the time very detailed information was not available. Alternatively, starting from the NREL 5 MW reference wind turbine (Jonkman, Butterfield et al., 2009), the characteristics of the blades were scaled to be compatible with the wind turbine under study. The blades are modelled by 3D bar elements, divided into multiple sections to which the average mass, stiffness and inertia characteristics have been attributed. Since there is no rotation of the rotor, the blades were modelled with the pitch angle observed during the ambient vibration tests. The nacelle and hub are represented by concentrated loads applied at their centres of gravity. The connection between the tower, blades and the geometric centres of the nacelle and hub is modelled with rigid links of negligible mass. Autodesk: Robot Structural Analysis Professional (Version 29.0.05650(x64)), 2016. Jonkman, J., Butterfield, S., Musial, W., and Scott, G.: Definition of a 5-MW Reference Wind Turbine for Offshore System Development: National Renewable Energy Laboratory (NREL), 2009.
Author's changes in manuscript	Section 3.1 was rewritten in the revised manuscript based on the description presented above.

Table 10 - Comment 2: page 7, figure 8

Comment from Referee	It’s not clear how much data was used to construct the frequency tables in figure 8. Are these single observations of frequency or are they averages of multiple observations? It would also be good to know how much deviation is observed to give context to the level of difference between ’non-operational’ and ’operational’.
Author's response	The values of the natural frequencies presented in figure 8 were obtained from single observations (10 minutes time series of accelerations) under operating and non-operating conditions. In the experimental campaigns conducted for a first estimation of the modal properties, several 10 minutes setups were measured, but in this paper only the values of one of the observations are presented. The number of datasets collected during the described ambient vibration tests is not enough for a reliable statistical characterization The evaluation of the variation of the modal parameters of the structure within the various operating regimes is still being performed.
Author's changes in manuscript	Add line 93 of the revised manuscript: “***<u>Several 10 minutes of accelerations time series</u>*** were measured ***<u>(sample rate of 100 Hz)</u>*** with 4 standalone seismographs (Figure 5 a), with internal tri-axial force balance sensors, that were placed in the horizontal platforms of the tower (Figure 5 b). Figure 8 caption on revised manuscript corrected for: “Figure 8. Ambient Vibration test results for wind turbine 1 in operating and non-operating conditions: average power spectra and natural frequencies ***<u>(results obtained from 10 minutes single observation setups with very low variance of the environment and operational parameters)</u>***.”

Table 11 - Comment 3: page 7, line 129

Comment from Referee	Line 129: it’s mentioned that turbine 5 behaves ’differently’ to the other turbines. Although a difference can be seen in figure 9 it would be clearer for the reader to say in the text what this difference is.
Author's response	It is verified that wind turbine 5 presents a different dynamic behaviour due to the differences observed at the values of the natural frequencies of the first and second tower bending modes associated with the side-side direction (1SS lower than the others and 2SS higher than the others).
Author's changes in manuscript	“All of them present quite similar natural frequencies, but wind turbine 5 seams to present a slightly different behaviour, ***<u>expressed by the differences observed at the values of the natural frequencies of the first and second tower bending modes associated with the side-side direction (1SS lower than the others and 2SS higher than the others)</u>***.”

Table 12 - Comment 4: section 4.2

Comment from Referee	In section 4.2, I don't think it's ever mentioned what the sampling rate of any of the sensors are. Since a comparison is generally invited between the different sensors, such as that strain gauges can be used for an OMA purpose, it would be useful for the reader to know how comparable these sensors are regarding aspects such as the sampling rates.
Author's response	Samples rates of: • force-balance accelerometers = 20 Hz; • Strains and rotations tower monitoring systems = 50 Hz; • MEM accelerometers (blades and tower) = 62.5 Hz; • Blades strains monitoring system = 100 Hz Some of these sampling rates resulted from hardware constrains. For the application of OMA algorithms, a sampling rate of 20Hz is already quite conservative taking into account the natural frequencies of the most relevant modes.
Author's changes in manuscript	The sampling frequencies for each of the described monitoring systems have been added in the respective sections of the revised manuscript.

Table 13 - Comment 5: page 13, line 242

Comment from Referee	Line 242: It's mentioned that a model is conducted in FAST, also mentioned before in section 3.1, and the results are compared to the measurements. This is all moved on from too quickly. Why is a FAST model used? How important for that purpose is the difference from the measured results? Please give a bit more of the pertinent details on this and explain the aspects of this which might be of interest to the reader.
Author's response	The main goal of the WindFarmSHM research project is the development, validation and optimization of a monitoring strategy to be applied at the level of the wind farm, suitable to both bottom fixed and floating solutions, which should be able to evaluate the structural condition of wind turbines and their consumed fatigue life. Since there are still very few floating wind turbines in operation and due to the confidentiality associated with this very promising technology, during the course of the project it is unlikely to have access to real monitoring data. Therefore, the development and validation of the monitoring strategy to be proposed for this type of offshore wind turbines will be based on artificial experimental data generated by numerical models. Firstly, numerical models of the instrumented onshore wind turbine in Tocha Wind Farm, taking into account their aerodynamics, control systems and flexibility of structural elements, are being constructed and tuned to replicate the experimental data. Then, these will be converted to floating wind turbine models including the hydrodynamics effects. The numerical models to be developed will also be used to simulate damage scenarios for both bottom fixed (e.g. stiffness reduction in the tower-foundation connection) and floating wind turbine (e.g. damage of a mooring line) to validate the algorithms that will be proposed for damage detection.
Author's changes in manuscript	In Table 9, it is included a suggestion for an update on the text that introduces the FAST model. Since the construction of this model is out of scope of the present paper, the authors believe that it is not necessary to provide further details, the interested reader is referred to another paper on this specific topic (Pimenta, Branco et al., 2019).

Table 14 - Comment 6: page 2, figure 1

Comment from Referee	Figure 1 is good for expressing the process, but the bottom three rows are confusing, what do the bars to the right of ’Blades’, ’Tower’ and ’Foundation’ mean?
Author's response	The bars represent in a simplistic fashion the damage detection check for the structural elements (blades, tower and foundation) and the colour scale of the bar is related to the severity of the respective damage. The bars corresponding to the lifetime prediction are related to the fatigue assessment of the structural elements (blades and tower) and indicate the percentage of useful life consumed up to the moment of analysis.
Author's changes in manuscript	Figure caption corrected for: “Figure 1. Monitoring strategy. ***Meaning of the horizontal bars at the bottom: the colour bars represent in a simplistic fashion the structural health, the green/white bars represent the consumed fatigue life***.”

Table 15 - Comment 7: page 7, figure 9

Comment from Referee	Figure 9, it would help the reader to state in the caption that these measurements were from the non-operational condition.
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	Figure caption corrected for: “Figure 9. Comparison of the natural frequencies of four wind turbines ***in non-operational conditions*** (1st and 2nd pairs of bending modes).”

Table 16 - Comment 8: page 13, line 246

Comment from Referee	The description in the text of figure 17 (line 246) doesn’t quite match the figure. It seems the results for ’Force-balance accelerometers’ was added without updating the text.
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	“Figure 17 shows the average spectra of ***the six force-balance accelerometers (first row)***, 4 longitudinal deformations recorded by sensors A, B, C and D (***second*** row) and clinometer 3 (***third*** row), considering the rotor parked (left) and in operation (right).”

Table 17 - Comment 9: page 7, line 122

Comment from Referee	Line 122: please define the acronym ANPSD before using it.
Author's response	ANPSD: average normalized auto-spectral density function. This has been included in the revised manuscript.
Author's changes in manuscript	“Thus, Figure 8 compares ANPSD ***(average normalized auto-spectral density function)*** obtained for stopped rotor and in operation.”

Table 18 - Comment 10

Comment from Referee	A few minor typos and some grammatical errors throughout, though not too bad. Some examples: 1. I think you should capitalize ’Robot Structural Model’ (page 4, line 80); 2. Check grammar in line 86-87, page 4. 3. Table in Figure 7 (page 6): I think the second f_{exp} should be f_{model} 4. Please check the grammar in the sentence at line 144, page 8: “The main goal of the simple monitoring layout is to characterize the differences in the behaviour of wind turbines and to understand the interaction between neighbouring wind turbines.”
Author's response	These typos have been corrected in the revised manuscript. Furthermore, the revised manuscript has been carefully read and some other typos corrected.
Author's changes in manuscript	1. “In order to understand and interpret the experimental results, a numerical model of the wind turbine was developed using ***ROBOT STRUCTURAL ANALYSIS*** software (Autodesk, 2016), according to the technical drawings provided by the manufacturer.” 2. Section 3.1 was rewritten in the revised manuscript (see Table 9) 3. Second row: f_{model} $[Hz]$ 4. This sentence has been rewritten in the revised manuscript: “The simple monitoring layout has two main objectives: to characterize and identify differences in the dynamic behavior of wind turbines and to understand the interaction of the wake effects between nearby wind turbines.”

Interactive Comment 3

Lisa Ziegler (Referee)

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Referee general comment:

> *"The authors present their experimental field for structural monitoring of onshore wind turbines. They introduce sensor setups and first results on modal parameters. The topic has high relevance for the wind industry due to aging fleet of assets.*
>
> *The paper is cleary written, the content is sound and well presented.*
>
> *Introduction misses a review on state-of-art and existing literature. What is the research gap you wish to fill?*
>
> *Presented results are clearly, however, I miss novelty here. Furthermore, I wish there would be critical discussion in the paper. For example, interesting questions would be:*
>
> ** Why is the specific instrumentation chosen?*
>
> ** How are number and positions of sensors chosen, e.g. sensitivity study of desired results to sensor palcement?*
>
> ** How do you deal with measurement noise and varying operational conditions?*
>
> ** How do you clear and pre-process data?*
>
> *In addition the following is missing or must be adapted:*
>
> ** Results on the comparison between bending moments obtained from strain gauges and clinometers shall be presented.*
>
> ** A feedback from results of blade monitoring to tower monitoring. Can you now explain some more of the excitation frequencies?*
>
> ** Blade results are presented although the calibration is not completed. Please finish first the calibration, then present results.*
>
> *I do not understand why the results from FAST are presented. There are not enough details given to understand what was done in FAST, nor what it tells us. I suggest to either extend these results massively or to leave it out completely.*
>
> *To conclude, I believe the study in general is beneficial for the scientifc community. I expect the authors to use this as an initial paper with follow-ups with more technical content later on. Nevertheless, the authors shall add some novelty to this paper, such as suggested above, to justify a journal paper.."*

Author's response:

The authors acknowledge the very detailed analysis of the paper that contributed to the implementation of significant improvements in the revised manuscript.

The main goal of the paper is indeed to present for the first time in a journal paper the ongoing experimental campaign. The detailed data processing of each monitoring component is an ongoing work that will for sure lead to complementary publications.

The authors' feedback to more detailed comments are presented in the next tables.

Table 19 - Comment 1: page 1, abstract

Comment from Referee	Abstract misses an overview of (quantitative) results. What was achieved in the paper?
Author's response	We assumed as important goals of the paper the demonstration of the monitoring system good performance and the presentation of preliminary results, as stated in the last sentence of the abstract.
Author's changes in manuscript	The last sentence of the abstract was improved in order to include a more complete description of the results presented in the paper: "At this preliminary stage, the capabilities of the very extensive monitoring layout will be demonstrated. The results presented in paper demonstrate the ability of the different monitoring components to track the modal parameters of the system composed by tower and rotor and to characterize the internal loads at the tower base and blade roots."

Table 20 - Comment 2: page 2

Comment from Referee	A review of current state-of-the art is missing. What has already been published for structural monitoring for wind farms? Where is your research gap?
Author's response	The article is already quite extensive and for this reason it was decided not to include a very complete review of current state-of-the art. Still, the authors understand the concern of the reviewer and so, some new references were added in the revised manuscript. Weijtjens, W., Noppe, N., Verbelen, T., Iliopoulos, A., and Devriendt, C.: Offshore wind turbine foundation monitoring, extrapolating fatigue measurements from fleet leaders to the entire wind farm. Journal of Physics: Conference Series, 753(9), 1742-6596, 2016. Loraux, C. and Brühwiler, E.: The use of long term monitoring data for the extension of the service duration of existing wind turbine support structures. Journal of Physics: Conference Series, 753(7), 1742-6596, 2016. Weijtjens, W., Verbelen, T., Capello, E and Devriendt, C.: Vibration based structural health monitoring of the substructures of five offshore wind turbines. Procedia Engineering, 199, 2017. Considering the actual state-of-the art, our research is motivated by the need to optimize the monitoring systems for cost reduction, the need for an approach at the level of the wind farm, based on the instrumentation of only few wind turbines and the need to demonstrate the advantages of the proposed monitoring tools in the context of innovative floating wind turbines concepts.
Author's changes in manuscript	Line 33 on the revised manuscript was improved in order to include more complete information. "Considering this background ***and previous research (Weijtjens, Noppe et al., 2016, Lorax and Brühwiler, 2016, Weijtjens, Verbelen, et al. 2017)*** the main goal of the WindFarmSHM research project is the development, validation and optimization of new methodologies to continuously assess the structural elements of wind turbines: tower, blades and 35 foundation."

Table 21 - Comment 3: page 2, line 35

Comment from Referee	"adequate for onshore and offshore solutions" Onshore and floating? I somehow miss the transition. What about offshore bottom-fixed?
Author's response	The main goal is to develop and apply the algorithms developed to all types of wind farms (onshore, bottom-fixed and floating). In Portugal, there are more than 2500 onshore wind turbines in operation and a floating offshore wind farm that is currently under construction (WindFloat Atlantic). For these reasons, we intend to develop tools for onshore and floating in the first place.
Author's changes in manuscript	"The monitoring strategy is being designed to be applied in the context of a wind farm, adequate for onshore and floating solutions ***(the two types of foundation being used in Portugal),*** using optimized instrumentation layouts at a subgroup of wind turbines, and taking profit from the data provided by the acquisition systems already available in all wind turbines (SCADA), for the use of extrapolation techniques to assess all the wind turbines of the same wind farm (Figure 1)."

Table 22 - Comment 4: page 2, line 40

Comment from Referee	"artificial experimental data" There are no measurements on floating platforms, right? I believe "experimental data" might be misleading.
Author's response	Since there are still very few floating wind turbines in operation and due to the confidentiality associated with this very promising technology, during the course of the project it is unlikely to have access to real monitoring data. Therefore, the development and validation of the monitoring strategy to be proposed for this type of offshore wind turbines will be based on artificial experimental data generated by numerical models.
Author's changes in manuscript	"The research project will include three monitoring layouts of wind turbines of an onshore wind farm, comprehending accelerometers, strain gages and clinometers and the development of numerical models for the generation of ***virtual monitoring*** data to validate the monitoring strategy in floating wind turbines."

Table 23 - Comment 5: page 2, line 44

Comment from Referee	"detection of stiffness reductions motivated by the appearance of damage" What damages do you plan to detect here?
Author's response	As already performed in previous works, The experimentally identified natural frequencies will be modified with natural frequency shifts associated with the simulated damages, such as: • Scour problems at the foundation of an offshore monopile wind turbine; • Foundation problems in onshore wind turbines; • Blade damage; • Mooring line problems in floating wind turbines;
Author's changes in manuscript	"The data processing will be based on the continuous evaluation of the parameters that drive the structure dynamic behaviour (vibration frequencies and damping) estimated from the structure response to ambient excitation (wind, waves, currents, soil vibrations) and advanced statistical modelling, having in mind two main goals: detection of stiffness reductions motivated by the appearance of damage ***(as performed in (Oliveira, Magalhães, et al. 2018))*** and evaluation of the remaining fatigue life of the main structural components (Figure 1)." Oliveira, G., Magalhães, F. Cunha, A. and Caetano, E.: Vibration based damage detection in a wind turbine using one year of data. Structural Control and Health Monitoring, 25, 11, 2018. [https://doi.org/10.1002/stc.2238].

Table 24 - Comment 6: page 2, line 45

Comment from Referee	"remaining fatigue life" How do you plan to calculate the remaining fatigue life? Do you have all design information needed for this?
Author's response	We are developing algorithms for data processing that should permit the evaluation of the remaining fatigue life of the main structural components based on the direct measurement of the curvatures with strain gages, curvature measurements using pairs of clinometers and accelerations to support the application of a virtual sensors approach. We have the necessary details for the tower and blades, but this is an ongoing research that it out of scope of the present paper
Author's changes in manuscript	No changes have been made in the revised manuscript.

Table 25 - Comment 7: page 2, line 47

Comment from Referee	"it"
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	"In the project a very extensive instrumentation is being deployed in order evaluate different monitoring layout alternatives, but the final goal ***is*** to propose a minimal optimized monitoring layout based on a few number of easy to install sensors."

Table 26 - Comment 8: page 2, figure 1

Comment from Referee	Very nice figure, gives a good overview. "Damage" Detection (spelling)
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	"Damage Detection"

Table 27 - Comment 9: page 3, line 56

Comment from Referee	Would be nice to see a drawing or picture of this, if available.
Author's response	Due to confidentiality agreements, we are not allowed to present constructive details of the wind turbines.
Author's changes in manuscript	No changes have been made in the revised manuscript.

Table 28 - Comment 10: page 4, line 68

Comment from Referee	"boltedconnections"
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	"The hub is placed at a height of 95 m and is supported by a steel tower, ***with a hollow circular cross-section with variable diameter and thickness, composed of four segments that are connected by bolted connections***."

Table 29 - Comment 11: page 4, line 86

Comment from Referee	"has also important" What does this mean? Do you use the modal parameters to tune the FAST model?
Author's response	We used in the FAST model the mode shapes of the tower and blades obtained with the finite element model and also the rotational stiffness of the tower foundation. The procedure is explained the reference (Pimenta, Branco et al., 2019).
Author's changes in manuscript	In the revised manuscript the last paragraph of section 3.1 was rephrased: "Still, it's important to note that more advanced models are currently being developed in FAST (Sprague, Jonkman et al., 2015) using some structural information that was derived from the previously described model. All the details of the FAST model are presented in (Pimenta, Branco et al., 2019)."

Table 30 - Comment 12: page 5, line 90

Comment from Referee	"divide into"
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	"The set of ambient vibration tests was ***divided into*** two campaign."

Table 31 - Comment 13: page 5, figure 5

Comment from Referee	Nice presentation of setup. However, some important technical details pn the measurement concept are missing: How long did you measure? What resolution? Did you monitor SCADA time-synchronized?
Author's response	In the experimental campaigns conducted for a first estimation of the modal properties, several 10 minutes time series of accelerations under operating and non-operating conditions were measured (sample rate: 100 Hz). In this study, the owner of the wind farm provides SCADA data with two types of sample: records the mean, maximum and minimum value from 10 min period (SCADA 10min) and data with a sampling interval of 15 sec (SCADA high resolution). Some further details were included in the revised manuscript.
Author's changes in manuscript	Add line 93 of the revised manuscript: "***Several 10 minutes of accelerations time series*** were measured ***(sample rate of 100 Hz)*** with 4 standalone seismographs (Figure 5 a), with internal tri-axial force balance sensors, that were placed in the horizontal platforms of the tower (Figure 5 b). Add line 100 of the revised manuscript: "***The owner of the wind farm provides SCADA data with the mean, maximum and minimum value from 10 minutes period, important information for the accelerations processing***"

Table 32 - Comment 14: page 5, line 107

Comment from Referee	"Among the various peaks identified are two that clearly stand out: one near 0.25 Hz and another near 1.80 Hz." Why do these stand out? What is the difference to other frequencies with stable poles and good MAC, e.g. around 2.2 Hz or 4.5 Hz?
Author's response	The peaks around 0.25 Hz and 1.80 Hz have high values of the average power spectra for both main directions (FA and SS). As opposition to the power spectra, in the stabilization diagram we cannot identify the energy that is associated with each alignment of stable poles. The referred stable poles have less energy in the tower response, so they are probably associated with rotor modes. The numerical model also helped in the selection of the frequencies that are associated with tower modes.
Author's changes in manuscript	In the revised manuscript the line 107 was rephrased: "Among the various peaks identified, there are two that clearly stand out in the presented ANPSD (higher amplitudes): one near 0.25 Hz and another near 1.80 Hz."

Table 33 - Comment 15: page 5, line 108

Comment from Referee	"These peaks correspond to the first and second pairs of tower bending modes." How do you confirm this?
Author's response	Comparing the experimental results with the numerical ones in the figure 7.
Author's changes in manuscript	"***<u>Comparing the experimental results with numerical ones (figure 7), it is confirmed that</u>*** these peaks correspond to the first and second pairs of tower bending modes."

Table 34 - Comment 16: page 6, figure 6

Comment from Referee	Please improve the caption and layout. Use a/b/c/d or top left/ right, bottom, ..., to indicate what we see where. Why are in the top right figure 3 red boxed but only two zooms below? (explanation in the caption needed)
Author's response	For the first two red boxes the two vertical alignments (FA and SS) of the poles in the stabilization diagrams are very close and barely noticeable in the figure top right. The two alignments for the third box are clearly visible in the top right figure, so there was no need to present a zoom In the revised manuscript the figure caption was changed considering your suggestions.
Author's changes in manuscript	Figure 6 caption: "Figure 6. Ambient Vibration test results for wind turbine 1: ***<u>a)</u>*** average power spectra for FA and SS directions; ***<u>b)</u>*** stabilization diagram produced by the SSI-COV method; ***<u>c)</u>*** two zooms of this diagram ***<u>for first (left) and second (right) pairs of tower bending modes</u>***."

Table 35 - Comment 17: page 6, figure 7

Comment from Referee	2x fexp?
Author's response	"fmodel" on second row.
Author's changes in manuscript	f_{model}

Table 36 - Comment 18: page 7, line 124

Comment from Referee	"harmonic frequencies" To which rotor speed correspond these harmonics? Is the wind turbine already at rated speed at 10m/s? How much variance did you have in the rotor speed during your test campaign?
Author's response	These harmonics correspond to (data in the table below the figure on the left) : - rotor speed = 14.9 rpm; - wind speed = 11.3 m/s; For these results we selected a 10 minutes time series of accelerations with very low variance of the environment an operational parameters.
Author's changes in manuscript	"The dashed vertical lines represent the harmonic frequencies associated with to rotor operation. The results obtained in terms of natural frequencies (f) are also compared for the identified vibration modes for the two analysed situations ***<u>(environment and operational parameters shown at the table on bottom left)</u>***." Figure 8 caption on revised manuscript corrected for: "Figure 8. Ambient Vibration test results for wind turbine 1 in operating and non-operating conditions: average power spectra and natural frequencies ***<u>(results obtained from 10 minutes single observations setups with very low variance of the environment and operational parameters)</u>***."

Table 37 - Comment 19: page 7, figure 8 (left)

Comment from Referee	Do I see it correctly that the first fnat is almost identical to 1P? Typically, this shall be avoided in design (resonance, high loads). Are you sure about these results?
Author's response	Although the first natural frequency is very close to the first harmonic (for the particular operating conditions associated with the presented plot), these frequencies are far enough apart. The control mechanisms of the wind turbine prevent these two frequencies from being too close.
Author's changes in manuscript	We prefer to not included any comment on this, because it is a sensitive topic for the wind turbine manufacture

Table 38 - Comment 20: page 7, figure 8 (right)

Comment from Referee	How do you explain the difference in frequencies between operation and non-operation?
Author's response	It is easily understood that the modal parameters of the wind turbine change due to different environmental and operational conditions, this is described for instance in reference (Oliveira, 2018). The evaluation of the variation of the modal parameters of the structure between within the various operating regimes is still being performed.
Author's changes in manuscript	No changes have been made in the revised manuscript.

Table 39 - Comment 21: page 6, figure 7

Comment from Referee	"present a slightly different behaviour" Do you know where this comes from? Are tower and foundation properties identical?
Author's response	All wind turbines have the same physical and geometrical characteristics, so in theory they should have a similar dynamic behaviour. The different dynamic behaviour of turbine 5 might be explained by the fact that it is subject to important wake effects, but this a topic that deserves further studies.
Author's changes in manuscript	Since we do not have definite justification for the observed differences, we prefer not to include comments on this in the revised manuscript.

Table 40 - Comment 22: page 8, line 135

Comment from Referee	"dynamic behavior of all generators" Misleading formulation. You are not interested in the dynamics of the generator in the drive train.
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	"In order to obtain data representative of the dynamic behavior of all ***<u>wind turbines</u>*** and based on the results of the ambient vibration tests described above, the experimental campaign includes the following three instrumentation layouts:"

Table 41 - Comment 23: page 8, line 137

Comment from Referee	"very complete" Extended?
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	"An ***<u>extended</u>*** monitoring layout installed on wind turbine 1;"

Table 42 - Comment 24: page 8, line 140

Comment from Referee	"Based on the wind conditions of the site (Figure 3) and the position of each wind turbine in the wind farm (Figure 2) wind turbine 5 is the wind turbine where higher turbulence is expected because it is in the wake of the other wind turbines, while wind turbine 1 is exposed to less disturbed winds." Repetition
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	See Table 43.

Table 43 - Comment 25: page 8, line 142

Comment from Referee	"For this reason, wind turbine 1 was instrumented according to the complete layout, while the intermediate layout was applied in wind turbine 5." Why this? Is it not even more interesting to completely instrument a turbine which sees both: free stream and wake conditions? In order to extrapolate results it should be beneficial if as many conditions as possible are represented in the dataset.
Author's response	In fact depending on the wind direction all the wind turbines of the farm are subjected to free stream and wake conditions. Considering the predominant wind direction WT 5 is more frequently affected by wakes.
Author's changes in manuscript	In the revised manuscript the paragraph of the line 140 was rephrased: "The distribution of the alternative monitoring layouts in the wind turbines of the farm was conditioned by the available time slot for installation of equipment (usually scheduled during other maintenance operations) and our will to instrument the rotor of one wind turbine that for the predominance wind direction (north) is loaded by an unperturbed flow and another one the is influenced by the wakes of the other turbines (see Figure 2 and 3)."

Table 44 - Comment 26: page 8, line 162

Comment from Referee	"SCADA system" What resolution? Do you use 10-min statistics or 1Hz data of SCADA?
Author's response	In this study, the owner of the wind farm provides SCADA data with two types of sample: - SCADA records the mean, maximum and minimum value from 10 min period (SCADA 10min); - SCADA data with a sampling interval of 15 sec (SCADA high resolution).
Author's changes in manuscript	Add line 162: "It should be noted that data on the environmental and operational conditions of each wind turbine is being obtained through the SCADA system ***<u>(10 minutes averages and sampled at 15 seconds)</u>***."

Table 45 - Comment 27: page 9, line 174

Comment from Referee	How do you choose the placement of the accelerometers? Why 6 pieces?
Author's response	These 3 sections coincide with the height of the technical platforms, in order to facilitate the installation and maintenance of the sensors. Instrumentation of three sections of the tower along two orthogonal horizontal directions (unidirectional accelerometers).
Author's changes in manuscript	Line 173: "As depicted in Figure 10, this involved the instrumentation of 3 sections of the tower along two orthogonal horizontal directions. ***<u>These 3 sections coincide with the height of the technical platforms, in order to facilitate the installation and maintenance of the monitoring equipment.</u>***" Line 172: "In order to obtain the best possible characterization of the tower accelerations a commercial system based on 6 force-balance ***<u>unidirectional</u>*** accelerometers connected to a 24bits acquisition system was deployed."

Table 46 - Comment 28: page 8, line 179

Comment from Referee	"MEM based system" What resolution do you measure?
Author's response	Samples rates of: • force-balance accelerometers = 20 Hz; • Strains and rotations tower monitoring systems = 50 Hz; • MEM accelerometers (blades and tower) = 62.5 Hz; • Blades strains monitoring system = 100 Hz Some of these sampling rates resulted from hardware constrains. For the application of OMA algorithms, a sampling rate of 20Hz is already quite conservative taking into account the natural frequencies of the most relevant modes.
Author's changes in manuscript	The sampling frequencies for each of the described monitoring systems will be added in the respective section.

Table 47 - Comment 29: page 11, line 204

Comment from Referee	"on important"
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	"These monitoring components are essential for fatigue assessment of the tower and ***<u>one</u>*** important goal is the evaluation of two alternatives for estimating static and dynamic bending moment diagrams along the tower"

Table 48 - Comment 30: page 11, line 205 and page 13, line 251

Comment from Referee	"extensions measurements" and "extensions" What is this? Strain measurements?
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	"…using ***<u>strain</u>*** and rotation measurements, combined with accelerometers." "…so measuring ***<u>strains</u>*** can be very useful in distinguishing tower modes from the rotor modes observed in the tower.

Table 49 - Comment 31: page 11, line 216

Comment from Referee	How do you measure bending moments from the clinometers?
Author's response	By measuring the rotation in two sections of the tower $(rot_A \; and \; rot_B)$ it is possible to determine the curvature of the middle section(y''_{AB}). $$y''_{AB} = \frac{rot_A - rot_B}{length\;\overline{AB}}$$ $$Bending\;Moments = E * I * y''_{AB}$$ $E{:}\,Young\;modulus\;of\;the\;steel\;of\;the\;tower$ $I{:}\,Second\;moment\;of\;inertia\;of\;the\;middle\;cross\;section\;AB$
Author's changes in manuscript	No changes have be made in the revised manuscript.

Table 50 - Comment 32: page 12, figure 14

Comment from Referee	This strain gauge seems quite close to a welded joint. Have you checked that yours are out of range of stress concentration due to the weld?
Author's response	The monitoring project was prepared according to code IEC 61400-13. There is no influence of welding on measurements.
Author's changes in manuscript	No changes have be made in the revised manuscript.

Table 51 - Comment 33: page 13, line 239

Comment from Referee	Can you please present the bending moments you obtain with the SGs in comparison to the clinometers?
Author's response	The results obtained with the clinometers still need further calibration. In theory equivalent values should be obtained, but we are observing some differences that triggered further studies.
Author's changes in manuscript	No changes have be made in the revised manuscript.

Table 52 - Comment 34: page 13, figure 16

Comment from Referee	Where do the differences between FAST and the measurements come from? Do you use data from the met mast to calibrate the inflow in field? I am not sure what this comparison shall tell us. That the FAST results show some similarities in the time series on one side, are quite different on the other side? E.g. Side-side moments are considerably different in the left figure (much larger amplitudes in measurements).
Author's response	The goal of the plot is to provide a qualitative comparison. The inflow is different, we just generated a wind with the same average speed and turbulence. More extensive comparisons between numerical and experimental results are being performed.
Author's changes in manuscript	In the revised manuscript the line 242 was rephrased: "The experimental results are compared with numerical ones, obtained from a model developed on FAST and calibrated using the methodology described in (Pimenta, Branco et al., 2019). Please note this is just a qualitative comparison, the inflows in the experiment and numerical model are difference, only the average wind speed and turbulence intensity are the same."

Table 53 - Comment 35: page 13, figure 16

Comment from Referee	FAST (capital letters)
Author's response	This has benn corrected in the revised manuscript.
Author's changes in manuscript	FAST

Table 54 - Comment 36: page 13, line 251

Comment from Referee	"more pronounced and clearer" Why is this the case?
Author's response	In the average spectra of longitudinal strains gauge, the peaks motivated by the tower bending modes are clearer than in the spectrum obtained from accelerations. The tower strains measurements are also less influenced by the rotor modes.
Author's changes in manuscript	No changes have been made in the revised manuscript.

Table 55 - Comment 37: page 16, figure 20

Comment from Referee	How can you feedback this to the tower monitoring? Can you now explain more of the excitation frequencies you see in the tower?
Author's response	Indeed one of the goals of this monitoring component is a more deep understanding of the tower measurement. However, this is still ongoing research.
Author's changes in manuscript	No changes have been made in the revised manuscript.

Table 56 - Comment 38: page 17, line 303

Comment from Referee	I believe that these results shall not be presented if they are not completed yet. Please finish first the calibration and then present the results.
Author's response	The higher inaccuracies are in the lead-lag direction, so the second plot was eliminated in the revised manuscript.
Author's changes in manuscript	The second plot (below) was eliminated in the revised manuscript.

Table 57 - Comment 39: page 18, figure 24

Comment from Referee	Figures have too low quality, adjust resolution please.
Author's response	This has been corrected in the revised manuscript.
Author's changes in manuscript	The first figures will be replaced in the revised manuscript by the same figure with higher resolution. (The second plot was eliminated)

Development of new strategies for optimized structural monitoring of wind farms: description of the experimental field

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Abstract. The main goal of the recently started WindFarmSHM research project is the development, validation and optimization of monitoring strategies to be applied at the level of the wind farm, which should be able to evaluate the structural condition of a set of wind turbines and their consumed fatigue life, using the response to operation loads. In this context, a quite extensive experimental campaign is being performed in Tocha wind farm, an onshore wind farm located in Portugal, which includes the simultaneous instrumentation of several wind turbines adoting strain gages, clinometers and accelerometers distributed in the tower and blades. This paper introduces the Tocha wind farm, presents the different layouts adopted in the instrumentation of the wind turbines and shows some initial results from the already fully instrumented wind turbine. At this preliminary stage, the capabilities of the very extensive monitoring layout will be demonstrated. The results presented in this paper demonstrate ~~and it will be evaluated~~ the ability of the different monitoring components to track the modal parameters of the system composed by tower and rotor and to characterize the internal loads at the tower base and blade roots.

1 Introduction

Wind energy is one of the most promising renewable energy sources, having registered a truly remarkable evolution in the last two decades. This evolution, practically worldwide, is verified both in terms of installed capacity, as well as in terms of technological evolution. In the EU, wind was the fastest growing energy source between 2005 and 2017, surpassing coal in 2016 as the second largest total installed power generation capacity (EWEA, 2018). Future forecasts are equally optimistic. It is expected that cumulative capacity of wind energy in the EU will continue to grow and that it will even double in a minimum interval of 10 years, considering the most optimistic forecast (EWEA, 2017). Thus, based on this scenario, it is possible to identify several challenges that will arise in the coming years. Among them, the following stand out:

- Costs of energy production: the reduction of the unit cost of wind energy is a major factor to guarantee the competitiveness and growth of the wind sector. The reducing operation risk through monitoring is one away;
- The extension of the lifespan of the existing wind turbines: wind turbines were designed to operate 20 years, so it is estimated that about one half of the accumulated capacity currently installed in the EU will reach the end of design

life in 2030 (EWEA, 2017). It is therefore essential to create a regulatory framework that defines the rules for the actions to be taken when the expected design life of the structures is exhausted;

- Limited technical knowledge: the increase in the size of wind ~~generators~~ turbines and the exploration of offshore sites still involve a certain degree of uncertainty.

Considering this background and previous research (Weijtjens, Noppe et al., 2016, Lorax and Brühwiler, 2016, Weijtjens, Verbelen, et al. 2017), the main goal of the WindFarmSHM research project is the development, validation and optimization of new methodologies to continuously assess the structural elements of wind turbines: tower, blades and foundation. The monitoring strategy is being designed to be applied in the context of a wind farm, adequate for onshore and floating solutions (the two types of foundation being used in Portugal), using optimized instrumentation layouts at a subgroup of wind turbines, and taking profit from the data provided by the acquisition systems already available in all wind turbines (SCADA), for the use of extrapolation techniques to assess all the wind turbines of the same wind farm (Figure 1).

The research project will include three monitoring layouts of wind turbines of an onshore wind farm, comprehending accelerometers, strain gages and clinometers and the development of numerical models for the generation of virtual monitoring ~~artificial experimental~~ data to validate the monitoring strategy in floating wind turbines.

The data processing will be based on the continuous evaluation of the parameters that drive the structure dynamic behaviour (vibration frequencies and damping) estimated from the structure response to ambient excitation (wind, waves, currents, soil vibrations) and advanced statistical modelling, having in mind two main goals: detection of stiffness reductions motivated by the appearance of damage (as performed in (Oliveira, Magalhães, et al. 2018a)) and evaluation of the remaining fatigue life of the main structural components (Figure 1).

In the project a very extensive instrumentation will be deployed in order evaluate different monitoring layout alternatives, but the final goal is~~t~~ to propose a minimal optimized monitoring layout based on ~~a few~~ reduced number of ~~easy to install~~ sensors that can be easily installed.

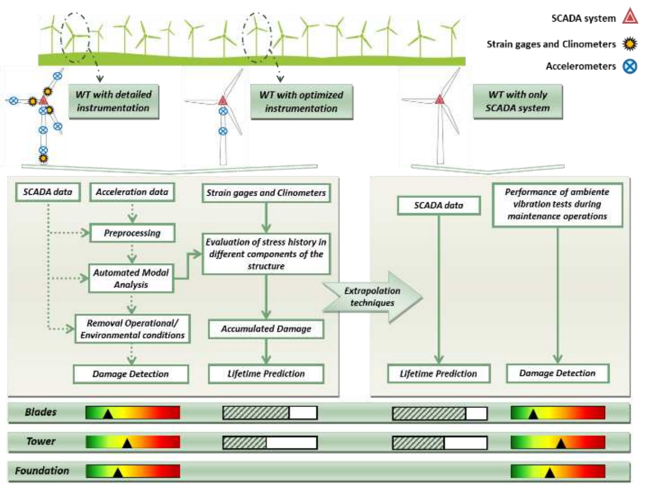


Figure 1. Monitoring strategy. Meaning of the horizontal bars at the bottom: the colour bars represent in a simplistic fashion the structural health, the green/white bars represent the consumed fatigue life.

2 Tocha Wind Farm

The Tocha wind farm is owned by EDP Renewables and started its operation in May 2012. It is located in the central region of Portugal approximately 3 km from the coastline. It consists of five Vestas wind turbines, model V100 with 1.8 MW of rated power, totalling 9.0 MW of installed power. Figure 2 presents a geographic location of the wind farm and the distribution of the five wind turbines, identified with numbers that will be used throughout this work. This figure also identifies a substation position, as well as a meteorological mast.

It is important to note that the wind farm fits into a coastal area, with very soft orography of the terrain and where the foundation's soil is predominantly sandy, which is why deep foundations are used in all wind turbines. Thus, the steel tower of the turbines is connected to a 14-by-14 m concrete slab with variable height (1.50 m at the ends and 3.00 m in the central area). In turn, sixteen concrete piles with 1 m diameter support the slab.

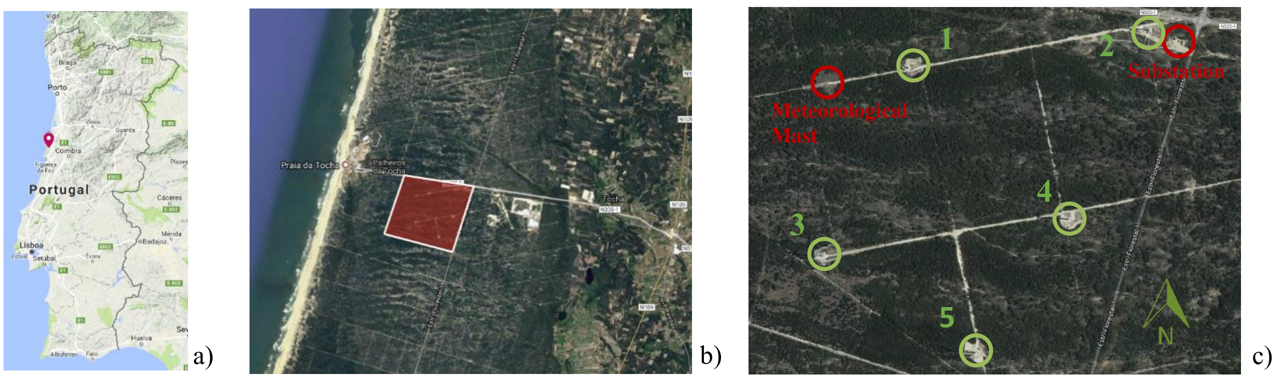


Figure 2. Tocha wind farm: a) Geographic location in Portugal (Google, n.d.-a); b) View of the implantation area (Google, n.d.-b); c) Identification of wind turbines and auxiliary structures (Google, n.d.-c).

Figure 3 shows a wind rose, which characterizes the wind speed and direction for the year 2017 at the Tocha wind farm. The predominant wind direction is approximately north. Thus, considering the very smooth terrain and the proximity of the coast, wind ~~generators~~ turbines 1, 2 and 3 are exposed to slightly disturbed offshore winds, while the remaining generators are exposed to wind with additional turbulence caused by the wake effects.

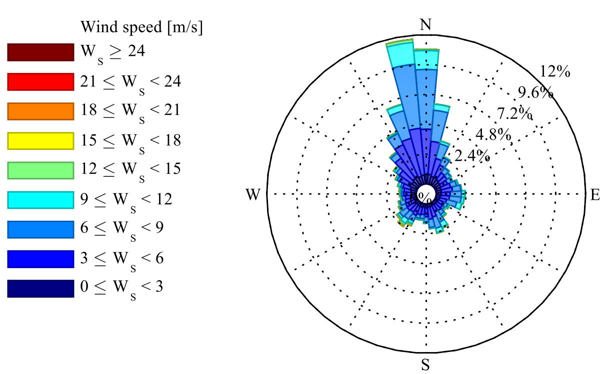


Figure 3. Characterization of the wind conditions observed during 2017 (SCADA data of wind turbine 1).

Vestas V100-1.8MW wind turbine is an onshore turbine model with a 100 m diameter rotor. It is a variable speed, 3 blades rotor with individual pitch control for each blade. The hub is placed at a height of 95 m and is supported by a steel tower, with a hollow circular cross-section with variable diameter and thickness, composed of four segments that are linked on site with bolted connections ~~of variable height in section, composed of four segments that are connected by boltedconnections~~. The wind turbines operate for wind speeds between 4 and 20 m/s and achieve the rated power for wind speeds of about 12 m/s (Figure 4).

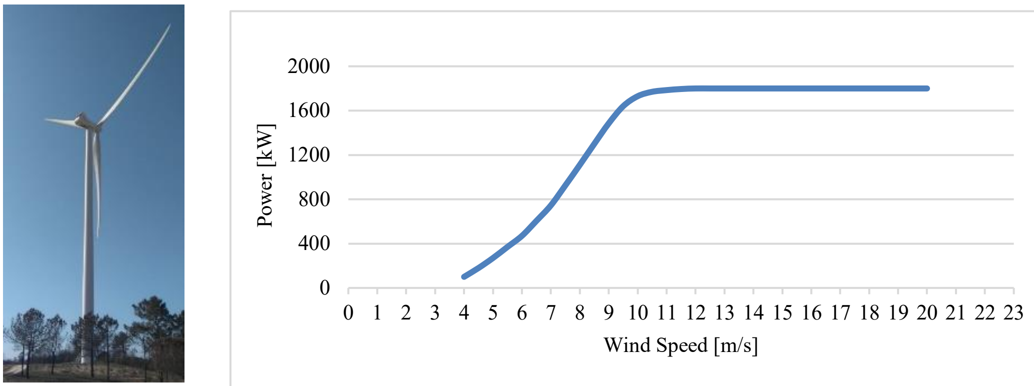


Figure 4. Photo of one wind turbine at Tocha wind farm and power curve (https://en.wind-turbine-models.com).

3 Preliminary evaluation of the modal properties of the wind turbines

In order to obtain an initial estimate of the wind turbine dynamic properties before the installation of the monitoring systems, a set of ambient vibration tests was performed in four of the five wind turbines in operating and non-operating conditions. Additionally, a numerical model of the wind turbines was deployed. In the next sections the preliminary evaluation of the modal properties of the wind turbines will be described.

3.1 Numerical Models

~~In order to understand and interpret the experimental results, a numerical model of the wind turbine was developed using Robot structural analysis software (Autodesk, 2016), according to the technical drawings provided by the manufacturer. It is a simplified model, in which only a static component of the structure is modelled. Rotational movement of the rotor and all control systems are disregarded, since the main purpose of the numerical model is to simulate the dynamic behaviour of the tower under the test conditions presented in the following section.~~

In order to better interpret the experimental results, a numerical model of the wind turbine was developed using ROBOT STRUCTURAL ANALYSIS software (Autodesk, 2016), following the technical drawings provided by the manufacturer. It is a simplified model, in which the operation of the turbine is not modelled. Rotational movement of the rotor and all control systems are disregarded, being the main purpose of the numerical model the simulation of the dynamic behaviour of the tower under the test conditions presented in the following section.

It is considered that the foundation does not allow any kind of relative movements and is not considered the opening of the door (a specific numerical model for this detail has shown that it has a reduced influence on global behaviour). Thus, for the modelling of the tower was based on 3D bar elements to which the corresponding cross sections were assigned.

Regarding blade modelling, at the time very detailed information was not available. Alternatively, starting from the NREL 5 MW reference wind turbine (Jonkman, Butterfield et al., 2009), the characteristics of the blades were scaled to be compatible with the wind turbine under study. The blades are modelled by 3D bar elements, divided into multiple sections to which the average mass, stiffness and inertia characteristics have been attributed. Since there is no rotation of the rotor, the blades were modelled with the pitch angle observed during the ambient vibration tests.

The nacelle and hub are represented by concentrated loads applied at their centres of gravity. The connection between the tower, blades and the geometric centres of the nacelle and hub is modelled with rigid links of negligible mass.

Still, it is important to note that advanced models are currently being developed in FAST (Sprague, Jonkman et al., 2015) using some structural information that was derived from the previously described model. ~~and some results are presented in the next section. This preliminary model has also important to obtain structural information then used in the FAST model~~ All the details of the FAST model are presented in (Pimenta, Branco et al., 2019).

3.2 Ambient Vibration Tests

The set of ambient vibration tests was divided into two campaign. In the first campaign, the main goal was to accurately identify the natural frequencies and the configuration of the tower vibration modes, considering two different situations: wind turbine in operating conditions and wind turbines in non-operating conditions (the rotor was stopped or idling). At this stage, only the wind turbine 1 was tested. ~~The~~ Several 10 minutes of accelerations time series were measured (sample rate of 100 Hz) with 4 standalone seismographs (Figure 5 a), with internal tri-axial force balance sensors, that were placed in the horizontal platforms of the tower (Figure 5 b).

In the second campaign, the main objective is to identify the natural frequencies of all wind turbines of the wind farm, in order to characterize the variability of the natural frequencies. The same equipment was used and with the same data acquisition parameters, but only the two highest sections of the towers were instrumented. It should be noted that in this second tests the rotor of the wind turbines was stopped.

The collected acceleration time series were first analysed in the frequency domain and then processed with Covariance driven Stochastic Subspace Identification method (SSI-COV) (Magalhães and Cunha, 2011). The operating scenarios observed during the performance of the ambient vibration tests are shown in Figure 5 c) (1st campaign: red circles, 2nd campaign: green triangle). It can be seen that the wind conditions observed during the two test are quite different. The owner of the wind farm provides SCADA data with the mean, maximum and minimum value from 10 minutes period, important information for the accelerations processing.

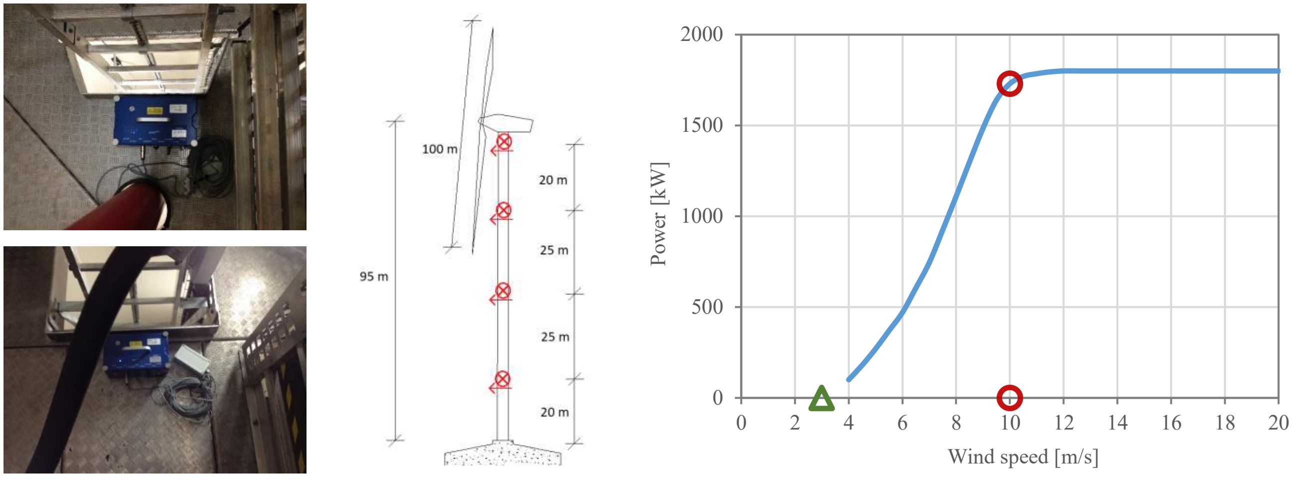


Figure 5. Ambient vibration tests: a) Sensors; b) Section instrumented; c) Operating scenarios.

Figure 6 shows some of the results obtained from the first campaign in non-operating condition. The top left plot shows two averaged normalized spectra (ANPSD): one for the for-aft direction, FA, (perpendicular to the rotor plane) and another for the side-side direction, SS, (parallel to the rotor plane). It is possible to identify several abscissa in correspondence with the most relevant peaks of the spectrum, which represent good estimates of natural frequencies. Among the various peaks identified, there are two that clearly stand out in the presented ANPSD (higher amplitude): one near 0.25 Hz and another near 1.80 Hz. Comparing the experimental results with numerical ones (figure 7), it is confirmed that these peaks correspond to the first and second pairs of tower bending modes. In the stabilization diagram covering the full frequency range under analysis, the position of the first three pairs of tower bending modes is marked. The two zooms presented at the bottom of the figure show that with the SSI-COV method it is possible to separate the very close modes within the first two pairs of frequencies. There are still other stable pole alignments relevant to the dynamic characterization of the structure, however they are probably associated with vibration modes dominated by the rotor, which can only be identified and characterized using the more detailed instrumentation, which will be described in the next section.

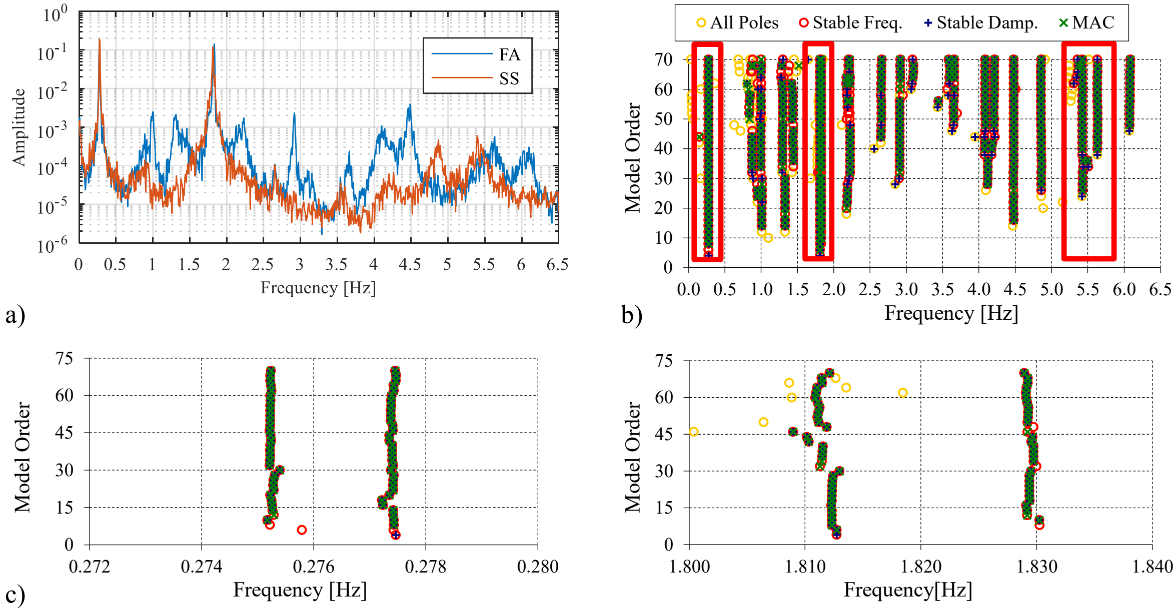
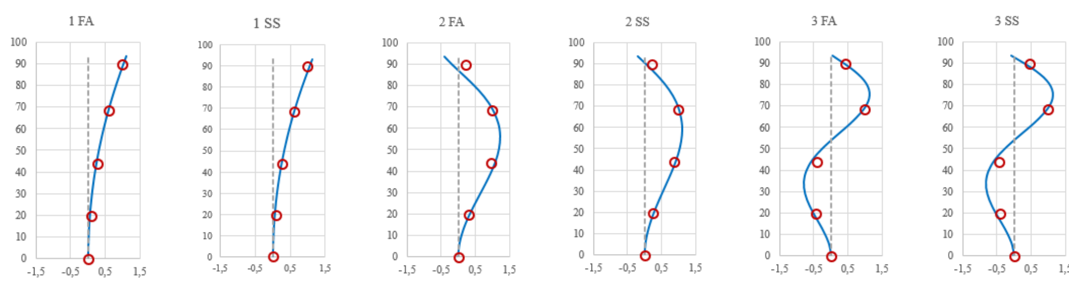


Figure 6. Ambient Vibration test results for wind turbine 1: a) average power spectra for FA and SS directions;, b) stabilization diagram produced by the SSI-COV method; ~~and~~ c) two zooms of this diagram for first (left) and second (right) pairs of tower bending modes.

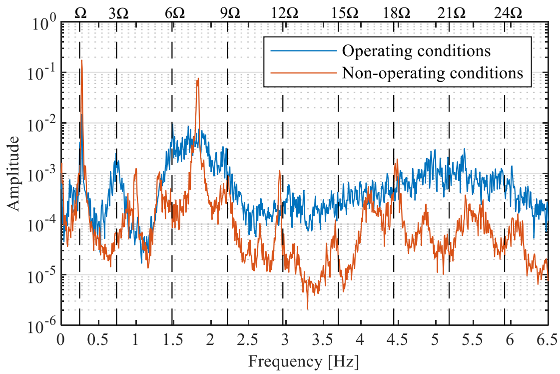
Figure 7 presents the identified mode shapes and natural frequencies, which are compared to numerical results obtained from a preliminary simple numerical model. There is an excellent relationship between numerical results (blue line) and experimental results (red circles).



$f_{exp}[Hz]$	0.275	0.277	1.829	1.812	5.635	5.426
$f_{model}[Hz]$	0.269	0.271	1.765	1.834	5.431	5.433
$\Delta f[\%]$	-2.18	-2.17	-3.50	1.21	-3.62	0.13
$MAC[\%]$	99.9	99.9	95.1	95.7	98.9	97.3

Figure 7. Mode shapes and natural frequencies identified with the ambient vibration test and numerical model of wind turbine 1.

Still, for the first test campaign, it is important to understand the influence that the normal operation of the rotor has on the dynamic characteristics of the structure. Thus, Figure 8 compares ANPSD (average normalized auto-spectral density function) obtained for stopped rotor and in operation. It should be noted that the represented ANPSD were calculated considering together the signals measured along the FA and SS directions. The dashed vertical lines represent the harmonic frequencies associated with the~~o~~ rotor operation (Ω, 3Ω, 6Ω, ...). The results obtained in terms of natural frequencies (f) are also compared for the identified vibration modes for the two analysed situations (environment and operational parameters shown at the table on bottom left).



	Rotor speed [rpm]	Wind speed [m/s]	Pitch angle [º]
Non-operating condition	0.0	9.3	90
Operating condition	14.9	11.3	9.8

Vibration Modes	Non-operating condition f $[Hz]$	Operating condition f $[Hz]$
1 FA	0.275	0.296
1 SS	0.277	0.275
2 FA	1.829	1.795
2 SS	1.812	1.896
3 FA	5.635	5.489
3 SS	5.426	5.355

Figure 8. Ambient Vibration test results for wind turbine 1 in operating and non-operating conditions: average power spectra and natural frequencies (results obtained from 10 minutes single observation setups with very low variance of the environment and operational parameters).

For the first tower bending modes there are two very pronounced peaks for the two considered operating conditions. For the second pair of tower bending modes only in non-operating conditions there is a clear peak in ANPSD. In Figure 11 this comparison will be addressed again.

Figure 9 compares the results obtained for the four tested wind turbines. All of them present quite similar natural frequencies, but wind turbine 5 seams to present a slightly different behaviour expressed by the differences observed at the values of the natural frequencies of the first and second tower bending modes associated with the side-side direction (1SS lower than the others and 2SS higher than the others). For this reason and because this is the wind turbine where higher turbulence is expected the monitoring camping will be focused on wind turbines 1 and 5.

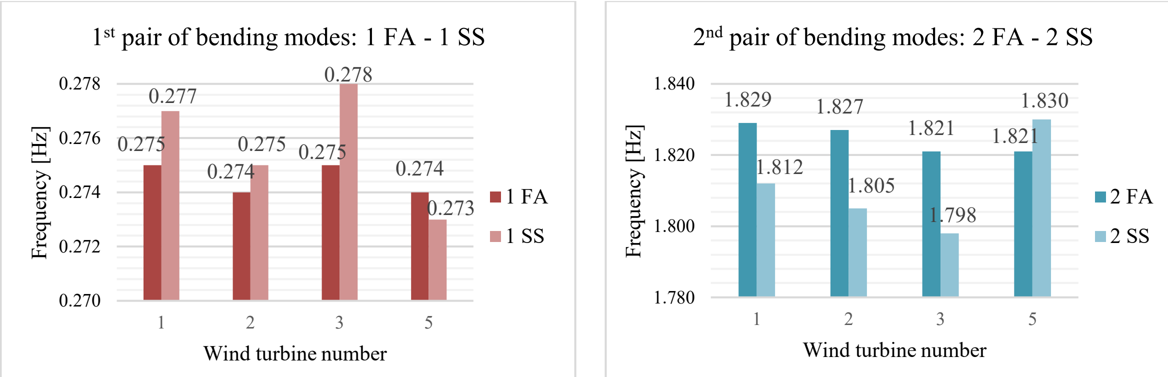


Figure 9. Comparison of the natural frequencies of four wind turbines in non-operational conditions (1st and 2nd pairs of bending modes).

4 Monitoring Systems and Preliminary Monitoring Results

The experimental campaign in Tocha wind farm involves the simultaneous monitoring of several wind turbines during a period of about two years. In order to obtain data representative of the dynamic behavior of all generators wind turbines and based on the results of the ambient vibration tests described above, the experimental campaign includes the following three instrumentation layouts:

- An very completeextended monitoring layout installed on wind turbine 1;
- An intermediate monitoring layout installed on wind turbine 5;
- A simple monitoring layout to be installed on the other wind turbines, considering shorter instrumentation periods;

The distribution of the alternative monitoring layouts in the wind turbines of the farm was conditioned by the available time slot for installation of equipment (usually scheduled during other maintenance operations) and our will to instrument the rotor of one wind turbine that for the predominance wind direction (north) is loaded by an unperturbed flow and another one the is influenced by the wakes of the other turbines (see Figure 2 and Figure 3).Based on the wind conditions of the site (Figure 3) and the position of each wind turbine in the wind farm (Figure 2) wind turbine 5 is the wind turbine where higher turbulence is expected because it is in the wake of the other wind turbines, while wind turbine 1 is exposed to less disturbed winds. For this reason, wind turbine 1 was instrumented according to the complete layout, while the intermediate layout was applied in wind turbine 5.

The simple monitoring layout has two main objectives: i) to characterize and identify differences in the dynamic behavior of wind turbines; ii) to understand the interaction of the wake effects between nearby wind turbines.The main goal of simple monitoring layout is to characterize the differences of the behaviour wind turbines and to understand the interaction between neighbouring wind turbines. This simple layout will be applied to all other structures, considering time periods limited to two or three months. If justified or atypical behaviors are identified, these wind turbines can be instrumented by adopting a complementary layout, suitable for each situation that is intended to be analysed.

The complete monitoring layout includes the following components:

- Two alternative systems to characterize accelerations at the tower: a commercial system based on a set of very low noise accelerometers and a customized low-cost system based on MEMs (micro electromechanical systems) accelerometers designed and assembled in FEUP (Moutinho and Cunha, 2019);
- Strain gages at the tower base to characterize the stresses during different operating conditions;
- Clinometers to characterize the rotations and, indirectly, the bending moments at the base of the tower;
- A set of fiber optic strain gages to estimate bending moments at the blades roots;
- MEM accelerometers placed at the blades (10 m from the root) to characterize their dynamics.

The intermediate layout includes the characterization of the accelerations at the tower through the optimized low-cost MEM accelerometer system and the characterization of the rotor dynamic behavior through fiber optic strain gauges and MEM accelerometers installed on the blades.

Finally, the simple monitoring layout consists solely of using the MEM accelerometer system to collect data regarding tower vibrations. As mentioned, this system will be applied to all other wind turbines and may be supplemented as appropriate.

It should be noted that data on the environmental and operational conditions of each ~~generator~~ wind turbine is being obtained through the SCADA system (10 minutes averages and sampled at 15 seconds). The meteorological mast is also important to characterize the history of environmental conditions in the ~~park~~ wind farm (wind direction and wind speed) since the beginning of its operation. This information is very useful for estimating the current state of fatigue of the various structures.

Wind turbines 1 and 5 are already instrumented. The following section describes the various instrumentation systems adopted, together with the presentation and analysis of preliminary results for wind turbine 1. Since the installation of these components is still being adjusted and the amount of data acquired is still limited, the results presented here are intended to demonstrate what is being measured, to certify the correct functioning of the systems and to demonstrate the capabilities of the most complete monitoring layout.

4.1 Tower Monitoring System: Accelerometers

In order to obtain the best possible characterization of the tower accelerations a commercial system based on 6 force-balance unidirectional accelerometers connected to a 24 bits acquisition system was deployed. As depicted in Figure 10 a), this involved the instrumentation of 3 sections of the tower along two orthogonal horizontal directions. These 3 sections coincide with the height of the technical platforms, in order to facilitate the installation and maintenance of the monitoring equipment. The sensors are connected by cables to a central acquisition system that continuously records acceleration time series with a sample rate of 20 Hz. This data is accessible from FEUP through an internet connection.

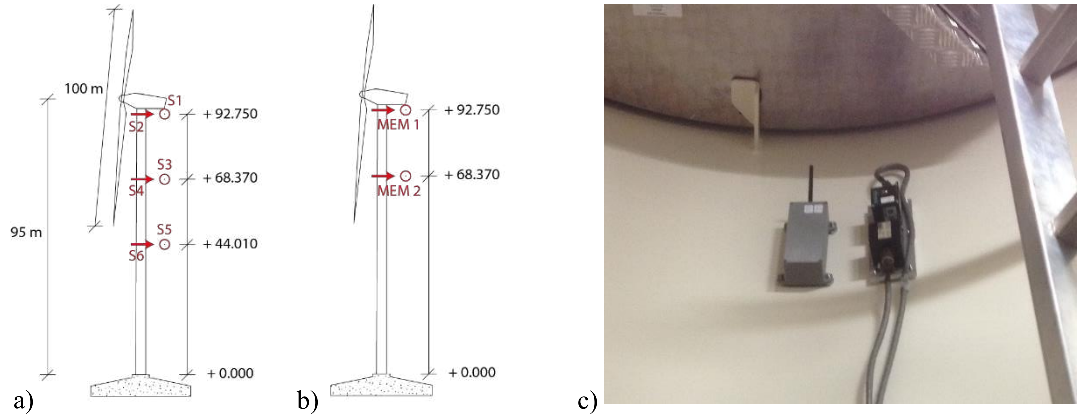
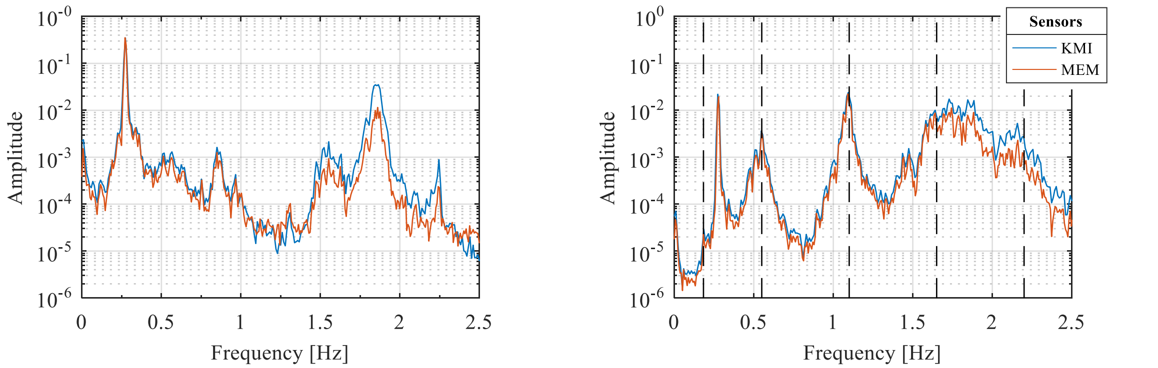


Figure 10. Sections instrumented with accelerometers: a) force balance sensors; b) MEM sensors; c) photos of the force balance sensors (connected to cables) and of the MEM based acquisition system (grey box with antenna).

Complementary, a MEM based system was also installed. This is a standalone system developed at FEUP that integrates a tri-axial acceleration sensor (in this application just the two horizontal directions are being recorded with a sample rate of 62.5 Hz), a set of batteries that ensure 5 months of continuous operation, a memory card for data storage, high-precision clocks and a radio for data transmission (in the present application the data transmission is limited to state-of-health parameters to increase the system autonomy). Two of these devices were installed in the tower in the positions marked in Figure 10 b). One of the project goals is the development and test of easy to deploy and cost effective systems for wind turbines testing and monitoring, so the evaluation of the performance of these devices designed and assembled in FEUP is very relevant.

Figure 11 shows two examples of spectra obtained from acceleration series recorded by the two alternative sensor under test, considering the wind turbine in production (figure on the right) and parked (figure on the left). It appears that the system designed at FEUP demonstrates a performance that is comparable to the more expensive and difficult to install commercial system (KMI). These figures are in accordance with the results of the ambient vibration test presented above. Under non-operating conditions, the peak pairs associated with the first two tower mode pairs clearly stand out. In operating conditions, additional peaks associated with the rotor rotation frequency appear. The peaks associated with the second pair of bending modes become much more diffuse, which makes their tracking over time quite challenging.



Pitch angle = 90º; Rotor speed = 0.0 rpm; Wind speed = 2.9 m/s   Pitch angle = -1.7º; Rotor speed = 11.1 rpm; Wind speed = 5.4 m/s

Figure 11. Power spectra from force balance (KMI) and MEM sensors (1Ω, 3Ω and 6Ω marked with dashed vertical lines).

Figure 12 shows the colormaps obtained from spectra of singular values calculated with the acceleration time series acquired with the commercial system during January 2019, after their projection according to the FA and SS directions. As might be expected, variations in frequency content are observed over time due to varying operating conditions. It is also possible to visually track the time evolution of the natural frequencies associated with the first two pairs of tower modes.

The data collected by both systems is being processed with the algorithms presented in (Oliveira, Magalhães et al., 2018b).

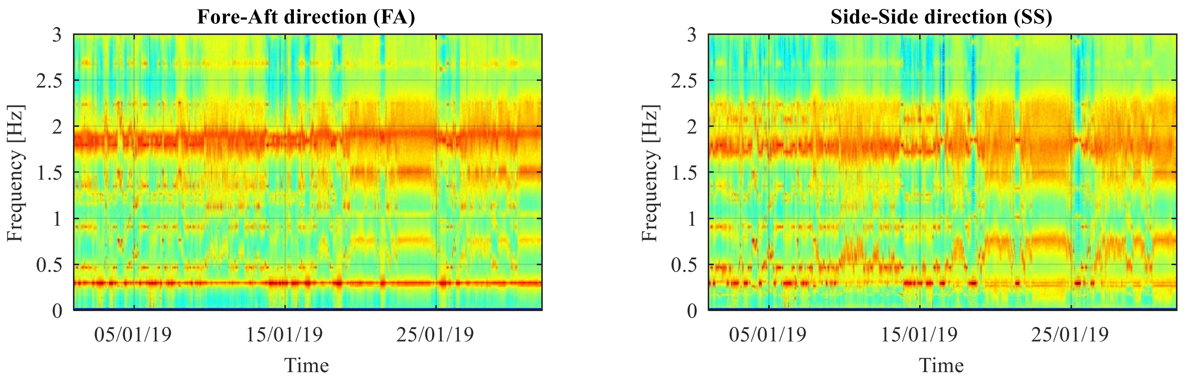


Figure 12. Colour maps with singular value spectra for the FA and SS directions during January/2019.

4.2 Tower Monitoring System: Strains and Rotations

These monitoring components are essential for fatigue assessment of the tower and one important goal is the evaluation of two alternatives for estimating static and dynamic bending moment diagrams along the tower: using ~~extension measurements~~ strain and rotation measurements, combined with accelerometers.

The strains system is composed of six 2D rosette strain gages (measurement of the strain in two orthogonal directions) and 4 temperature sensors. In order to try to evaluate the static bending moment diagrams evolution along the tower, the six strain gauges are distributed in two sections: four sensors at 6.5m from the base of the tower (bottom section) and two sensors at 7.7m (top section) as shown in Figure 13. The four temperature sensors are located in the bottom section, close to the strain gauges. Measuring deformation in the direction perpendicular to the tower axis and temperatures is important to allow the evaluation of alternative procedures to minimize the influence of temperature on the measured longitudinal deformations.

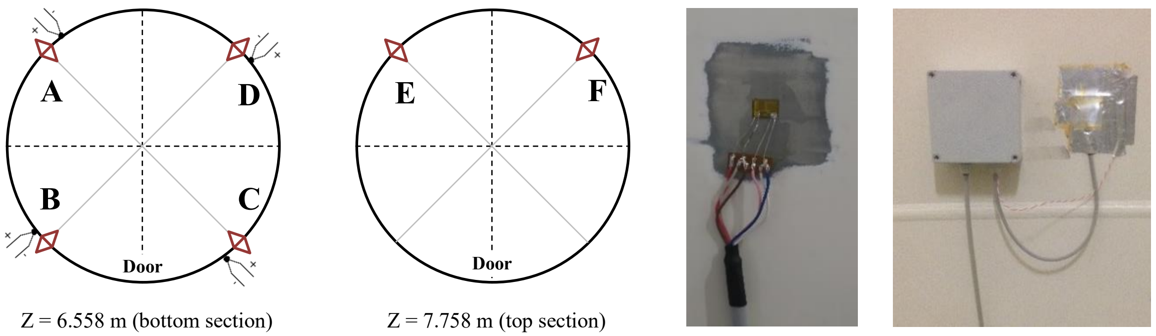


Figure 13. Locations of the strain gages (◊) and temperature sensors ( ); photo of a 2D rosette strain gage before protection; and photo of the strain rosette and temperature sensor after protection and box for signal conditioning.

The installation of the clinometers aims to measure the rotation at the base of the tower and to alternatively estimate the extensions from the measurement of rotations in two close sections. The main advantage of estimating bending moments from rotations is that the installation of the clinometers is less intrusive than the installation of strain gauges, which involves removing of tower painting. The three clinometers were installed along the vertical alignment formed by strain gauges A and E. One of the clinometers was installed close to the foundation (near the base flange), while the two ones are positioned according to the diagram in Figure 14.

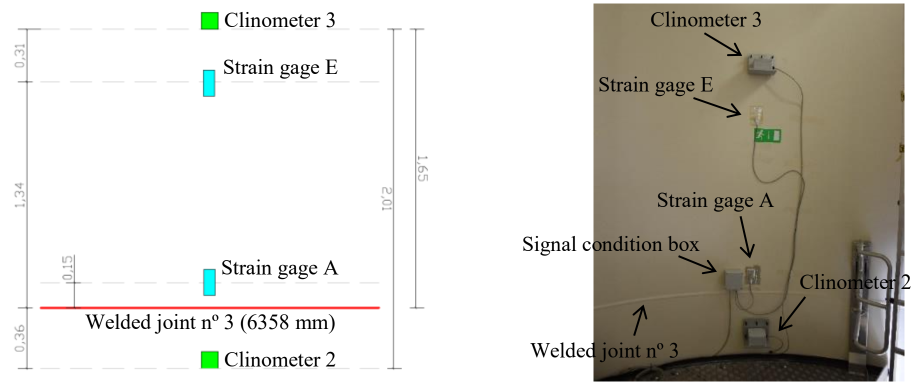


Figure 14. Elevation diagram and photograph of the position of the clinometers and strain gauges along the same vertical alignment.

The two monitoring components are connected to a National Instruments digitizer and processor (model cRio 9056 - http://www.ni.com), installed at the base of the tower. Data acquisition is ensured by a program developed in LabView for this specific application (sample rate of 100 Hz).

Figure 15 a) shows an example of the strains time series obtained for stop event of the rotor. Although the main purpose of this monitoring system is to characterize the static component of the response, it is possible to characterize the dynamic component with good accuracy. With this data, it will be relevant to test and compare the various approaches for estimating the dynamic stresses in the tower from acceleration measurements (Maes, Iliopoulos et al., 2016).

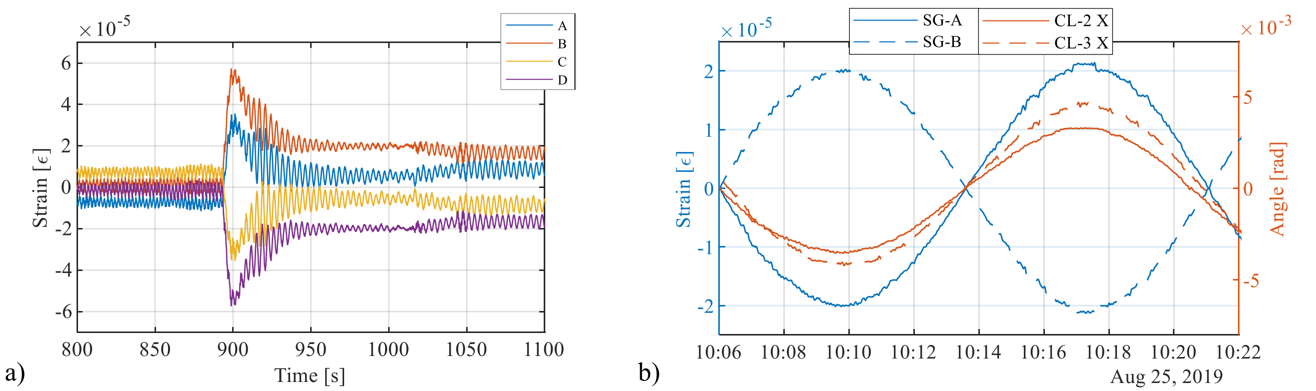
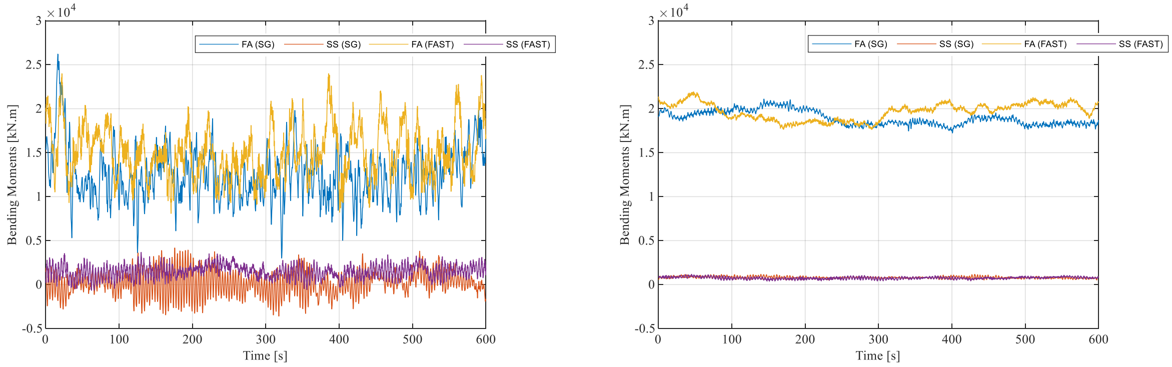


Figure 15. Tower Monitoring System Strains and Rotations: a) Example of strain time series; b) Strain and rotations during nacelle yawing, SG – strains; CL - rotations (see sensor positions in Figure 13 and Figure 14).

The records obtained from strain gauges are influenced by several factors, including the effect of temperature. Thus, the experimental determination of bending moments in the tower requires the acquired raw data to be pre-processed to obtain the real deformation. In the present application, as a first trial, the methodology presented in (Loraux, 2018) is being followed. In a general way, this methodology consists of the following three steps: a) correction of the effect of temperature on strain gauges; b) signal correction based on the average value of the extensions recorded on diametrically opposed sensors; c) signal calibration according to (IEC 61400-13, 2015). For this last step it is necessary to have a record of strain time series measured during a 360º nacelle rotation, with wind speeds lower than the generator cut-in wind speed. The eccentricity of the nacelle and rotor mass generates a sinusoidal signal in the sensors, being the mean value of this signal the zero baseline Figure 15 b). Applying the described method to the recorded series, in Figure 16 the temporal evolutions of the bending moments observed in the bottom instrumented section are presented, for the two main directions, considering two alternative turbine operation scenarios. The experimental results are compared with numerical ones, obtained from a model developed on FAST and calibrated using the methodology described in (Pimenta, Branco et al., 2019). Please note this is just a qualitative comparison, the inflows in the experiment and numerical model are difference, only the average wind speed and turbulence intensity are the same.



Rotor speed = 14.9 rpm; Wind speed = 13.0 m/s; TI = 14.6 %

Rotor speed = 13.0 rpm; Wind speed = 7.9 m/s; TI = 4.4 %

Figure 16. FA and SS bending moments in the bottom instrumented section considering two different operating situations and comparison with FAST numerical results (TI: turbulence intensity).

Figure 17 shows the average spectra of the six force-balance accelerometers (first row) longitudinal deformations recorded by sensors A, B, C and D (second~~first~~ row) and clinometer 3 (third ~~second~~ row), considering the rotor parked (left) and in operation (right). These spectra show excellent agreement of results between the alternative monitoring components and demonstrate that it is possible to perform operational modal analysis from the data collected by all these systems.

Comparing the spectra with those shown in Figure 11, it is clear that the peaks corresponding to the tower bending modes are more pronounced and clearer, so measuring ~~extensions~~ strains can be very useful in distinguishing tower modes from the rotor modes observed in the tower.

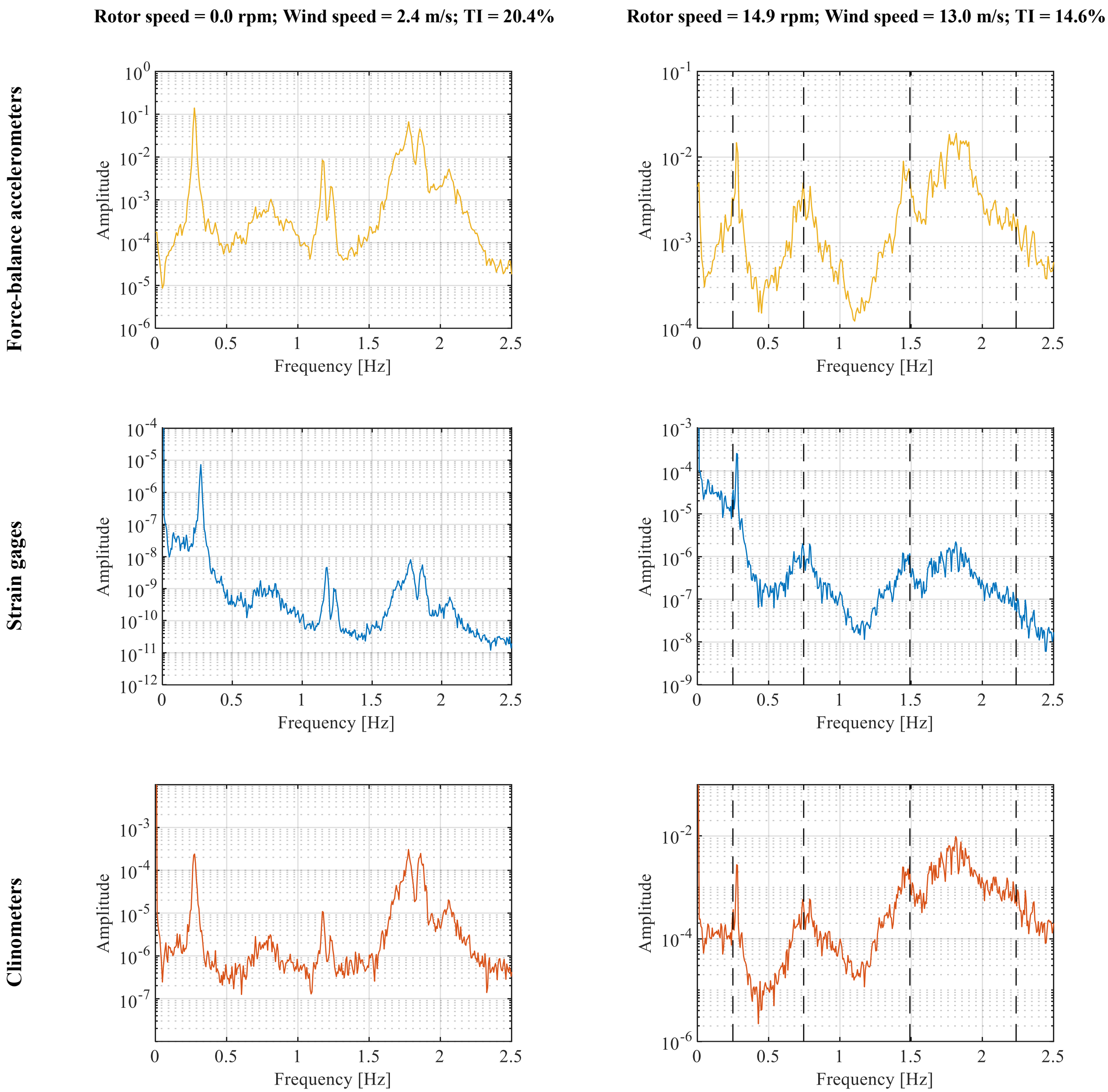


Figure 17. Averaged power spectra: longitudinal strains A to D (first row) and rotation at clinometer 3 (second row) in non-operating condition (left column) and operating condition (right column).

4.3 Rotor Monitoring System: Accelerometers

The goal of this monitoring system is the characterization of the rotor under different operating conditions. The analysis of the results of the ambient vibration tests show the existence of several resonance frequencies that could not be attributed to the tower fundamental modes. These are certainly related to modes more dominated by the rotor. In addition, direct identification of rotor modes may be beneficial for automatically detecting blade changes, driven either by reduced stiffness due to damage or by additional masses due to ice formation. In this way, the same MEM based devices that were installed in the tower were also installed inside the blades, one in each blade, 10 m from the blade root, as shown in Figure 18 (sample rate of 62.5 Hz).

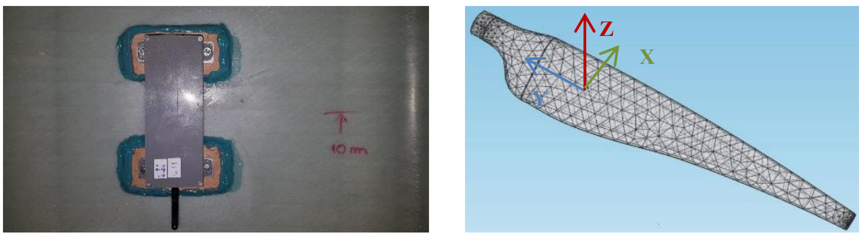
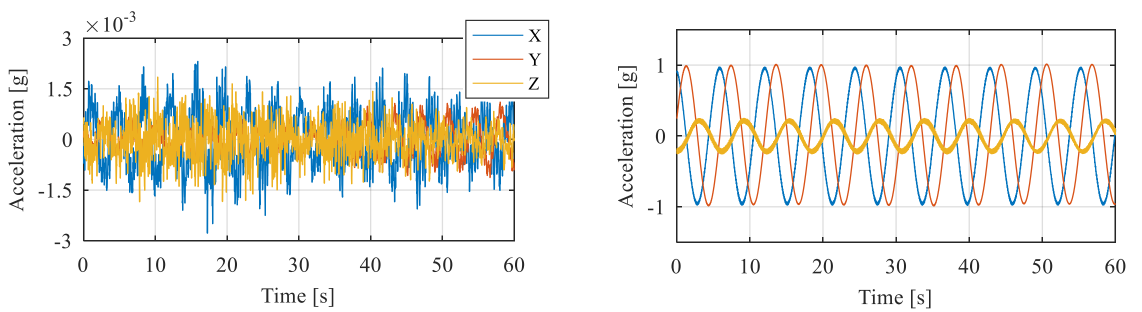


Figure 18. MEM based system installed inside one blade and direction of measurements (X approximately aligned with edgewise direction).

From the simultaneous recording of the acceleration time series on the blades it is possible to estimate the modal parameters of the rotor, in particular their modal configurations. However, as this is a preliminary step, and since the data available so far is limited, only examples of the time series (Figure 19) and their spectra (Figure 20), considering the stopped rotor (left) and in operation (right) are presented. Signals X, Y and Z are in accordance with the referential presented in Figure 18. Considering the figures obtained with the rotor parked, in addition to the various peaks corresponding to the main tower modes, peaks are also identified for various other resonant frequencies that are certainly associated with the rotor modes. Already when the rotor is in operation, the adopted sensors measure the gravity, being the registered accelerations dominated by the rotor rotation frequency. Several other frequencies associated with vibration modes in flapwise (Z) and edgewise (X) directions can still be observed.



Pitch angle = 90º; Rotor speed = 0.0 rpm; Wind speed = 5.5 m/s   Pitch angle = 0º; Rotor speed = 10 rpm; Wind speed = 5.9 m/s

Figure 19. Example of acceleration time series and corresponding operation parameters.

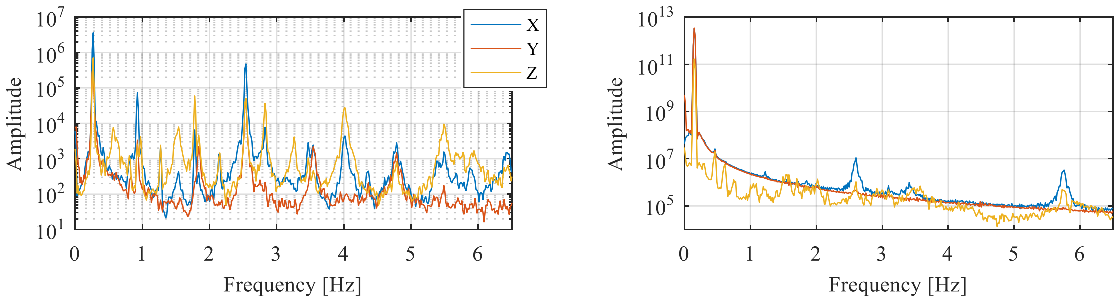


Figure 20. Power spectra of acceleration time series represented in Figure 19.

4.4 Rotor Monitoring System: Strains

The main goal of the blades strains monitoring is to collect data to estimate the fatigue condition of these elements, as well as to evaluate their structural performance from the evolution of the continuously estimated modal parameters. On the other hand, the joint analysis of the wind characteristics, the moments acting at the blades and the bending moments at the tower will also be relevant to understand the mechanism of transmission of loads from the rotor to the tower and to validate numerical modelling.

The solution adopted is based on a commercial system provided by HBM / FiberSensing called WindMeter (https://www.hbm.com) with a sample rate of 100 Hz. Each blade is instrumented with 4 fiber optic strain sensors and temperature sensors for compensation of the temperature effects. As shown in Figure 21, each set of sensor is connected to a central acquisition system installed on the hub, which in turn allows remote access to data via a 3G modem.

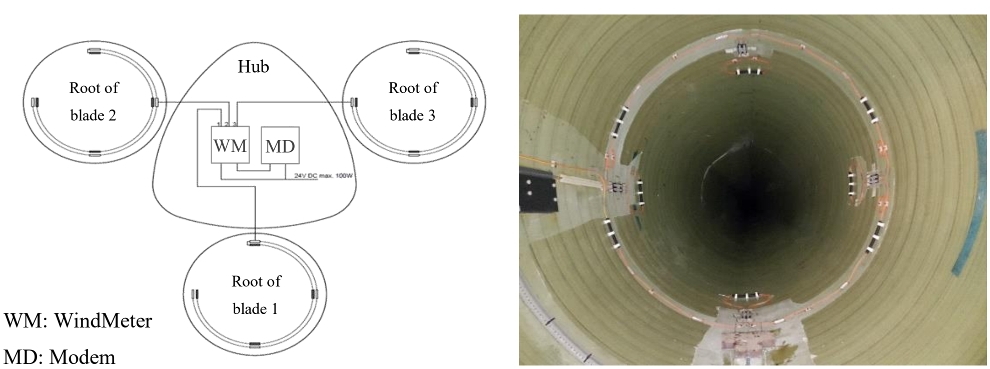
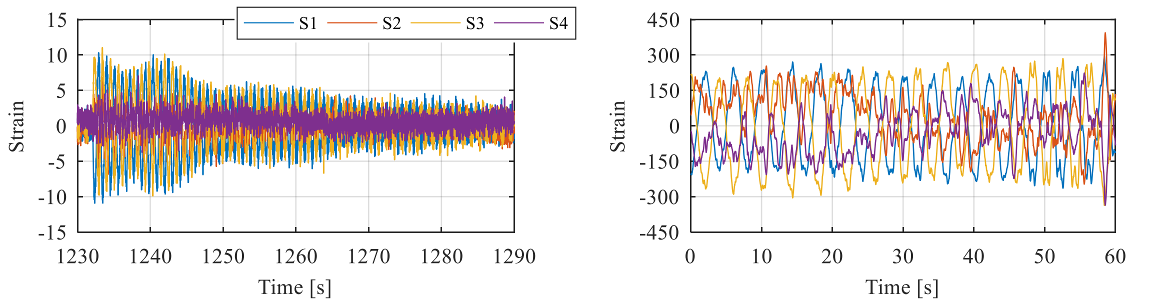


Figure 21. Strain measurement at the blades root: wiring and photo.

As an example, Figure 22 shows two strains time series and in the Figure 23 their spectra, considering the rotor stopped (left) and in operation (right). Sensors $S1$ and $S3$ correspond to blade bending according to edgewise direction, while sensors $S2$ and $S4$ correspond to flapwise direction. The following results show that the acquired data, besides being fundamental to obtain the stress history for fatigue analyses, can also be used for operational modal analysis of the structure.

It should be noted that the deformations measured on the blades are not as sensitive to the tower bending modes as in the case of accelerations, since although tower movement produces blade movements, it does not lead to relevant bending levels. Thus, the spectra peaks shown in Figure 23 can only be motivated by the contribution of the blades modes.

By comparing the spectra of Figure 20 and Figure 23 for the parked situation, it is possible to identify several coincident peaks for the same frequencies. While in operation, the observed resonant frequencies depend on the rotor speed of the rotor, so the peaks do not coincide.



Pitch angle = 90º; Rotor speed = 0 rpm; Wind speed = 3.2 m/s   Pitch angle = 3º, Rotor speed = 15 rpm; Wind speed = 10.5 m/s

Figure 22. Example of detrended strain time series (static component was removed) and corresponding operation parameters (S1, S3 bending in the edgewise direction; S2, S4 bending in the flapwise direction)

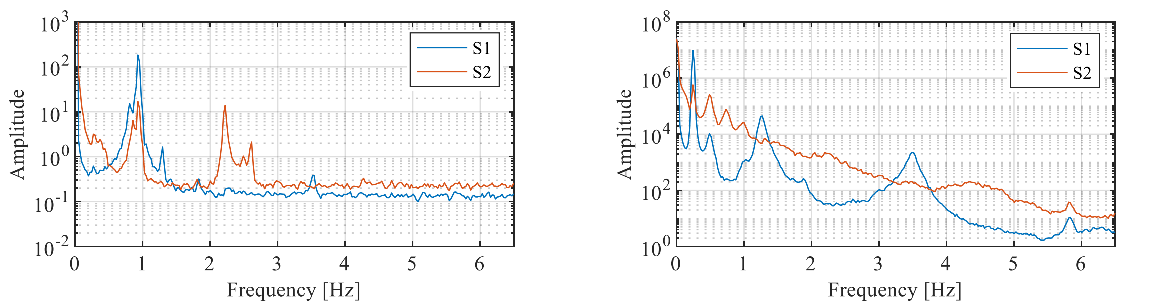


Figure 23. Power spectra of the time series presented in Figure 22.

As noted with respect to measuring tower extensions, a similar methodology was also followed for processing the blade strains records. Note that the calibration step according to the standard (IEC 61400-13, 2015) is not yet fully tuned. However, the data acquired so far allowed the elaboration of Figure 24, which represents the evolution of the bending moments at blade root B (wind turbine 1) to the flapwise ~~and lead lag~~ direction~~s~~ as a function of wind speed and considering different turbulence intensities. Firstly, the moment value increases as the wind speed increases. When the wind turbine's nominal wind speed (9 m/s) is reached, the actuation of the pitch angle mechanism causes the momentum to decrease even though the wind speed continues to increase.

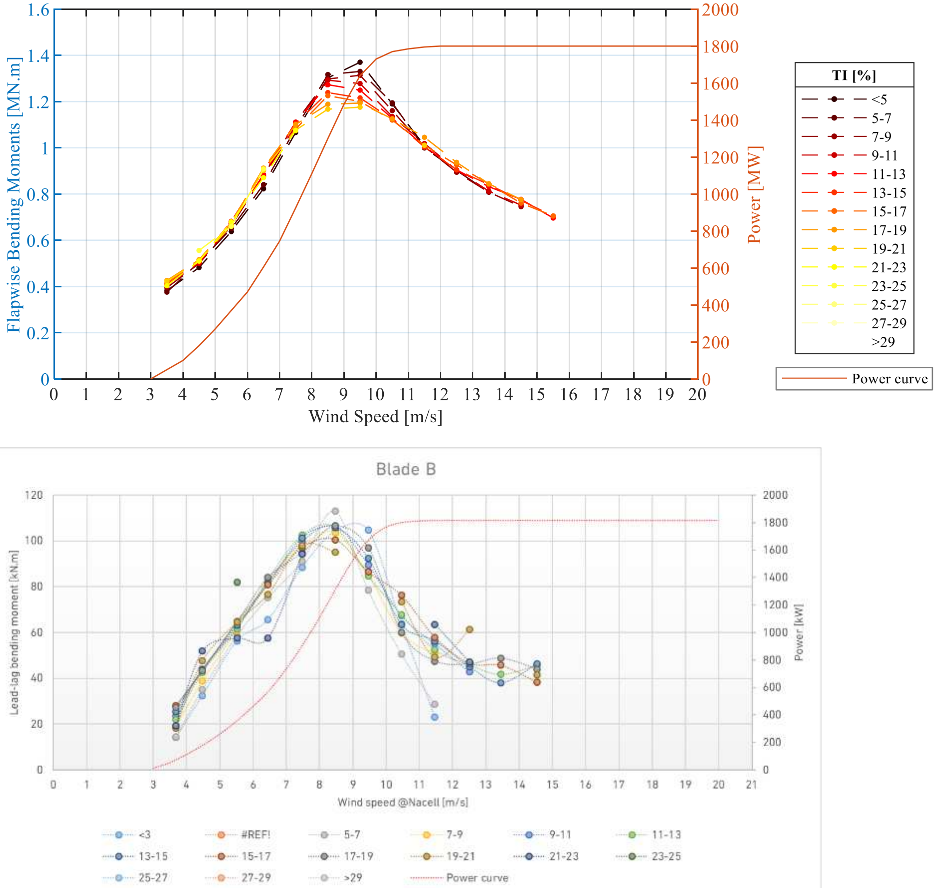


Figure 24. Wind turbine power curve and bending moments recorded at blade root B according to flapwise direction ~~(first) and lead-lag direction (second)~~ as a function of wind speed and considering different turbulence intensities (05-Fev a 17-Dec-2019: 20027 10 minutes times series).

5 Conclusions

This paper presented the quite extensive monitoring camping that is being conducted in Tocha wind farm, described the installation of the monitoring components that are already in operation and presented some preliminary results.

The preliminary analyses performed in the frequency domain show that operational modal analysis has the potential to extract useful information from both strain and acceleration measurements performed either in the tower or in the blades.

A deeper processing of the data that is being continuously collected by all the monitoring components will certainly contribute to better understand the in-operation dynamic behavior of these quite complex structures, to devise processing procedures for effective evaluation of their structure health and to calculate accumulated damage due to fatigue. This step will be instrumental in defining the most effective procedures for assessing structural performance and for estimating accumulated fatigue damage.

The analysis of data simultaneously collected in several wind turbines will be very important for understanding the relation between the observed fatigue wear and to devise techniques to extrapolate results from ones to the others.

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