



APPLICATION OF OMA TO AN OPERATING WIND TURBINE: NOW INCLUDING VIBRATION DATA FROM THE BLADES

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ABSTRACT

The presented study continues the work on application of Output Only Modal Analysis (OMA) to operating wind turbines. It is known from previous studies that issues like the time-varying nature of the equations of motion of an operating wind turbine (in particular the significant harmonic components due to the rotor rotation) as well as the considerable aerodynamic damping make OMA of operating wind turbines a difficult task. While in the previous works OMA was based on data provided by sensors mounted on the wind turbine tower and nacelle, we here attempt to improve the results by instrumenting the blades as well. It is believed that the availability of vibration data from the blades will improve the observability of the main global vibration modes (especially the heavily damped out-of-plane modes), and thus will assure a better estimation of modal parameters, especially the damping.

The paper discusses the technical challenges regarding blade instrumentation and data acquisition, data processing applied to eliminate the time-varying nature of an operating wind turbine in the resulting eigenvalue problem and, finally, it presents and discusses the initial results.

Keywords: OMA, Operating Wind Turbine, Blade Acceleration Measurements, Multi-blade (Coleman) transformation

1. INTRODUCTION

An optimal, economically efficient design of wind turbines requires understanding of wind turbine dynamics. Dedicated aeroelastic simulation packages have been developed for aiding engineers in the wind turbine industry to design efficient wind turbines by simulating their dynamic response under different wind conditions, and thereby estimating their performance and durability during the life time. However, numerous uncertainties are inevitable in the numerical modeling (including numerical models and algorithms behind the scenes, properties of the materials used in the design, joints of substructures, their boundary conditions, etc.). This requires validation of the numerical model against reality and, if necessary, a corresponding model tuning.

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A typical engineering approach to analyze structural dynamics of a wind turbine involves its representation as a linear time-invariant (LTI) system of equations followed by its modal decomposition. However, modeling an operating wind turbine, even by a simple analytical model [1, 2], one arrives at a time-variant system, whose equations of motion (EOM) can be written as a set of first order equations:

$$\dot{\mathbf{x}}(t) = \mathbf{A}(t)\mathbf{x}(t), \quad (1)$$

where \mathbf{x} is a state vector describing the state of the rotating rotor with N blades and its non-rotating supporting structure:

$$\mathbf{x} = \{\dot{q}_{1,1} \dots \dot{q}_{1,M}, \dots, \dot{q}_{N,1} \dots \dot{q}_{N,M}, \dot{s}_1 \dots \dot{s}_L, q_{1,1} \dots q_{1,M}, \dots, q_{N,1} \dots q_{N,M}, s_1 \dots s_L\}^T, \quad (2)$$

in which the state of each blade is described by M variables, q_{ij} , where the first index is the blade number, and the second index is the number of the variable on the blade. $s_1 \dots s_L$ describe the non-rotating part. Assuming the rotor speed, blade pitch and yaw angle not changing significantly during the observation period, one arrives at a periodic system. If we further assume moderate deflection perturbations on a mean deflection field, the system of equations may finally be approximated by a linear periodic time variant (LPTV) system with periodic system matrix

$$\mathbf{A}(t+T) = \mathbf{A}(t), \quad (3)$$

where T is the rotor revolution period.

There are two common approaches to LPTV systems: 1) Lyapunov-Floquet (L-F) transformation [3]; and 2) Coleman transformation (also known as multi-blade transformation, MBC) [4]. MBC is more straightforward but assumes, however, rotor isotropy, and is thus applicable only for wind turbines with at least 3 blades (uniformly azimuthally distributed). L-F transformation does not have these limitations. L-F transformation does not have these limitations. It can be shown that under MBC-specific assumptions, there is a similarity between these two transformations [5].

In the case of a three-bladed rotor, the MBC transformation transforms each set of variables $\{q_{1,k} q_{2,k} q_{3,k}\}^T$ into so-called multi-blade coordinates given by

$$a_{0,k} = \frac{1}{3} \sum_{i=1}^3 q_{i,k}, \quad a_{1,k} = \frac{2}{3} \sum_{i=1}^3 q_{i,k} \cos \psi_i, \quad b_{1,k} = \frac{2}{3} \sum_{i=1}^3 q_{i,k} \sin \psi_i, \quad (4)$$

where ψ_i is the azimuth angle of the i^{th} blade¹.

After substituting the multi-blade coordinates into the EOM, the original LPTV system will convert to an LTI system:

$$\dot{\tilde{\mathbf{x}}}(t) = \tilde{\mathbf{A}} \tilde{\mathbf{x}}(t), \quad (5)$$

with a new time invariant system matrix $\tilde{\mathbf{A}} = \text{const}(t)$, and the state vector

$$\tilde{\mathbf{x}} = \{\dot{a}_{0,1}, \dot{a}_{1,1}, \dot{b}_{1,1} \dots \dot{a}_{0,N}, \dot{a}_{1,N}, \dot{b}_{1,N}, \dot{s}_1 \dots \dot{s}_L, a_{0,1}, a_{1,1}, b_{1,1} \dots a_{0,N}, a_{1,N}, b_{1,N}, s_1 \dots s_L\}^T. \quad (6)$$

Applying the MBC transformation to analytically derived EOM for a simple but representative model of a wind turbine, followed by model decomposition, Hansen [1] arrives at modes in multi-blade (MB)

¹ For a three-bladed rotor, $\psi_2 = \psi_1 + 2\pi/3$ and $\psi_3 = \psi_1 + 4\pi/3$. Note, $\sum_{i=1}^3 \cos \psi_i = 0$ and $\sum_{i=1}^3 \sin \psi_i = 0$.

coordinates, which are subsequently translated into the original coordinates \mathbf{x} by the inverse MBC transformation:

$$q_{i,k} = a_{0,k} + a_{1,k} \cos \psi_i + b_{1,k} \sin \psi_i. \quad (7)$$

Here some interesting features of wind turbine dynamics become apparent. For example, the theory predicts that the blade dynamics can be described as a sum of collective, backward- and forward-whirling components which are evolving with the change of the rotor speed [1].

The approach described above presumes the EOM are known. Let us now focus on the experimental parameter identification when the EOM are not known. The use of L-F transformation was demonstrated by Allen and coworkers [6]. In the presented study, another approach is utilized: the time histories of acceleration signals measured on the blades are combined with the measured azimuth angle into the MB coordinates (4); and subsequently, a standard output only modal analysis algorithm (e.g., OMA SSI) is applied to the obtained MB time histories. This approach was first suggested in [7] and demonstrated on simulated time histories from the ALSTOM Eco-100 wind turbine. The presented paper applies the same approach to the measured full-scale data.

In 2010, *Brüel & Kjaer* and *ALSTOM Wind* conducted a project aimed at modal identification of operating 3MW Eco-100 wind turbine [8, 9]. In that project the measurements were done on the tower and nacelle only. The project showed that most of the lower tower and rotor global modes could be successfully extracted from the tower/nacelle measurements only. By means of Campbell diagram, the evolution of the modal frequencies and damping coefficients with rotor speed was demonstrated. Applying the same approach to a large number of datasets recorded during 5 months of observation, it was possible to provide estimation of uncertainties of modal parameters. However, since the blades were not instrumented, it was not possible to visualize the mode shapes of the rotor. Also the identification of the rotor modes based on the tower and nacelle mode shapes was not a straightforward task. Finally, the uncertainties with damping estimation especially for out-of-plane modes were too high. It is anticipated that availability of the data from the blades will help to overcome the abovementioned problems.

To the authors' knowledge, there are very few published works which refer to vibration measurements on a wind turbine rotor while operating, for example [10]. Perhaps, the main limiting factor is technical difficulties in obtaining such data. Indeed, there are many technical challenges such as mounting accelerometers on the blades isotropically; wireless data transfer from the rotating part to the ground and synchronization of the data from the rotor with the data from the non-rotating parts (tower and nacelle). In order to collect enough data for different wind conditions, the sensors and data acquisition system should be able to survive under sometimes harsh weather conditions for a long time, not to mention that the acquisition system should be robust enough to operate unmanned. This defines the scope of the paper: the main focus is on the description of the measurement system and the setup. The feasibility of the setup is demonstrated by the results for the case when the turbine is on brake (i.e., not rotating). However, we have to limit the scope of the paper presenting only the preliminary results for an operating wind turbine that are available at the time of writing.

2. MEASUREMENT SYSTEM AND INSTRUMENTATION

The availability of a wind turbine often defines the scale of the measurement campaign. Vestas V27 which belongs to DTU Wind Energy, (former Risø Danish National Lab for Sustainable Energy) was chosen for the present campaign. On today's scale, this is a small wind turbine with 225kW rated power, 27 m rotor diameter and the hub about 30 m above the ground. However, despite its age, V27 has a design similar to many modern horizontal-axis wind turbines; most importantly,



Figure 1. Vestas V27

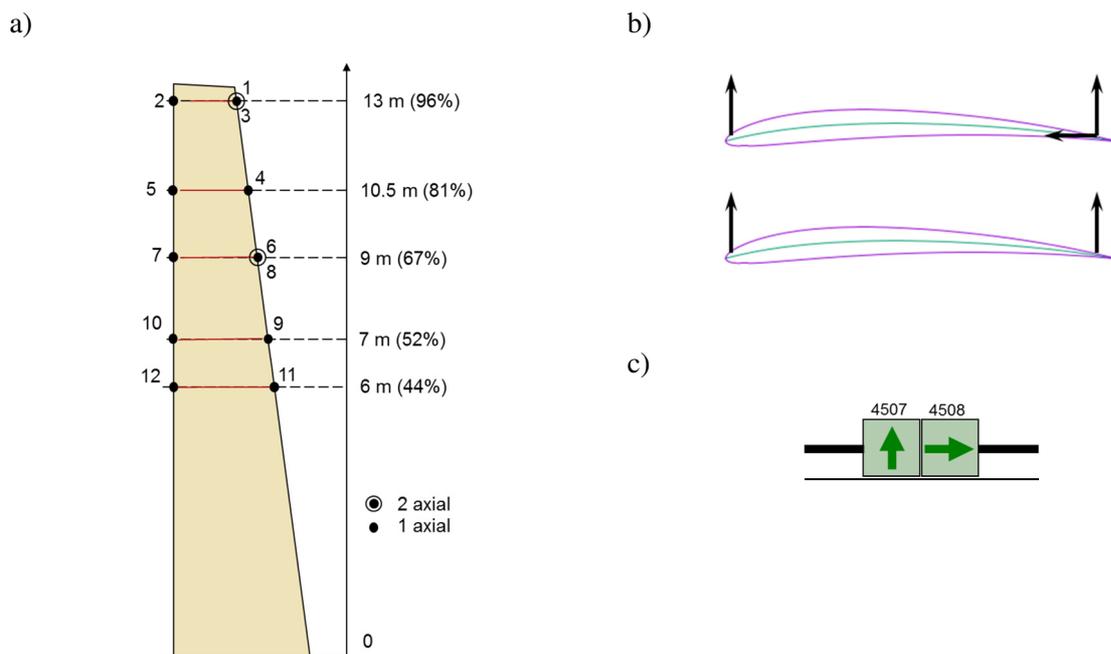


Figure 2 a) Accelerometers location on the blade; b) blade sections equipped with three and two accelerometers; c) placement of the accelerometers with the side mounted and top mounted connectors.

it is pitch-regulated and has three blades. The blades are relatively stiff, and their small size determines the high rotor speed: nominally 46 RPM.

2.1. Instrumentation of the blades

Selection of the number of accelerometers to be mounted on each blade is a result of a compromise between the spatial resolution of the obtained mode shapes (which is directly linked with the ability to identify higher modes) and the complexity and cost of the acquisition system. Knowing the approximate shapes of the lowest flapwise, edgewise and torsional modes, it was decided that 12 channels would be used per blade. The same approximated mode shapes aided with the choice of the accelerometer locations: 5 blade sections were chosen; 10 accelerometer positions were selected to monitor the flapwise vibrations (to resolve flapwise and torsional modes), and two positions were selected for edgewise vibration monitoring (Figure 2). Experience gained as results of numerical simulations using the HAWC-2 simulation software guided the selection of the accelerometers' sensitivity. Three types of accelerometers were chosen¹: the less sensitive to be located closer to the blades, tip, more sensitive – closer to the blades' root. The accelerometers with top-mounted connector were used in the edgewise monitoring, while those with side-mounted connector were used for the flapwise monitoring (Figure 2c).

For MBC transformation, it is important that accelerometers on all blades are mounted similarly, for example, that the position and orientation of the accelerometers mounted at point 1 (Figure 2) on all three blades are as similar as possible. This is quite difficult to implement in practice since it involves precise work at height. Due to a small size of V27, it was possible to dismount the entire rotor and place it on the ground, which significantly simplified the instrumentation task. In order to ensure similarity in accelerometers position and orientation, a special template was made (Figure 3a). A laser distance meter ensured the same distance from each blade section to the hub. The accelerometer cables run on the outer surface of the blade, along the trailing edge. Some free cable length was allowed to account for blades' operational deformation. The cables were fixed with silicon and covered by "helicopter tape" (Figure 3b).

¹ B&K Type 4507-B-006 (0.2-6000Hz, 500mV/g, $\pm 14g$), Type 4508-B-004, same specifications as the first one but with top mounted connector and more sensitive Type 4507-B-002 (0.4-6000Hz, 1000mV/g, $\pm 7g$).

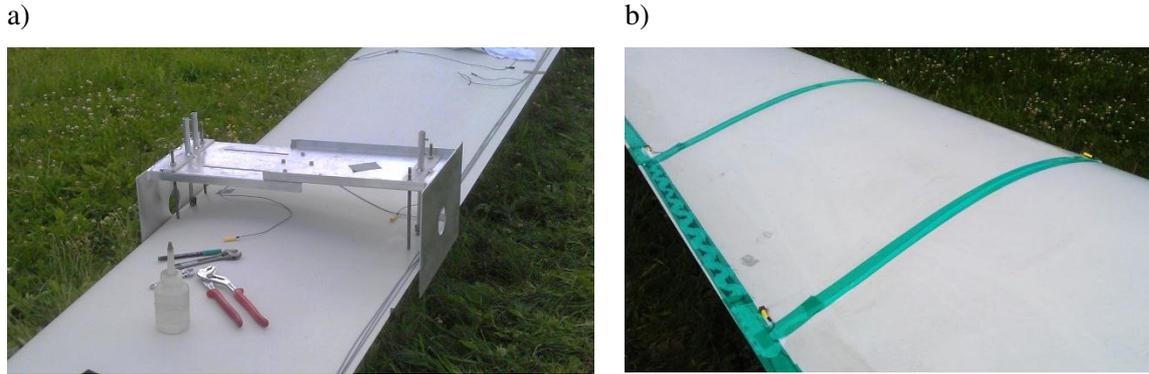


Figure 3 a) Template for accelerometer mounting; b) Cabling

2.2. Data acquisition system

The data acquisition system consists of two parts: a 42-channel front-end in the hub and one 12-channel module in the nacelle. Special requirements are set for the sub-system in the hub: since it shall be rotating with the rotor and is exposed to tough environmental conditions, it shall be extra robust and waterproof. It was decided to implement the system based on 5-Module Brüel & Kjær (B&K) LAN-XI frame Type 3660-C fitted with three 12-channels modules Type 3053-B-120 with 50-pin Sub-D panel (one module per blade). This panel ensures the robust connection of accelerometer cables to the front-end. The fourth module is a 6-channel Type 3050-A-060 with a panel equipped with four LEMO and two BNC connectors. This module collects data from a synchronization IRIG-B signal as well as from two DC accelerometers for measuring azimuth and pitch angle signal. The purpose of this equipment will be explained later.

The frame was placed in a waterproof box (Figure 4a) together with a Cisco access point AP-1262 and an IRIG-B time code generator ES-292. The box was mounted inside the V27's spinner (Figure 4b). The equipment in the box is powered over a slip ring (24VDC).

The nacelle sub-system is a 12-channel B&K LAN-XI data acquisition module Type 3053-B-120. Three 3-axial accelerometers¹ placed on the nacelle structure are connected to the module. The tower is not instrumented in the current scenario. There is also a high-speed shaft tachoprobe and an IRIG-B signal generator connected to the same module.

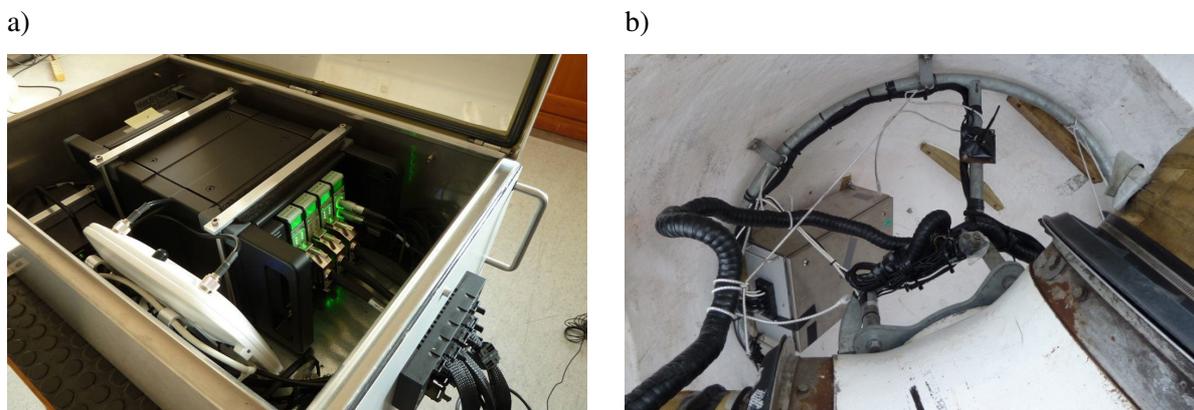


Figure 4 a) Waterproof box with 42-ch. data acquisition system; b) the box mounted inside V27's spinner.

¹ B&K Type 4506-B-3 (0.3-2000Hz, 500mV/g, $\pm 14g$)

2.3. Wireless data transmission

B&K LAN-XI data acquisition modules transmit data using Ethernet protocol. This makes it possible to employ a standard 3rd party wireless access point to replace a wired link by a wireless connection between the rotating and non-rotating sub-systems. In order to avoid drops in connection, advanced access points were employed. Cisco AP-1262 supports wireless protocol 802.11n ver.2 with multiple-input multiple-output with two spatial streams. This is important in the current scenario where transmitting and receiving parts move against each other, and the line of sight between antennas is often blocked by rotating elements.

The connection employs two AP-1262. One is inside the waterproof box and uses two omnidirectional 5GHz antennas for data transmission. The other is located in the nacelle and receives the data using two directional antennas.

2.4. Other equipment

MBC-transformation requires the instantaneous position of the rotor (azimuth angle) as well as orientation of the blades (pitch angle). In the previous project [8, 9], the pitch, yaw and azimuth angles were possible to obtain from the wind turbine control system. This is not the case with the current setup. V27 does not allow any access to its control system; thus the pitch and azimuth angles that are necessary for the modal analysis need to be measured.

The azimuth is measured indirectly by means of two DC accelerometers (B&K Type 4574-D, 0-500Hz, 200mV/g, $\pm 10g$). The accelerometers are mounted inside the waterproof box.

In-plane and out-of-plane stiffness of the rotor depends on pitch angle. The pitch on V27 is regulated mechanically using a hydraulically driven rod passing inside the main shaft. The position of the rod defines the pitch angle and a position sensor (ASM WS10-420T) is employed to measure the rod position. There is a geometrical non-linearity between pitch angle and rod position, and to resolve this, a multi-point sensor calibration was performed.

The two DC accelerometers and the pitch sensors are connected to the hub front-end.

A laser tachoprobe (B&K Type 2981) is mounted on the generator providing one pulse per revolution of the high speed shaft. The tacho signal is used to estimate the rotation speed of the rotor. The tachoprobe is connected to the nacelle front-end.

2.5. Synchronization

B&K LAN-XI technology uses Precision Time Protocol (PTP) for module synchronization over Ethernet. However, the wireless Ethernet protocols cannot guarantee that the transit time of a message going from the master module to a slave module is equal to the transit time of a message going from the slave to the master, which is one of the main PTP assumptions. This means that LAN-XI modules cannot be synchronized when a wireless connection is used.

In order to overcome this, external synchronization events can be utilized. A GPS signal holds information about precise time, and it can be used for module synchronization. An IRIG-B signal can be generated from the GPS signal by means of IRIG-B code generator (e.g., ES-292). IRIG-B signal (Figure 5) is an amplitude modulated signal with 1kHz carrier frequency which encodes precise time. By recording IRIG-B signals synchronously with other signals, on two non-synchronized front-ends, one can post-synchronize the two data streams.

Figure 5 shows two IRIG-B signals, the top one is recorded by the nacelle front-end, the bottom one by the hub front-end. There is about 0.5ms delay between the two signals. The delay constantly changes, and can become both positive and negative. The biggest delay observed in the recordings was about 2 ms, which may result in a 72^0 phase error on 100Hz if post-synchronization is not performed.

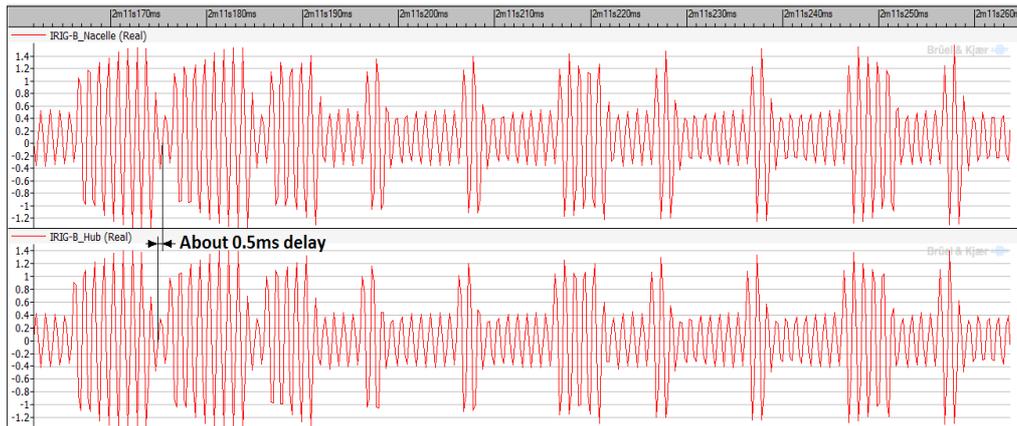


Figure 5. IRIG-B signals from the nacelle front-end (top) and hub front-end (bottom) and the delay between them.

3. MEASUREMENTS

The data collected by the hub and nacelle front-ends are transmitted via standard Ethernet cable to a computer located on the first platform in the tower (about 4m above ground). No analysis is performed; the data are simply recorded to an external hard disk using B&K PULSE Time Data Recorder Type 7708. A total of 51 channels are sampled at 4096Hz. Such a high sampling frequency is not necessary for modal analysis where the concerned modes have frequencies below 40Hz. The high sampling frequency was chosen as the data will be used for purposes that are out of scope of this paper. The data is saved in 5 minutes chunks with the possibility of appending the chunks if post-processing requires a longer time history.

The measurements were started on 31 October 2012, and are going on at the time of writing. Weather condition information during the observation period is available from one of the weather masts located nearby the V27. The weather mast provides full information including temperature, wind speed and wind direction at different heights, etc., stored as mean values and standard deviations for every 10-minute interval.

4. RESULTS

At the time of writing, only preliminary results are available. Three cases are considered below: the wind turbine with brake applied; idle case and normal operating case.

4.1. V27 with the brake engaged

This case is the simplest for analysis but it is quite a rare state of a wind turbine. Typically, when a wind turbine is not operating, it is set to *idle*. This means that the blades pitch set to maximum thus creating least aerodynamic loads from the wind. The rotor freely and slowly rotates due to wind loading. The idle case will be considered in the next section.

When the brake is engaged, the rotor is fixed. In the case of no pitch and yaw activity, the wind turbine becomes a time-invariant system. This greatly simplifies modal analysis since all OMA assumptions are fulfilled. This trivial case is briefly considered here to revisit the main modes of a typical horizontal axis wind turbine.

The V27 brake was engaged when one of the blades was pointing upwards and 15 minutes of data were recorded. OMA was performed using B&K PULSE OMA Type 7760, and the Stochastic Subspace Iterations with Un-weighted Principal Components (SSI UPC) method was employed.

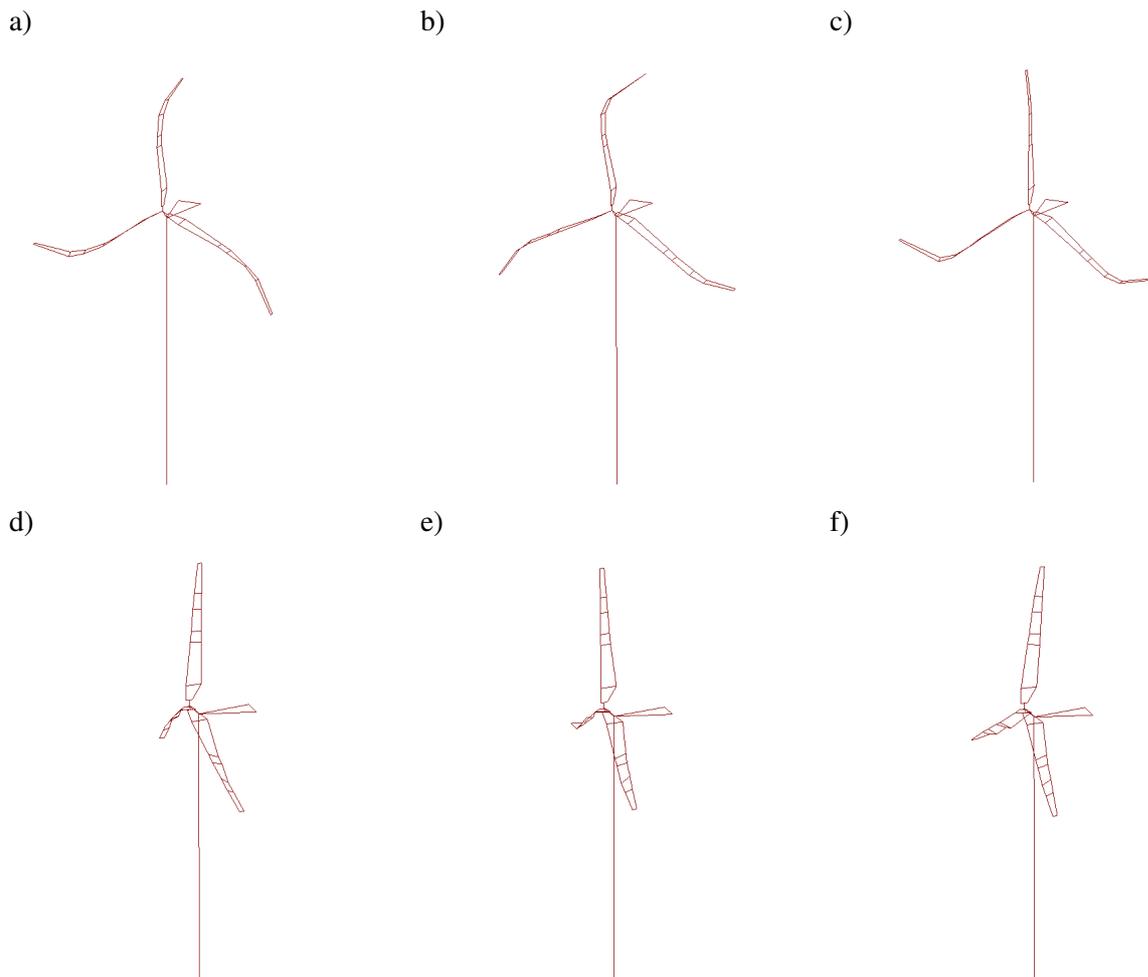


Figure 6. Typical families of modes for a horizontal axis wind turbine. Top: 2nd in-plane mode, a) collective, b) yaw, c) tilt; Bottom: 1st out-of-plane mode: d) collective, e) yaw, f) tilt.

Let us consider a *single* blade clamped at the root. The blade has a number of modes can be categorized into three categories: flapwise, edgewise and torsional. This subdivision is artificial since the modes often interact. Now let us consider a *rotor* with three almost identical blades joined together via the hub. Each mode of a *single* blade constitutes a *family* of three rotor modes. Depending on their phase and the reaction of the rest of the structure, the modes in the family are called collective, tilt- and yaw-mode [1]. Figure 6 demonstrates two such families. The second flapwise mode of the single blade becomes a family of *three* second in-plane modes (since the pitch is almost 90^0 when the brake is engaged), Figure 6 a,b,c. The first edgewise mode of the single blade becomes a family of three first out-of-plane modes, Figure 6 d,e,f. The rotor modes interact with the nacelle and tower, and can also involve torsional motion of the blades. The frequencies of the modes in the same family differ since the supporting structure (the tower and nacelle) is not symmetric. In-plane modes have generally higher damping compared to the out-of-plane modes due to the higher aerodynamic damping of a blade in flapwise direction.

4.2. Idle case

The idle and braked cases are very similar: the turbine is not operating and the pitch angle is set to maximum. However, from the dynamic perspective the cases are different. Allowing free rotation of the low-speed shaft adds an extra degree of freedom to the system. This should affect the modes involving rotor in-plane motion, mainly collective modes and drive-train modes.

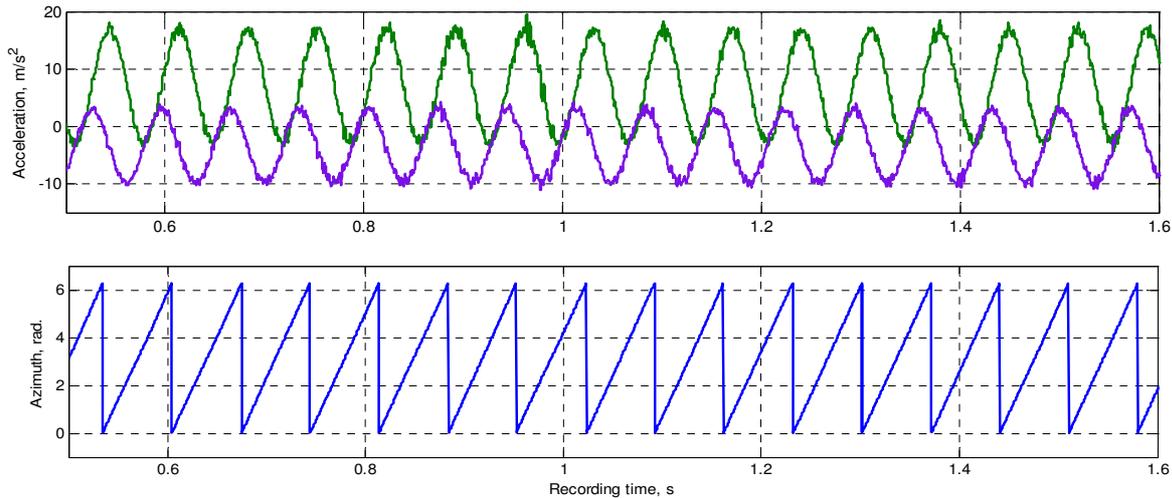


Figure 7. Top: row DC accelerometers signals; bottom: calculated azimuth angle.

As mentioned above, when the turbine is idle, the rotor is slowly rotating due to wind loading. This prevents the modelling of idling wind turbine as an LTI system. At the same time, the speed of rotation is not constant, which prevents using methods designed for LPTV systems.

To overcome this, one has the following options:

- 1) Use the datasets where the rotor is not rotating for a sufficiently long observation time. However, according to experience, this happens only when no wind is present. Unfortunately, in this case, there is also no wind excitation of the structure that can cause vibrations sufficient for application of OMA.
- 2) Ignore data from the blades. As was shown in [9], it is possible to identify the modal parameters based on the accelerations measured on the non-rotating parts only. In this case, however, the mode shapes of the rotor will not be observed.

4.3. Operating case

For the operating case, the datasets characterized by constant rotor speed and no pitch activity were selected. Signals from the DC accelerometers were LP-filtered to refine the sinusoidal component due to the rotor rotation in the field of gravity. Subsequently, the mean was subtracted from the obtained time histories to remove the DC-offset due to the centrifugal force due to eccentricity of the DC-accelerometer mounting point. Using zero-crossings of these conditioned time histories, the azimuth angle was estimated assuming constant rotor speed within each half revolution which, taking into account the huge moment of inertia of the rotor, is believed to be a valid assumption¹. The input and output of the algorithm outlined above are shown in Figure 7.

Since the azimuth angle can be determined up to a constant phase, it is also possible to use a high-speed shaft tacho signal for this purpose. However, the exact gear ratio of the V27 gearbox was not known. Using the known approximate gear ratio could lead to a significant bias error in the azimuth estimation during a long observation period; thus this method was not used.

The estimated instantaneous rotor azimuth angle was used to convert the accelerations measured on the rotating parts into multi-blade coordinates according to (4). The acceleration signals measured on non-rotating parts were appended to the multi-blade coordinate time histories as they are. Subsequently, a standard OMA SSI was applied to the aggregated dataset. The results are the modal parameters of the underlying LTI system. The modal frequencies and damping coefficients can be used directly; the visualization of the physical mode shapes can be obtained from the inverse Coleman

¹ This assumption was verified against the RPM-profile calculated based on the HSS tacho signal.

transformation (7), where ψ_1 could either be selected fixed or changing in time as $\psi_1(t) = \Omega t$, where Ω is the mean rotor angular velocity.

At the time of writing, analysis of the data is not complete; just a few datasets were processed to check the validity of the results (Figure 8). As expected, the harmonics are clearly seen in the spectra, which calls for some harmonic removal pre-processing, either by synchronous averaging or by the cepstral-based method suggested in [11]. Also, since the OMA assumptions are not completely fulfilled under operating loading [12], many sporadic computational modes are experienced. It has been shown [13], that a clustering approach can be successfully used for filtering these modes.

5. FURTHER RESEARCH

It is planned to develop a procedure that will be able to apply all above-mentioned pre-processing steps (post-synchronization, harmonic removal, multi-blade transformation) and perform SSI-based modal parameters estimation in an automatic manner. As for the post-processing, automatic clustering will filter out the computational modes. Having the modal parameters for known weather conditions will allow creation of a map of normal/reference states of the particular wind turbine, which can be used, for example, for structure health monitoring purpose.

Multi-blade coordinate transformation employed in this study assumes rotor isotropy as well as isotropy of the sensors. In reality these assumptions are never exactly fulfilled. Therefore it is also appealing to take advantage of the Lyapunov-Floquet analysis approach, which does not set any requirements regarding the isotropy.

6. CONCLUSIONS

The paper presents the main steps to convert a periodic time-variant dynamic system to a time-invariant analogy, which then can be analysed using conventional output-only modal analysis. The approach, which has been previously validated on simulated data, is now being applied to full scale measured data. For this reason, a data acquisition system was designed and mounted on a test Vestas V27 wind turbine. The system is capable of measuring accelerations on the blades when the turbine is operating, and synchronizing the data stream from the rotating part with the data measured on non-rotating part of the wind turbine. The details of the acquisition system are given. Some preliminary results of output-only modal analysis applied to a parked and operating wind turbine are presented and discussed.

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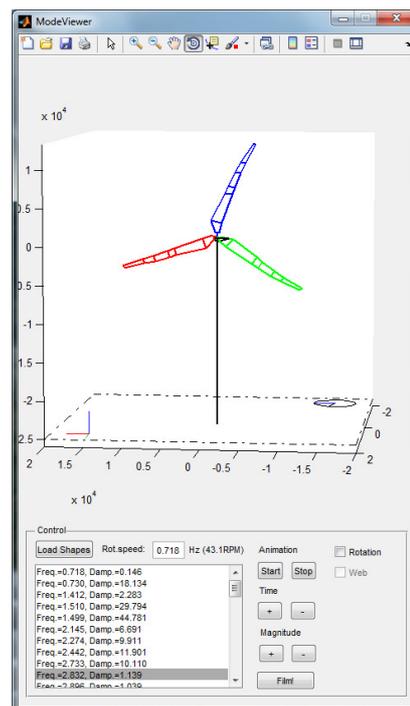


Figure 8. MATLAB® GUI for mode visualization on operating wind turbine. Presumably, the first in-plane forward whirling mode is shown.

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