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Structural Health Monitoring challenges on the 10-MW offshore wind turbine model

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Structural Health Monitoring challenges on the 10-MW offshore wind turbine model

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Abstract. The real-time structural damage detection on large slender structures has one of its main application on offshore Horizontal Axis Wind Turbines (HAWT). The renewable energy market is continuously pushing the wind turbine sizes and performances. This is the reason why nowadays offshore wind turbines concepts are going toward a 10 MW reference wind turbine model. The aim of the work is to perform operational analyses on the 10-MW reference wind turbine finite element model using an aeroelastic code in order to obtain long-time-low-cost simulations. The aeroelastic code allows simulating the damages in several ways: by reducing the edgewise/flapwise blades stiffness, by adding lumped masses or considering a progressive mass addiction (i.e. ice on the blades). The damage detection is then performed by means of Operational Modal Analysis (OMA) techniques. Virtual accelerometers are placed in order to simulate real measurements and to estimate the modal parameters. The feasibility of a robust damage detection on the model has been performed on the HAWT model in parked conditions. The situation is much more complicated in case of operating wind turbines because the time periodicity of the structure need to be taken into account. Several algorithms have been implemented and tested in the simulation environment. They are needed in order to carry on a damage detection simulation campaign and develop a feasible real-time damage detection method. In addition to these algorithms, harmonic removal tools are needed in order to dispose of the harmonics due to the rotation.

1. Introduction

The growth of the wind energy market is driven by several factors. One of the most important is the impressive improvements in the wind turbine technologies. The rated power capacity for a single wind turbine has dramatically increased from some kW in the 1980s to 8-MW in 2014. At the same time the rotor diameter has reached values higher than 150 meters.

Historical trends suggest that the on-shore wind turbine size and power capacity will be continuously increasing. On the other hand, since high potential sites on the land have already been taken, in the past years the off-shore wind potential has been exploited taking advantage of the strong and steady wind.

In the offshore sector, the cost associated to Operation and Maintenance (O&M) is extremely high. In order to reduce this cost, efficient Structural Health Monitoring (SHM) techniques need to be developed for such systems. Wind turbine manufacturers, owners and operators would benefit financially from SHM technology, which provides an indication of the reliability of each wind turbine in its lifecycle. SHM will provide actionable information that the maintainers can use to schedule maintenance ahead of time to avoid more costly unforeseen maintenance actions.

A finite element model of a 10-MW reference wind turbine has been built by using an aeroelastic code. The final aim of the work is to combine together Operational Modal Analysis and SHM techniques by developing a feasible damage detection method based on the modal parameters of the structure. Most existing modal parameter estimation techniques assume that the system to be analysed is a Linear Time Invariant (LTI) system. In the case of a wind turbine, this can be considered true if the brake is engaged and the blades are not rotating. When the wind turbine is in operating conditions, the structure cannot be considered anymore as LTI. If the angular speed can be approximated with a constant value, then the wind turbine can be considered as a Linear Time Periodic (LTP) system. Several modal parameter estimation techniques can be adapted and applied to such a case.

2. Operational Modal Analysis for LTP systems

Operational Modal Analysis (OMA) is a suitable tool for estimating the modal parameters of a structure. It has its main application in cases of huge systems such as bridges, stadiums, airplanes, and spacecraft because there are very limited or no practical ways to excite them in controlled manner.

Several pre-processing techniques have been developed in the past years in order to apply standard modal parameter estimation techniques to rotating structures, such as helicopters and wind turbines. The main two techniques which will be analysed in details are the so-called Multi-Blade Coordinate (MBC) transformation and the Harmonic Power Spectrum (HPS) method.

2.1. Multi-Blade Coordinate transformation

The MBC approach is also known as Coleman theory because it was developed, in its first formulation, by Coleman [1] for helicopter analysis. The transformation allows converting the rotating degrees of freedom into a non-rotating frame. In [2] a numerical approach has been introduced for wind turbines. It properly models the dynamic interaction between the non-rotating systems such as tower and nacelle, and the spinning rotor. It also offers a better understanding of the interaction between fixed and rotating bodies. One of the main advantages of the technique is that it filters out all the periodic terms except those ones which are integral multiples of NΩ, where Ω is the rotor angular speed and N is the number of blades.

Considering a rotor with 3 blades, we need to assume that the blades are equally spaced around the rotor azimuth. In such case, the azimuth angle of the *b*-th blade can be obtained by using equation (1). ψ represents the instantaneous azimuth angle of a reference blade by assuming that this blade is vertically up when $\psi = 0$.

$$\psi_b = \psi_1 + (b-1)\frac{2\pi}{3}, \qquad b=1,\ 2,\ 3 \tag{1}$$

The blade coordinates $q_{b,i}$ can be, for example, the accelerations measured by sensors placed along the blades at the location *i*. They can be transformed into the multi-blade coordinates $q_{0,i}$, $q_{c,i}$ and $q_{s,i}$ by means of equation (2).

$$q_{0,i} = \frac{1}{N}\sum_{b=1}^{N} q_{b,i} \qquad q_{c,i} = \frac{2}{N}\sum_{b=1}^{N} q_{b,i}\cos(\psi_b) \qquad q_{s,i} = \frac{2}{N}\sum_{b=1}^{N} q_{b,i}\sin(\psi_b) \tag{2}$$

The physical interpretation of the new coordinates is not immediate and it depends on the considered degree of freedom. Anyway the first coordinate $q_{0,i}$ represents the collective symmetric behavior of the blades, while the other two coordinates represent the asymmetric one.

Concluding, MBC transformation can be used as a data pre-processing step before an OMA algorithm is applied. The following steps need to be accomplished:

- acquire the accelerations at several locations along the blades and along the tower;
- transform the accelerations of the blade by using equation (2) and by taking into account the azimuth angle, whereas the accelerations acquired on the non-rotating subsystems remain unchanged;
- combine the two sets of accelerations together and perform OMA by using Operational Polymax [3] for estimating the modal parameters (natural frequencies, damping ratios and multi-blade mode shapes);
- apply equation (3), also known as inverse MBC transformation, in order to get the physical mode shapes.

$$q_{b,i} = q_{0,i} + q_{c,i}\cos(\psi_b) + q_{s,i}\sin(\psi_b) \tag{3}$$

Previous studies have shown the applicability of this procedure to operating wind turbines built by using aeroelastic codes [4], [5]. The application of the same technique to real operating data obtained in the experimental field has been addressed only in few works [6], [7].

2.2. Harmonic Power Spectrum method

For Linear Time Invariant (LTI) systems, the signal of fundamental importance is the complex exponential signal, also referred as sinusoidal signal. When such a signal of a given frequency is injected into a LTI system, the output response is a complex exponential signal of the same frequency, but with possibly different amplitude and phase. Instead, for a Linear Time Periodic (LTP) system the response to the same input will be at a combination of frequencies, each separated by the fundamental, or rotating, frequency *Ω*.

In order to extend the concept of transfer function to LTP systems, Wereley [8] introduced the Exponentially Modulated Periodic (EMP) signals which can be expressed as the complex Fourier series of periodic signals of fundamental frequency *Ω*, modulated by sinusoidal signals. They can be seen as a collection of frequency shifted signals, which are described by equation (4). Theoretically, an infinite number of harmonics should be considered to characterize a LTP system, but most part of the systems is well approximated with a finite, perhaps small number.

$$u(t) = \sum_{n=-\infty}^{\infty} u_n e^{(j\omega + jn\Omega)t} \qquad y(t) = \sum_{n=-\infty}^{\infty} y_n e^{(j\omega + jn\Omega)t} \tag{4}$$

The property for which an EMP input signal *u(t)* causes an EMP output signal *y(t)* of the same frequency but with possibly different amplitude and phase allows defining the Harmonic Transfer Function (HTF). The HTF is completely analogous to the commonly known transfer function for LTI systems. The main difference between the two transfer function is that the standard one relates the output at a single frequency to the input at the same frequency, whereas the HTF relates the input at a collection of frequencies each separated by *Ω* to the output at the same collection of frequencies.

The use of the Harmonic Transfer Function (HTF) has been extended to output-only linear time periodic systems by introducing the so-called Harmonic Power Spectrum (HPS). The method can be seen as an extension of classical Operational Modal Analysis to time periodic systems [9].

The autospectrum $S_{yy}(\omega)$ of an EMP signal can be obtained in the standard way by breaking the modulated time signals into several blocks, applying a Hanning window, computing the Discrete Fourier Transform of each block and then averaging. The autospectrum formulation is shown in equation (5) where E denotes the expectation and $(\ )^H$ denotes the Hermitian, whereas $Y(\omega)$ is the frequency domain representation of the EMP output signal.

$$S_{yy}(\omega) = E\left[Y(\omega)Y(\omega)^H\right] \approx \sum_{r=1}^{N}\sum_{l=-\infty}^{\infty}\frac{C_{r,l}W(\omega)_{r,l}C_{r,l}^H}{\left[j\omega-(\lambda_r - jl\Omega)\right]\left[j\omega-(\lambda_r - jl\Omega)\right]^H} \tag{5}$$

In equation (5), $W(\omega)$ is a function of the input spectrum and the input characteristic of the system. The autospectrum of the output can be approximated by a sum of modal contributions if the excitation is reasonably flat in the frequency domain. The term λ_r corresponds to the complex eigenvalue of the r-th mode of the system and the mode vector $C_{r,l}$ is not the usual mode vector describing the mode shape at different points, but it is comprised of the Fourier coefficients for the r-th mode but with the position of the elements shifted by l in the coefficient vector [10].

Summarizing, the following steps need to be accomplished in order to apply successfully the HPS method:

- acquire the output signal $y(t)$ of a LTP system subjected to a white noise broadband excitation;
- construct the EMP signal by considering shifted copies of the output, as shown by equation (4);
- compute the autospectrum of the EMP signal by averaging multiple blocks of the time history;
- use Operational Polymax system identification technique to estimate the modal parameters from the autospectrum, as shown by equation (5);
- reconstruct the time periodic mode shapes using the identified Fourier coefficients $C_{r,l}$.

3. 10-MW wind turbine model

In the past years, DTU Wind Energy developed a new reference 10-MW offshore wind turbine (DTU 10MW RWT). A detailed report has been provided. It contains a description of the complete aerodynamic, structural and aeroelastic model for the DTU 10MW RWT [11]. The aeroelastic solution has been computed by using LMS Samcef Wind Turbines (SWT). This is an aeroelastic code which integrates all the main aerodynamic, structural, multi-body and control features of the wind turbine in a fully dynamic environment.

The model is shown in figure 1 and its main parameters are listed in table 1. The tower is made from steel and it has been modelled by using 10 beam elements with a constant thickness for each segment. The outer diameter is varying linearly from the tower bottom to the top. The three identical blades have been modelled by specifying the mass, elastic and aerodynamic properties provided in [11]. Finally, the drivetrain has been built by using rigid connection with a gear ratio equal to 50:1.

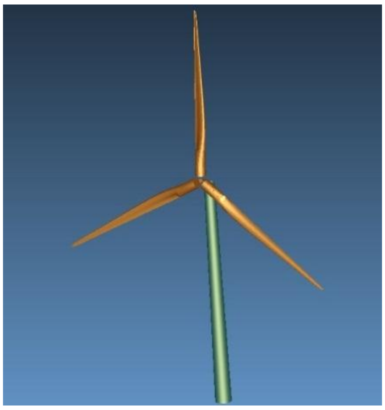

Figure 1. 3D view of 10-MW wind turbine model

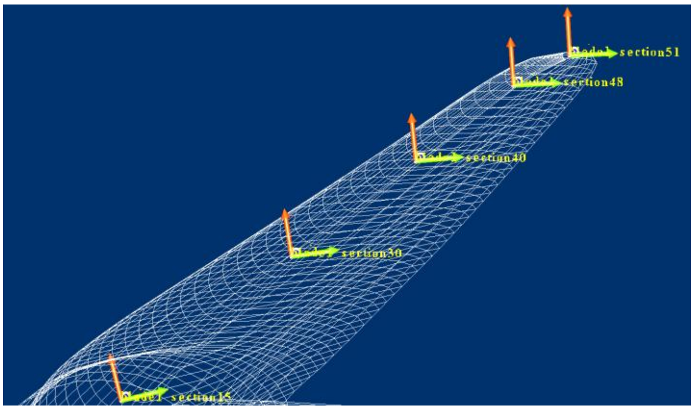

Figure 2. Virtual accelerometers placed along the blade

The Kaimal turbulence model has been selected for performing the analysis [12]. The main wind component is in the direction perpendicular to the rotor plane and the turbulent fluctuations are in the other two directions. The average wind speed has been set equal to 10 m/s.

In order to validate the model, the natural frequencies extracted from the model after the linearization process have been compared to the ones provided by DTU in [11]. A very good agreement has been found and the comparison is shown in table 2.

Table 1. Key parameters of the DTU 10 MW RWT

Main parameters	
Rated power	10 MW
Rated rotor speed	9.6 rpm
Rotor diameter	178.3 m
Tower height	119.0 m
Rotor mass	227962 kg
Tower mass	628422 kg
Gearbox ratio	50:1

Table 2. Natural frequencies comparison (FA = Fore-Aft; S2S = Side-to-Side)

Mode	DTU [Hz]	SWT [Hz]
1st Tower FA	0.249	0.247
1st Tower S2S	0.251	0.251
1st flap with yaw	0.547	0.550
1st flap with tilt	0.590	0.598
1st collective flap	0.634	0.636
1st edge with tilt	0.922	0.940
1st edge with yaw	0.936	0.956
2nd flap with yaw	1.376	1.413
2nd flap with tilt	1.550	1.573
2nd collective flap	1.763	1.812

4. Application of the pre-processing techniques to the wind turbine in operating conditions

The wind turbine has been instrumented by means of twenty virtual accelerometers: five along the tower and five for each blade distributed along the pitch axis as shown in figure 2. The sampling frequency has been set to 100 Hz and the simulations have been running for 1000 seconds. In general, long time histories are necessary for confident modal parameters estimation, but on the other hand a reasonable computational time is also needed. Afterwards, a down-sampling to 10 Hz has been performed since the modes of interests are below 5 Hz.

First of all the DTU 10MW RWT has been analysed in parked conditions, which means by disconnecting the generator and by activating the brake. In this case, the blades are not rotating and standard Operational Modal Analysis techniques can be applied because the system is linear time invariant. The time series can be exported to LMS Test.Lab in which the correlations and the spectra can be computed and Operational Polymax can be applied in order to extract the modal parameters. A very good agreement with the modal parameters listed in table 2 has been found, with a relative error lower than 1%.

While the application of OMA techniques is straightforward in case of parked wind turbines, the same does not apply to operating wind turbines. In fact, when the blades are rotating, the implemented algorithms discussed in Section 2 need to be applied to the time series in order to take into account the time varying nature of the system in operating conditions. In this case, the harmonics due to the rotation mask the dynamic behaviour of the structure, as shown in figure 3 where the comparison between operating and parked conditions has been done in terms of crosspowers. The rotor angular speed has been set to 9.6 rpm, which correspond to 0.16 Hz, and an accelerometer placed on the tower top has been chosen as reference channel for the computation.

By applying the Multi-Blade Coordinate transformation, all the periodic terms except those which are integral multiples of 3p, where p is the rotor angular speed are filtered out, as shown in figure 4. All pairs of asymmetric rotor edgewise modes in parked conditions become pairs of rotor whirling modes owing to the rotation. They can be observed and identified only after that one of the two techniques mentioned in Section 2 has been applied.

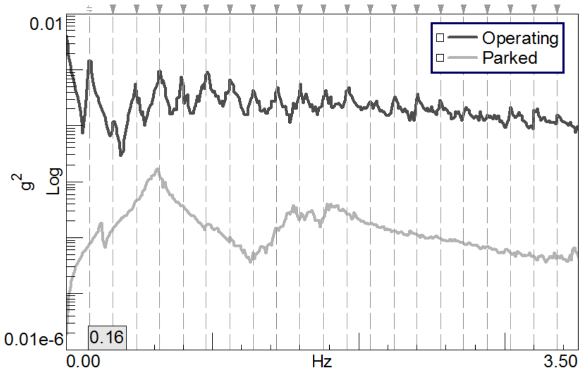

Figure 3. Crosspower comparison in parked configuration (light grey) and in operating configuration (dark grey)

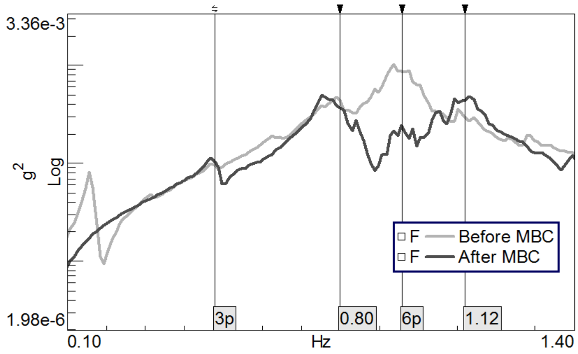

Figure 4. Crosspower comparison before (light grey) and after (dark grey) MBC transformation

The two whirling modes are identified at the frequencies listed in table 3. They are separated by 2p (0.32 Hz) in accordance with the literature. Once that the natural frequencies and damping ratios have been evaluated, the mode shapes need to be converted back to the physical coordinates in order to be animated and compared to the ones obtained by using the Harmonic Power Spectrum method. Table 3 shows the comparison of the results by applying OMA without any pre-processing technique and by applying the two techniques introduced in Section 2. A very good agreement in terms of natural frequencies has been found by applying MBC and HPS.

The whirling modes can also be identified by looking only at the tower accelerometers signals in the lateral direction. In figure 5 the autopowers of such signals are shown for three different conditions: a parked configuration and two rotating configurations with a different rotational speed (8 rpm and 9.6 rpm).

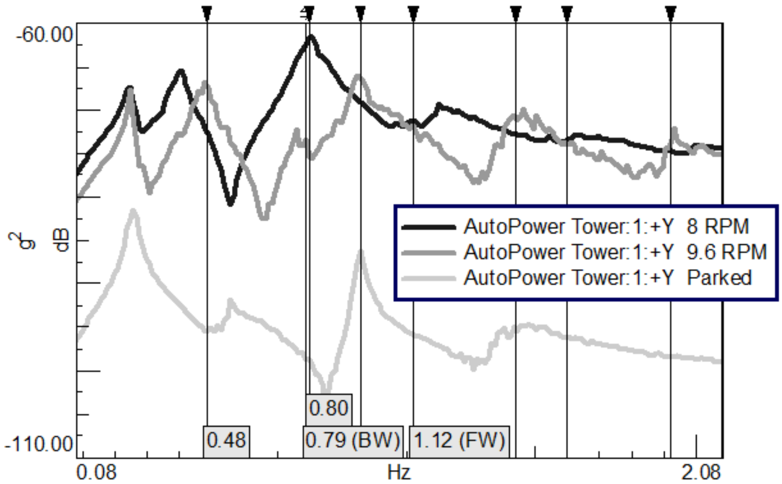

Figure 5. Whirling modes identification from tower accelerometers in three different conditions: parked configuration (light grey), operating configuration with p=8 rpm, operating configuration with p=9.6 rpm

In operating conditions the amplitudes of the signals are much higher than in the parked configuration. The shift toward lower frequencies of the 3p components can be seen in operating conditions by reducing the rotational speed from 9.6 rpm (nominal speed) to 8 rpm. The whirling modes are shifting as well because the difference among them, which is equal to 2p, reduces when the rotational speed decreases.

Table 3. Backward and forward whirling modes identification procedure

Mode	OMA Parked [Hz]	MBC + OMA Rotating [Hz]	HPS + OMA Rotating [Hz]
1^{st} edge with tilt/ BW	0.94	0.80	0.79
1^{st} edge with yaw / FW	0.95	1.12	1.12

5. Structural Health Monitoring considerations

In order to perform Structural Health Monitoring (SHM) studies, the first step is the identification of the most sensitive modal characteristic. In this paper we mainly look at the whirling modes which are the most identifiable modes in operating conditions. Both magnitude and phase of these mode shapes can be considered as damage detection indicators. By looking at the backward whirling mode, but the same considerations can be drawn also for the forward whirling mode, it can be seen that the shapes have constant amplitudes and the phase lag between the blades is constant and equal to 120°.

By considering a simple bi-dimensional model of the DTU 10 MW RWT, it can be seen that reducing the stiffness of one blade by 2%, the two properties of the whirling mode shape are lost. As shown in figure 6 and figure 7, the phase lag between the blades is not anymore equal to 120° and the amplitude is not anymore the same for all the blades.

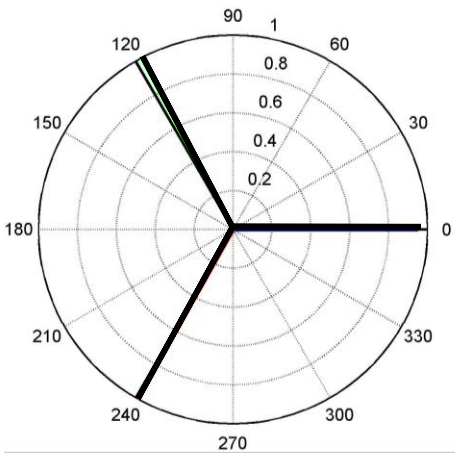

Figure 6. Normalized amplitude and phase of backward whirling mode in healthy conditions

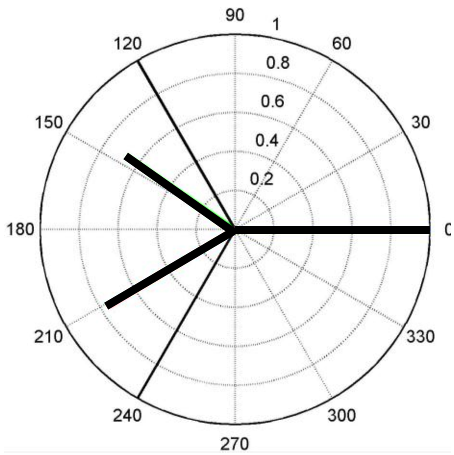

Figure 7. Normalized amplitude and phase of backward whirling mode in damaged conditions (0° blade stiffness reduced by 2%)

Conclusions

The operational data pre-processing techniques, known as Multi-Blade Coordinate transformation and Harmonic Power Spectrum method, seem to be very promising to allow the estimation of modal parameters in case of Linear Time Periodic system such as operating wind turbines and helicopters. Once they are successfully applied, standard techniques for estimating the modal parameters can be used. In this work, Operational Polymax has been used in order to perform the Operational Modal Analysis step.

The so-called whirling modes are always well identified in several conditions and with both the pre-processing techniques combined with OMA. The magnitude and phases between the blades for these modes have demonstrated to be very sensitive to the introduction of small blade damages. Anisotropies can be introduced in the system by modifying the stiffness parameters of a single blade. In a simulation environment, it has been proven that by looking at the in-plane whirling mode shapes it is possible to identify small variations of the stiffness, which means that small damages into the blade structure could be identified.

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