Application of OMA to operational wind turbine

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ABSTRACT: The presented study focuses on application of Output Only Modal Analysis to operational wind turbines. Issues like time varying nature of operational wind turbine, significant harmonic components due to rotor rotation and considerable aerodynamic damping make OMA of operational wind turbines a difficult task. The study presents the results of OMA applied to experimental data from ALSTOM Wind 3MW Eco-100 wind turbine. Issues like data handling, using clustering for modal identification and uncertainties analysis are presented and discussed.

1 INTRODUCTION

Providing cost effective and reliable wind turbines puts several challenges on wind turbine designers. Full understanding of wind turbine dynamics is required not only to produce light and reliable structural and mechanical components, e.g. Rodríguez-Tsouroukdissian et al. (2011), but also to design wind turbine control systems which ensure efficient and safe operation of a wind turbine, see Carcangiu et al. (2011) and Rossetti (2010). The effective design of a wind turbine requires precise numerical models that correctly represent wind turbine dynamics at all operating points. The accuracy of these models must be verified and validated against field tests, and the data from experiments can be used to improve models and thus, confidence of simulations.

Overall modal model describes global wind turbine dynamics with great accuracy. Such a model can be obtained via experimental modal analysis performed on entire turbine structure (Griffith and Carne (2010)), by finite element analysis, by performing experimental modal analysis on wind turbine structural elements (e.g. blades) and using hybrid approach where both experimental and numerical models are used together. Obviously, the first method requires a proper controlled measured excitation of the huge wind turbine structure, which is very difficult to implement on practice. The other methods, due to incorporated modelling (e.g. of boundary conditions), are prone to uncertainties and need to be validated against experimental data.

Operational Modal Analysis (also known as output-only modal analysis or OMA) techniques (Zhang (2005)) are one of the newer methods of performing modal analysis. OMA techniques aim at obtaining modal parameters characterizing the dynamics of the structure based only on the knowledge of response of the structure to various *ambient* excitations, which are not measured. The great advantage of OMA techniques in application to wind turbine generators is in providing the dynamic model of the structure under *actual operating conditions* and *real boundary conditions*.

Application of OMA methods to wind turbine seems very attractive. It is rather straightforward for the parked case, when a wind turbine is not under operation, see Chauhan et al. (2009). However, as it was shown in Tcherniak et al. (2010a), some important assumptions OMA is based upon, are not fulfilled when the wind turbine is in operation. Methods to overcome this OMA limitation were suggested and validated via simulated experiment (Tcherniak et al. (2010b)).

Based on the positive results of the simulated experiments, a field experiment was planned and performed. The overall goals of the project were to verify current FE and aeroelastic models but also to develop an *experimental methodology of obtaining modal parameters of operational wind turbines*.

The subject of the experiment was a prototype of the of ALSTOM Wind Eco 100 turbine which is a newly developed 3 MW turbine. The detailed description of the goals, planning and performing of the experiment can be found in Chauhan et al. (2011).

While the last mentioned study presented OMA on the wind turbine in a parked state, this study extends the analysis to the operational states. Resulting modal parameters for so-called RPM-regulated regime are presented as a function of rotor speed (Campbell diagram). Simple regression and uncertainty analysis is performed in order to understand the reliability of OMA results for different wind turbine modes.

2 MEASUREMENT CAMPAIGNS: DATA ACQUISITION AND HANDLING

To accomplish the objectives of the project keeping the instrumentation costs as low as possible, it was decided to carry out the measurement campaigns in two stages; a long term campaign and a short term campaign.

The main goal of the long term campaign was to experimentally determine the global modes of the entire wind turbine structure: i.e. tower- and rotor-related modes. Some of these modes are expected to depend on wind load and rotor speed. According to the project objectives, all operational wind speeds should be covered, thus the probability of strong wind during the campaign period together with some logistic issues defined the campaign duration.

The focus of the presented study is the global wind turbine modes, therefore only the data from the long measurement campaign is used. The detailed description of the goals of the short campaign is given in Chauhan et al. (2011).

In total, 80 channels were recorded during long measurement campaign, among them 68 channels measuring acceleration; 10 control signals and 2 tachoprobe signals. The detailed description of the wind turbine instrumentation is given in Chauhan et al. (2011).

Together with acceleration signals, a number of so called control signal were recorded. Most of these signals represent *metadata*, i.e. characterize the conditions during the measurements. Examples of such signals are wind speed, wind direction, rotor RPM, etc.; they are not directly used in any computations. In contrast, the yaw angle defines the mutual orientation of the nacelle and the tower; it plays important role in computation of global mode shapes.

It is important to note that knowledge of blade dynamics plays important role in modal analysis. Firstly, mode identification is much more straightforward when blades accelerations are known. Secondly, one can be more confident in damping estimations provided by OMA algorithms. The abovementioned points reflect the observability issue and are especially important for rotor-related modes. At the same time, previously performed simulated experiments (Tcherniak et al. (2009)) showed that the rotor-related modes can be extracted even without measuring blade acceleration.

It should also be noticed that measurement on the blades is a challenging task involving a number of technical issues: for example, obtaining data from the rotating part and synchronizing it with the static part is a difficult though feasible task. Additionally, blade instrumentation is a job which has to be performed by specially trained personal. Taken all these into consideration, it was decided to skip blade instrumentation and measurements.

It is necessary to note that measuring of such a big amount of channels is not necessary for identification of global modes: fewer accelerometers and control signals can be used. Providing the minimal number of accelerometers and selecting their optimal location are among the project results; these issues are discussed in the conclusion.

Long term measurement campaign started in July 2010 and ended in October 2010; in total the acquisition system was operational 3.5 months. The current study is based on the data collected during the first 41 days of the campaign. During this period about 4000 datasets each 15 minutes long were recorded. Data acquisition parameters can be found in Chauhan et al. (2011). Each recording file is about 70.5 MB totalling in 280 GB of data.

Obviously, such amount of data sets definite requirements on data management. First of all, the metadata channels have to be extracted from the recordings and various statistical characteristics have to be computed and saved to a recording database. The database with its sorting and filtering capabilities greatly facilitates the selection of datasets chosen for following modal analysis. Mean values such as mean wind speed and median rotor RPM define the series of recordings chosen for modal analysis; however the final selection of datasets is based on minimum variability of the structure during the test. For example, in pitch-regulated mode (defined in the next section), the requirement would be a minimal variability of the pitch angle during a recording. In this case, standard deviation and percentiles become useful statistical properties.

3 DATA ANALYSIS

3.1 Violation of the time invariance assumption

Time invariance of the structure under a test is one of the main assumptions of modal analysis. As it was mentioned in Tcherniak et al. (2010b), this assumption is violated in the case of operational wind turbines. Indeed, a wind turbine consists of several substructures which move with respect to each other during the operation: the nacelle follows the wind and thus rotates about the tower; the rotor rotates about its axis and the pitch of the blades changes depending on the wing conditions (Fig. 1). All these motions should be taken into account in order to perform a reliable modal analysis.

Yaw change. Rotation of the nacelle about the tower does not present a considerable problem for modal analysis. Firstly, the yaw (the angle of the nacelle axis in tower-fixed coordinates) does not change constantly but only when the rotor becomes significantly misaligned with the wind direction. Thus it is possible to select datasets when the yaw does not change at all. Secondly, the yaw speed is very low even compared to the slow vibrations of the wind turbine. Anyway, the yaw angle has to be taken into account in order to align directions of the accelerometers mounted on the nacelle with those mounted on the tower.

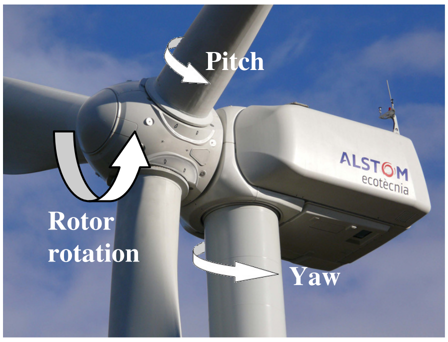

Figure 1: Mutual motions of wind turbine substructures

Rotor rotation. As it was discussed in Tcherniak et al. (2010b), rotor rotation represents a severe problem from structure invariance point of view. If accelerometers are installed on the blades, a special multi-blade coordinate transformation (MBC, also known as Coleman transformation) must be performed in order to convert the vibrations of individual blades described in the rotating blade frame into the ground-fixed frame. However, in the presented study, no blade accelerations were measured; the global dynamics of the structure is being characterized from the accelerations measured on the tower and nacelle, and the effect of the rotor is being considered as an external (both random and periodic) excitation, Tcherniak et al. (2010a).

Pitch change. Eco-100 is a pitch-regulated wind turbine. The wind turbine control system uses sophisticated algorithms to set optimal pitch angle maximizing the power output and minimizing aerodynamic loads on the structure according to the current wind conditions. The next section describes the different types of pitch behaviour.

3.2 Eco-100 regimes

Depending on wind speed, Eco-100 can be found in one of the three main states (or regimes), namely: parked, RPM-regulated and pitch-regulated. These states are quite distinct from the modal analysis point of view and are being addressed in this section.

Fig. 2 shows the three states in a 3-dimensional space where the axes are wind speed, rotor RPM and pitch angle. Each point represents one recording; mean values of wind speed, RPM and pitch observed during the recording form the coordinates of the points. When the turbine is parked (the zone in dash-and-dot oval), the pitch angle is set to maximum to reduce the wind load. The rotor does not rotate and the turbine does not produce power. This can happen at any wind condition, e.g. no wind, very strong wind when the turbine is stopped because of safety reasons, or simply when the turbine is stopped for maintenance.

When the wind is weak or moderate, the turbine is RPM-regulated (zone in the dashed oval). In this case the pitch is minimal, so the blades utilize all available wind energy. In this regime, the rotor RPM increases with the wind speed.

After the rotor speed reaches its nominal value, the turbine enters the pitch-regulated regime. The turbine control system keeps the RPM constant by correcting the pitch angle. In this regime the pitch changes constantly following the wind turbulence (denoted by the dotted oval). When the wind speed exceeds the limit value, the turbine stops and goes to the parked mode.

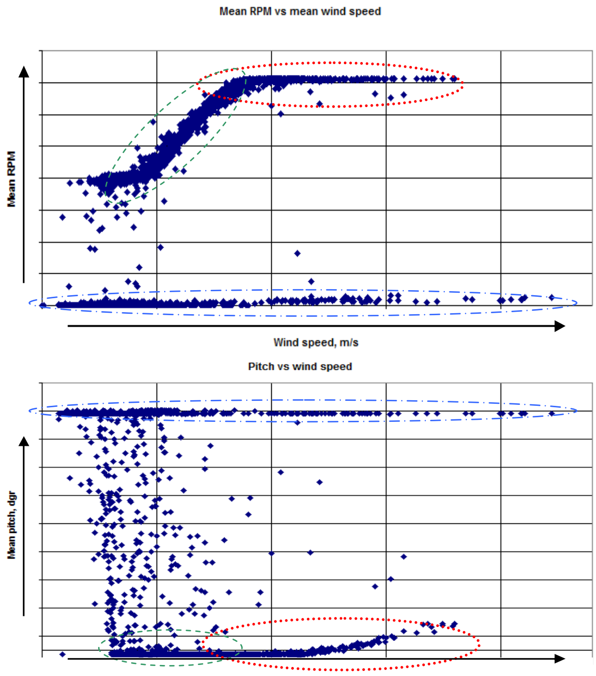

Figure 2: Wind turbine regimes. Each point is a data-set. Dotted – pitch-regulated regime; dashed– RPM-regulated regime; dash-and-dot –parked.

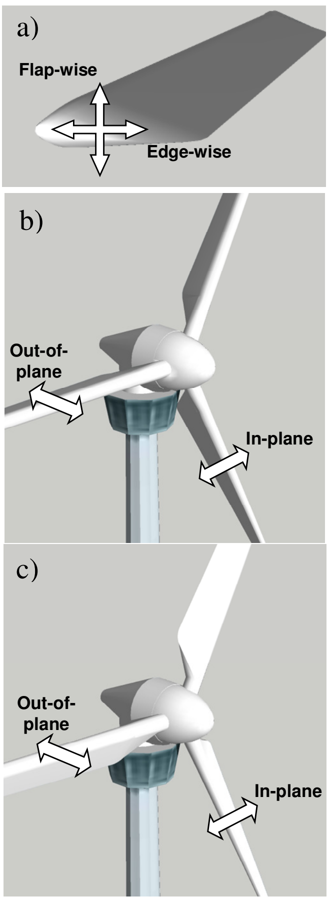

Figure 3: a) Blade modes; b) Max pitch (parked); c) Min pitch (operational)

Obviously, the parked state is the simplest one from the modal analysis point of view. All OMA assumptions are fulfilled, thus one can expect reliable results. In Chauhan et al. (2011) such results were presented. Though the results are valuable e.g. for correlation purposes, the objective of the project is to obtain the modal parameters for operational regimes.

A typical blade is much stiffer in the edge-wise direction than in the flap-wise one, therefore the natural frequencies of the in-plane and out-of-plane rotor modes are heavily dependent on the pitch angle (Fig. 3). When the turbine is in pitch regulated regime, the natural frequencies of the in-plane and out-of-plane rotor modes will constantly vary following the pitch, which in turn follows the wind turbulence. Observations show that it is hard to find datasets when the pitch does not change or changes slightly. Therefore it is quite challenging to apply the OMA methods to the data recorded when the turbine is pitch-regulated.

Let us consider the RPM-regulated regime. In this regime, the pitch is set to minimum and does not change in time. The wind turbine reacts on wind speed fluctuation by changing rotor speed. However, from analytical studies, e.g. Hansen (2007), it is known that the frequencies of some rotor-related modes depend on rotor speed. This is explained by (i) the centrifugal stiffening effect and (ii) complex modal interaction which causes the appearance of so-called backward and forward whirling modes depending on rotor speed.

The abovementioned means that under real operational conditions, when the wind speed constantly varies, it is almost impossible to find the conditions when the natural frequencies of the rotor-related modes are constant during the observation period. This holds for both RPM- and pitch-regulated operational regimes. However, the natural frequencies are much more sensitive to the pitch angle than to the rotor speed, and the rotor speed does not change as rapid as pitch does. This makes RPM-regulated regimes more suitable for operational modal analysis. The present study focuses on this regime; the OMA of wind turbine in pitch-regulated regime is discussed in the conclusion.

3.3 Automatic OMA

From the 4000 datasets recorded during the long term campaign, about 500 were recorded in the RPM-regulated state. From these 500 datasets 65 were selected for the further analysis based on two criteria: (i) variation of the rotor speed during the recording time is minimal and (ii) the mean RPM values of the selected datasets cover the entire RPM range specific for the RPM-regulated regime. The latest should guarantee enough points to perform statistical estimation of the uncertainties and plot a Campbell diagram for the RPM range.

OMA SSI (Zhang et al. (2005)) was selected as one of the most reliable OMA algorithms existing today. Bruel and Kjaer OMA software was used for the analysis. Application of OMA to such a big (though already reduced) number of datasets is a very laborious job; therefore OMA automation feature was employed. Modal estimation parameters (such as number of projection channels, maximum state space dimension, type of estimator, etc) were chosen and tested manually on a small number of datasets. Parameters for automatic mode selection were also chosen. Then the same parameters were used for batch processing of all datasets. The output of the batch process is a list of modal parameters for all found and selected modes and the files containing mode shapes. The same procedure was repeated for different modal estimation settings (e.g. decimation and low/high pass filter properties).

The result of the described above procedure is shown on Fig. 4. Each column of the points (e.g. like the ones in the dashed-line box) represents the automatically selected *poles* resulting from modal analysis performed on a dataset. The inset shows the example of a stabilization diagram obtained for one dataset with automatically selected poles. Abscissa of each column corresponds to dataset's median rotor RPM. The frequencies of the poles become the ordinates of the points on Fig. 4.

As it is known from operational modal analysis (Zhang et al. (2005)), a pole can represent a structural mode but can also be a result of periodic excitation (i.e. correspond to an operational deflection shape), or be a result of numerical noise. Huge amount of non-structural poles found and automatically selected by the SSI algorithm can be explained by the violation of OMA assumption. As it was reported in Tcherniak et al. (2010a), two OMA assumptions are not fulfilled when applying OMA to operational wind turbines:

- the excitation frequency spectra is not flat but characterized by "peaks with thick tails" at fundamental frequency, at blade passing frequency and its harmonics;
- there is a high degree of correlation between the excitation forces acting at different points

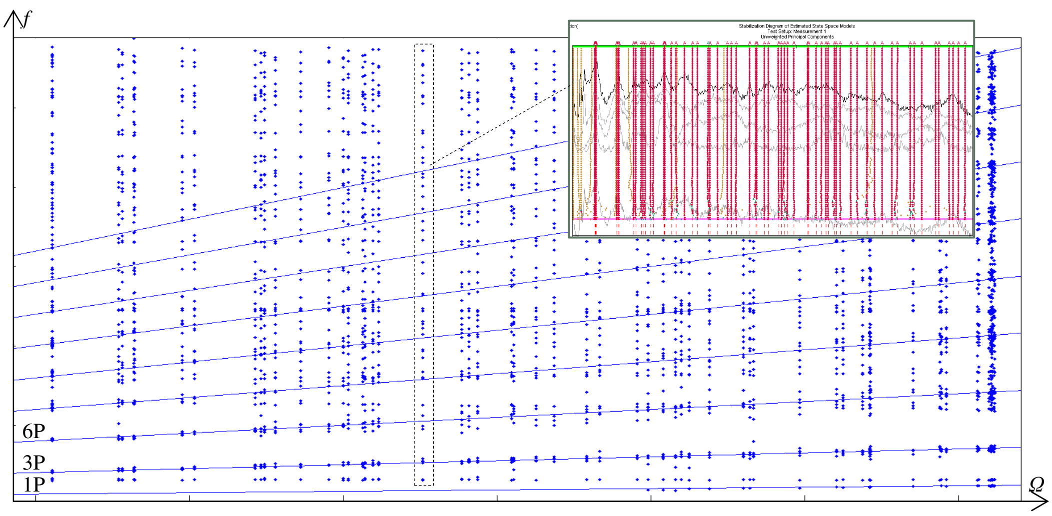

Figure 4: Results of SSI performed on 65 selected datasets in the RPM-regulated regime. Each point represents an automatically selected pole. The points in the dashed-line box are the results of SSI performed on one dataset. The inset shows the stabilization diagram for the same dataset.

of the structure. The correlation is high at fundamental frequency and its harmonics.

3.4 Clustering – the grouping of poles

In order to track global structural modes among the huge number of poles produced by the SSI algorithm, one has to pick the "right poles", i.e. the poles representing structural modes. These poles should be somehow consistent along the RPM axis. Mode shape is a good indicator of the consistency: indeed, it is anticipated that shape of global modes should not depend on rotor speed. In contrast, the modal frequency might not be selected as a consistency indicator; it is expected that the natural frequencies of some rotor-related modes will slightly depend on rotor RPM.

The present study suggests using a *hierarchical clustering* approach to automate tracking of the structural modes. The idea is to group the poles into some *clusters* according to some criteria (here, according to the similarity of the mode shapes associated to the poles). Clustering is based on an appropriate *metric* which is a measure of a *distance* between two poles. In this study the following distance was used:

$$d_{ij} = 1 - MAC_{ij}\,, \tag{1}$$

where MAC_{ij} is the modal assurance criteria computed between mode shapes i and j.

The result of clustering is typically presented via a *dendrogram*. A typical dendrogram is shown on Fig.5. The inset on Fig. 5 shows how a dendrogram interprets the distance: the numbered circles denote poles; the height of the "bridge" between a pair of the circles corresponds to the distance computed according to (1). Groups of poles A and B are clusters. The distance between clusters d_{AB} is defined by a *linkage criteria* and can be computed using different methods, e.g. as a distance between the most distant poles in the compared clusters.

In the presented study, *MultiDendrogram* software (Fernández and Gómez (2008)) was used for hierarchical clustering. The input to the software is the distance matrix; the output is the dendrogram. Final clustering is determined by selecting a threshold value (dashed line on Fig. 5); parts of the tree below the threshold define the final clusters. The clusters containing less than a certain number of poles can be discarded. Not discarded clusters are treated as structural modes. Selection of the threshold is not automated and done by trials and errors.

Fig. 6a presents the result of clustering. The majority of the noise poles are filtered out (*cf.* Fig. 4), and the poles belonging to the structural modes are grouped together.

3.5 Mode nomenclature and confidence intervals

Though the modes are now identified, i.e. the modal parameters and mode shapes are found, it is necessary to match the indentified modes to characteristic wind turbine modes known from analytical and numerical studies, in other words, give the modes correct names. This is nor-

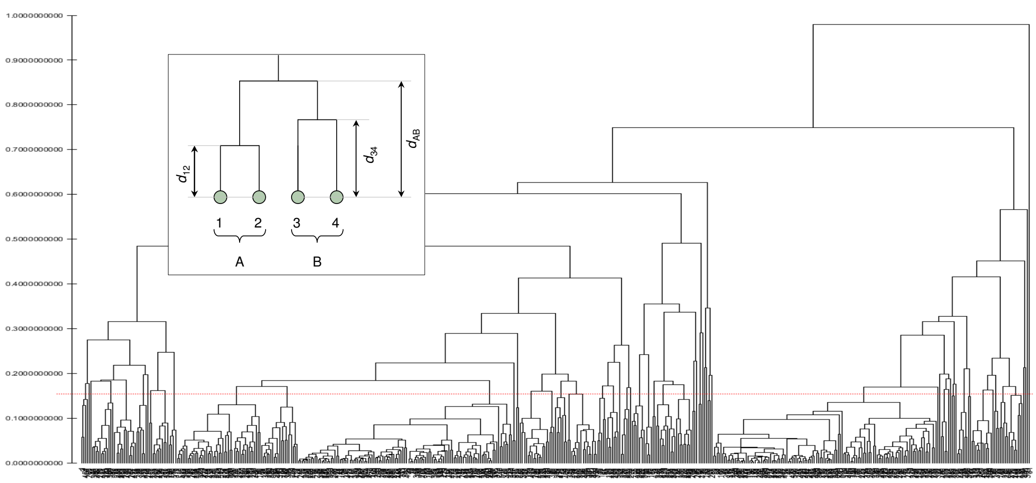

Figure 5: Typical dendrogram. Dashed line shows threshold line defining final clusters. The inset shows how the distances between poles and clusters are represented by a dendrogram.

mally done by visual inspection and comparing the obtained mode shapes with typical wind turbine mode shapes. However, since the blade vibration was not measured, the blades are not presented in the mode shape animations. This makes mode nomenclature a non-trivial task. Here, the priory knowledge of the wind turbine dynamics and its expected mode shapes (e.g. resulting from FE modelling) are used to form mode nomenclature. In Chauhan et al. (2011), a process of visual comparison was demonstrated; automated approach using correlation software is also possible, see Basurko et al. (2011) and Carcangiu et al. (2011b).

The number of poles in the clusters on Fig. 6a varies from 30 to 70; the level of scattering differs from cluster to cluster. If the dependence of *i*-th modal frequency on rotor speed is presented by a linear function:

$$f_i(\omega) = \alpha_i + \beta_i \omega, \qquad (2)$$

coefficients α_i and β_i can be found from cluster's poles using linear regression. In order to construct the confidence intervals, we assume that the errors in pole calculations are normally distributed; in this case Student's *t*-distribution is used. Then it can be shown that at confidence level (1-γ) the confidence bounds are

$$\begin{aligned} \alpha_i &\in [\hat{\alpha}_i \mp t^*_{n-2} s_{\alpha_i}] \\ \beta_i &\in [\hat{\beta}_i \mp t^*_{n-2} s_{\beta_i}] \end{aligned}, \qquad (3)$$

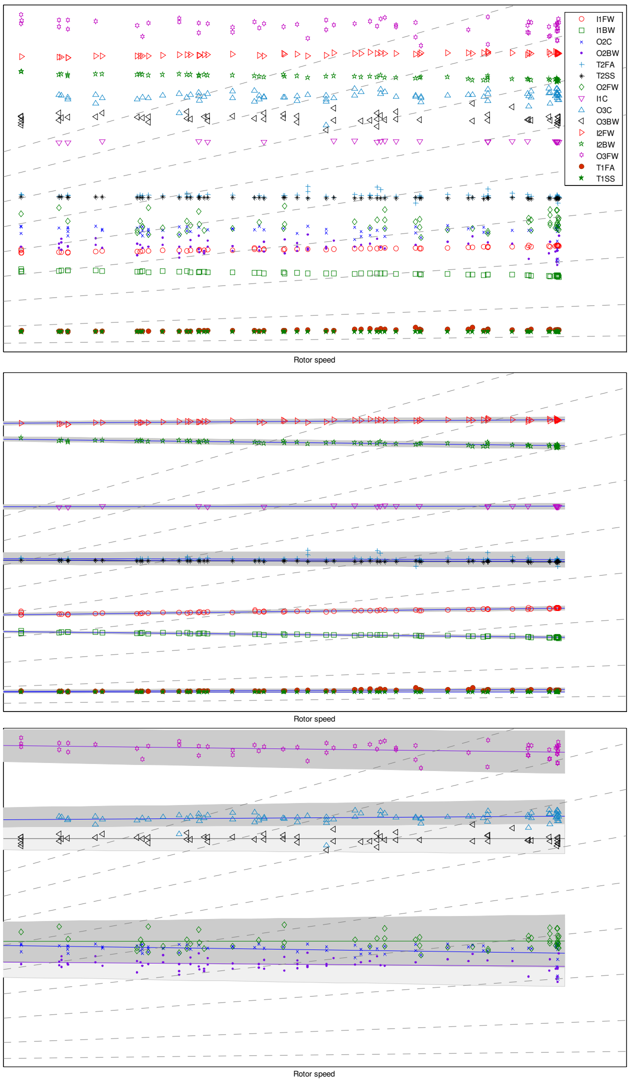

Figure 6: Modal frequencies as functions of rotor speed and confidence intervals. a) All lowest global modes; b) In-plane and tower modes; c) Out-of-plane modes.

where $\hat{\alpha}_i$ and $\hat{\beta}_i$ are the regression coefficients, t^*_{n-2} is (1-γ/2) quantile of the t_{n-2} distribution, n is poles number in the *i*-th cluster. s_{α_i} and s_{β_i} are the standard deviations of α_i and β_i respectively.

The results of the regression analysis and the corresponding confidence intervals at confidence level 95% (γ = 0.05) are shown on Fig. 6bc; Fig. 6b shows in-plane rotor-related and tower-related modes and Fig. 6c shows out-of-plane rotor-related modes.

In can be seen that all in-plane modes present in the shown frequency range are found, and the confidence interval is quite narrow. Same can be said for the tower modes except the 2nd tower for-aft mode which confidence interval is slightly wider. The dependence of the 1st and 2nd in-plane backward and forward whirling modes on rotor speed is also obvious; this correlates pretty well with analytical studies. In contrast to in-plane modes, the out-of-plane modes (Fig. 6c) are much more difficult to identify. The three first out-of-plane modes (collective, back- and forward whirling modes), which are expected to be in the range between 1P and 3P, were not found at all. The confidence intervals of the 2nd and 3rd out-of-plane modes are much wider compared to their in-plane counterparts.

Obviously, due to aerodynamic effects, the out-of-plane modes are heavily damped when the pitch is minimal (Fig. 3c). These modes may also have less influence on the tower and the nacelle than the in-plane modes; therefore these modes are less *observable* by the sensors located on these substructures. Therefore these modes are more difficult to identify; and the modal parameters have less degree of confidence compared to the in-plane and tower modes.

4 CONCLUSION

The study presents the application of OMA to data measured on operational wind turbine. The specifics of different operational regimes from OMA viewpoint are discussed. Practical issues such as handling of big amounts of data, automation of modal analysis, poles grouping (clustering) and uncertainty analysis are being presented and discussed.

The study contributes into the development of the *experimental methodology of obtaining modal parameters of operational wind turbines.* It confirms the ability of OMA to provide modal parameters of entire wind turbine structure under real operational loads. At the same time the issues like OMA applicability to pitch-regulated regime and correctness of the damping estimation remain to be addressed. These together with other issues like e.g. selection of minimal number of sensors necessary for successful OMA, form the scope of the future work.

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