Sereema White paper

Wind turbine rotor monitoring

by Bruno Pinto January 2017

Rotor balance of wind turbines

The Rotor and blades are the key components that convert wind energy into mechanical power for the wind turbine. Rotor blades are highly loaded components: even in normal turbine operations, stress to the blades and to the entire structure of the wind turbine is high. Additional loads and under performance may occur when rotor fault conditions exist [1], such as:

- Increased blade surface roughness due to pollution, icing, blow-holes, and exfoliation;
- Mass imbalance due to excessive weight following a blade repair, icing, water penetration through cracks and loose material moving inside the blades;

- Aerodynamics asymmetry due to differences between the three blades in respect to the angle of attack of the air flow, blade pitch angle errors, aerodynamic profile production tolerances and profile deformation during operations;

- Cracks on the blade surface and internal structure.

The blade faults mentioned above increase the structural loads and decrease the wind turbine's power output. This paper will be focused on the rotor faults concerning it's balancing quality. The imbalance of the rotor can generally be divided into two categories: mass imbalance and aerodynamic imbalance.

The results from in-situ rotor balancing of over 1.000 wind turbines [3] show that 45% of them present inadmissible rotor imbalance levels, as presented in Figure 1. This sub-divides into 15% each for mass imbalance, aerodynamic imbalance, and combined mass and aerodynamic imbalance.

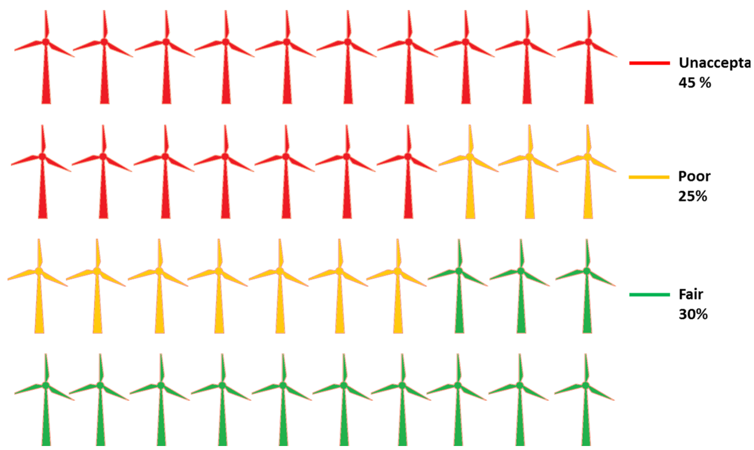

Fig.1 - Statistical results obtained from over 1.000 operating wind turbines [3].

Mass Imbalance

Mass imbalances result from inhomogeneous mass distributions in the blades that can be caused by multiple factors, as presented above. It can be described as a virtual mass m at a distance r of the center of the rotor that rotates at the same rotational speed as the rotor presented in Fig. 2.

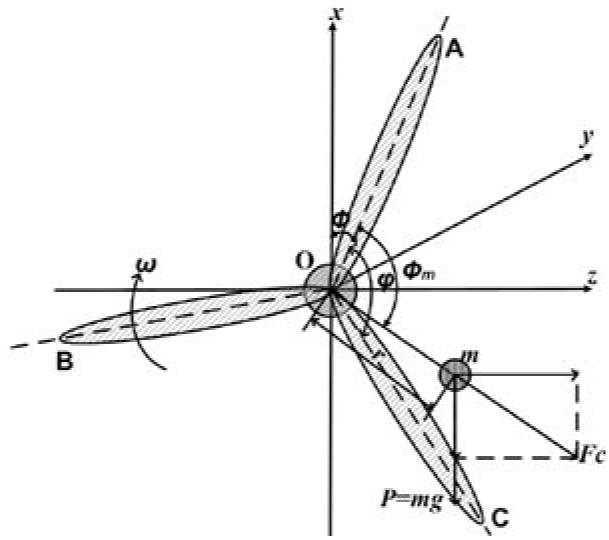

Fig.2 - Mass Imbalance Model [6].

Mass imbalance induces an additional centrifugal force on the rotor. This leads to a periodic transverse oscillation as well as a small torsion oscillation of the wind turbine's drive train that propagates to the nacelle.

Mass imbalances directly increase the wear of the blade, on the pitch control mechanism and on the drive train (bearings and gears) by generating asymmetrical loads. According to [7], wear out appears to be the main driver for gearbox and rotor failures. This underlines the importance of monitoring and correcting mass imbalance: which avoids shortening the lifespan of those major components.

Aerodynamic Imbalance

Aerodynamic imbalances induce an immediate loss in production and availability, lowering the yield of the turbine and generating higher risks of emergency stops. Real cases have shown that differences between pitch angles of rotor blades of about 1° lead to a decrease in the annual energy production of 2% [2] to 3% [3]. Studies have also shown that a linear relation can be made between blade angle difference and yield loss of the wind turbine in the range of attached flow, as presented on [3].

Since the aerodynamic forces are very sensitive to the angle of attack and blade profiles, a differential in these parameters leads to significant differences in the thrust force of the individual blades, creating imbalanced forces. These differentials can be caused, respectively, by a pitch angle offset and by a blade profile deformation.

An aerodynamic imbalance induces an additional axial and torsion oscillation of the rotor from the differential thrust of the blades, this effect will reduce the life expectancy of the structure and the drive train components.

To illustrate the impact that a pitch offset may present, from the difference in the angle of attack for the individual blades, Fig.3 compares the thrust force of a profile for an increasing angle of attack.

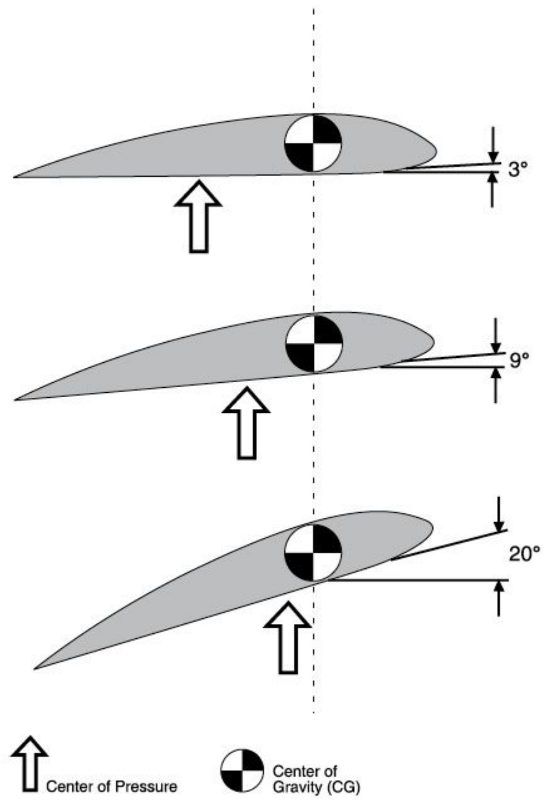

Fig.3 - Influence of the angle of attack on the thrust force and on the center of pressure of an aerodynamic profile.

Research on imbalance diagnosis

Most research articles on the rotor balance of wind turbines focus on the physical effects of the imbalances and on monitoring and diagnosis strategies. The main effect of an imbalance rotor is the existence of loads (both axial and transverse) at the rotating frequency of the rotor, called the 1p frequency.

Here we present 3 articles of rotor imbalance studies each based on a different approach.

Experimental and field test measurements [1]

The research work presented in [1] is focused on online condition monitoring of rotor balance using vibration analysis. The results were obtained from the output of 3 low frequency uniaxial accelerometers placed on the nacelle of the wind turbine (1 on the axial direction and 2 on the transverse direction). A spectral and order analysis is then performed on the acceleration measurements to calculate and monitor the 1p nacelle oscillations.

Experiments were carried out on a test wind turbine (nominal power of 33 kW) where aerodynamic and mass imbalances were imposed and the 1p acceleration levels were monitored during certain periods. The results are presented in figure 4.

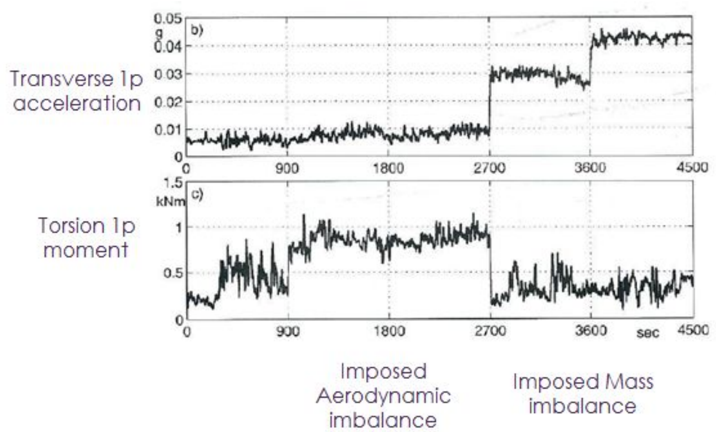

Fig.4 - Time series of the 1p amplitudes of the transverse accelerations and torsion tower bending moment for normal functioning condition and for imposed aerodynamic and mass rotor imbalance [1].

From these results and as a conclusion from this article, one can say that the magnitude of the 1p oscillation is significantly higher in case of an imbalance and that the amplitude depends on the intensity of the imbalance.

Numerical simulation results from advanced software [5]

A structural health and prognostics management case study of rotor fault and blade damage was presented in [5]. To do so, a multi-scale modeling approach was used to identify how the physics of the wind turbines were affected by the presence of damage and faults and how these changes manifested themselves in the operational response of a wind turbine.

The simulation results showed that the 1p frequency accelerations and angular accelerations were the most sensitive parameters to the rotor imbalance. The obtained results for an increasing aerodynamic imbalance and an increasing mass imbalance are shown in figures 5 and 6, respectively.

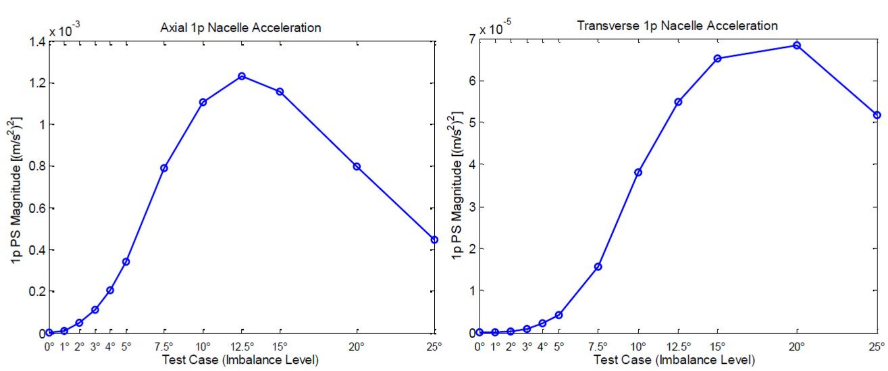

Fig.5 - Impact of an increasing pitch offset on 1p axial and transverse acceleration levels [5].

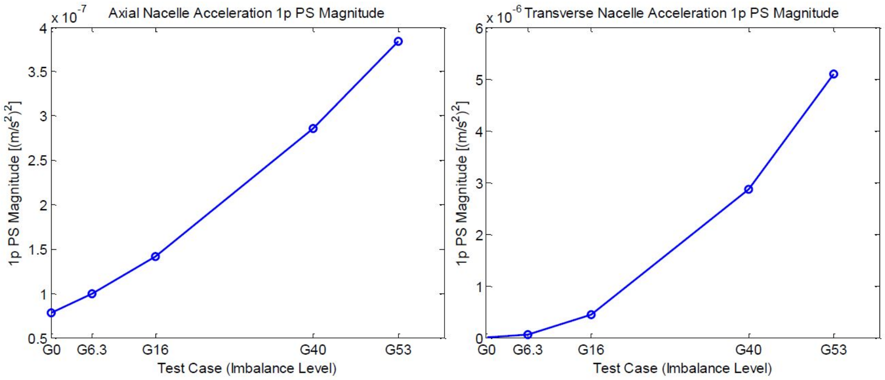

Fig. 6 - Impact of an increasing mass imbalance grade on 1p axial and transverse acceleration levels [5].

The 1p axial and transverse magnitudes follow a similar trend for both types of imbalances. When an aerodynamic imbalance is present, the axial oscillations are 2 orders of magnitude higher than the transverse ones, on the other hand, for a mass imbalance the 1p acceleration levels have similar magnitudes on both axes.

Mathematical modeling and analytical solutions [3]

In [6], a mathematical model was developed connecting the load caused by the imbalances to the resulting vibrations. Both the direct and the inverse problem (i.e. the calculation of the mass and aerodynamic imbalance from vibrational data) were solved. Numerical simulations, performed using artificial imbalance data, showed the impact of a mass and aerodynamic imbalance on the displacement at the 1p frequency. These results were obtained for a Vestas V80-2MW using the system mass and stiffness matrices, therefore the impact of any imbalance (or combination of imbalances) can be obtained for this wind turbine model.

In conclusion, results tend to show that the monitoring of the 1p oscillation levels is the most adapted strategy to identify and diagnose a rotor imbalance on wind turbines.

Monitoring strategies on operation

The most commonly used tool in the wind industry to detect rotor imbalance on wind turbines is on-site measurements either from vibration sensors or from optical instruments or analysis.

Vibration based diagnosis

The vibration measurements are mainly used to quantify mass imbalances and to provide a first diagnosis on the aerodynamic imbalance. The diagnosis is based on the oscillation levels at the 1p frequency: the wind turbine is equipped with low frequency accelerometers on the axial and transverse axis from which data is acquired from 15 to 60 minute periods at constant wind speed with and without generator load.

As presented in [4], when a mass imbalance is present the 1p analysis allows the determination of the balancing corrections to be applied. Test weights are then attached to the root of the concerned blade and a new vibration measurement control is done to validate the correction.

A similar approach is proposed by BerlinWind, where a complete vibration measurement campaign allows a mass imbalance estimation with high accuracy and an aerodynamic imbalance detection [3].

Optical blade angle measurements

The optical blade angle measurements are used to detect offset blade angles and therefore to detect the most common cause for aerodynamic imbalances.

The diagnosis is based on several pictures taken of the entire surface of the blades from the access platform right next to the turbine tower. Data processing algorithms are then used to detect wrongly adjusted blade angles and to analyze the blades twist, focusing the most common aerodynamic imbalance causes.

This method is very precise and has a sensibility of +/- 0.2 pitch offset detection. A view example used in this type of diagnosis is presented on the figure 7.

Fig. 7 - View example from a camera placed under a wind turbine blade.

Continuous monitoring of the rotor

The Sereema Lab has developed a single sensing and communication module that allows key data to be collected on the behavior of each wind turbine. Sereema's solution provides a continuous and online diagnosis of the rotor balance status of each equipped wind turbine. This diagnosis is based on the study of axial and transverse acceleration levels of the turbine's nacelle at the 1p frequency.

One of our first objectives was to validate the results obtained from online condition monitoring when compared to a more common on-site vibration based diagnosis. To do so, simultaneous measurements were taken using our acquisition module and a traditional on-site SPOT measurement system on multiple operating 1.7 MW wind turbines. Two spectrum of axial and transverse accelerations obtained from the two systems for the same period are compared in figure 8.

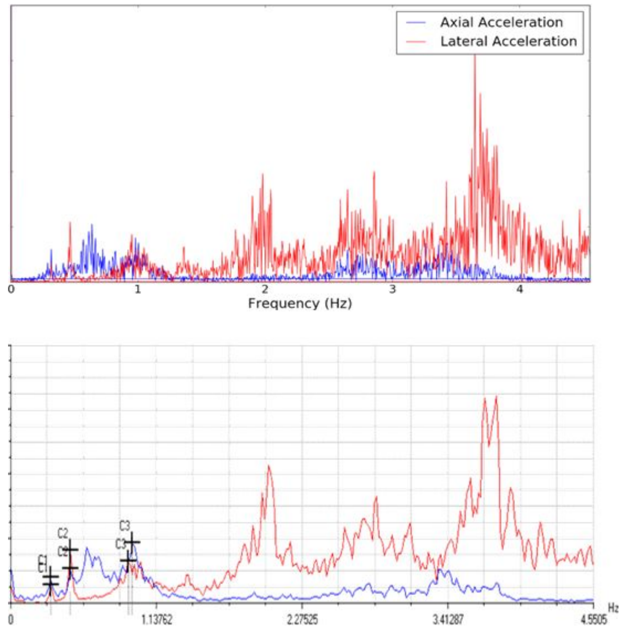

Fig. 8 - Online monitoring results(top) compared to SPOT measurements (bottom).

The comparative campaign allowed the validation of acceleration time series and frequency spectrum. The measured 1p peak accelerations were equal within a +/- 5% interval validating our rotor balance diagnosis algorithms.

The continuous presence of the module permits to select the perfect external conditions to apply the adequate sampling and to cumulate the obtained results allowing over 200 analysis per wind turbine per month. This data is then statistically processed in order to provide an automated and reliable diagnosis of the rotor balance. The algorithm adapts to every wind turbine.

Conclusion

The condition monitoring of rotor blades is mainly done by visual inspections or on-site vibration measurements at regular time intervals. Therefore only punctual information of the rotor condition is provided. Furthermore, on-site inspections require specialized equipment, expert personnel and a minimal wind speed, that implies an important financial investment. These inconveniences will become more problematic for offshore wind turbines.

Sereema's measurement campaign was able to demonstrate that online condition monitoring would improve operational availability and contribute to avoid rotor fault conditions, additional loads and loss in production. This type of monitoring is advantageous as it permits continuous data acquisition and surveillance, early default detection, perfect conditions selection for the analysis and a reliable diagnosis from the statistical treatment of the results.

References

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