EXPERIMENTAL VALIDATION OF PHARWEN CODE USING DATA FROM VERTICAL-AXIS WIND TURBINES

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1. Introduction

Offshore floating wind sector offers great perspectives in terms of offshore wind development, enabling to reach high-wind, large-depths areas, inaccessible to the actual fixed-bottom technology. Vertical-Axis-Wind-Turbines (VAWTs) may offer perspectives to improve floating offshore wind farms, as they are adapted for floating technology.

Modelling of VAWTs behavior is however a great challenge, as their aerodynamics is highly unsteady [1] and interactions between VAWT structure, controller and external environment (winds and waves) cannot be correctly simulated with the BEM (Blade Element Momentum) codes that are commonly used for Horizontal-Axis-Wind-Turbines (HAWTs).

NENUPHAR has developed, in collaboration with Adwen Offshore, the PHARWEN code, where the aerodynamics is modeled with a 3D vortex panel method which makes it particularly adapted for the design of VAWTs. NENUPHAR has also performed extensive testing on its two onshore VAWT large-scale prototypes and resulting measurements are used to validate the code. Experimental validation strategy and results from loads comparison are presented in the paper, with a focus on the loads variation over one rotation that are specific to VAWTs.

2. Experimental PHARWEN code validation strategy

To study the aerodynamic performance of the VAWT and the loads applied on its structure, NENUPHAR and Adwen Offshore have developed an offshore aero-servo-elastic code (PHARWEN3D). The code couples an aerodynamic three-dimensional unsteady vortex code (ARDEMA3DS), a structural simulation tool based on beam-element theory (NeSToR*), and a wind turbine controller module. The code is also able to take as inputs any rigid-body motions representative of a floating VAWT.

To guarantee the accuracy and reliability of PHARWEN 3D, NENUPHAR undertakes to experimentally validate the code by using measurements collected on its 600kW VAWT onshore prototypes operated on a test site near Fos-sur-Mer. The latter is currently the largest H-shaped VAWT in the world with a height of 42 m and a diameter of 50m. The process of validation considers all kinds of events that a wind turbine typically experiences during its lifetime (operation mode, parked mode, transient events such as start-ups and shut-downs) and focuses mainly on the following: loads experienced at points that are critical for the wind turbine design, rotor dynamic behavior, VAWT aerodynamics and power performance.

Fig.1. Two NENUPHAR's onshore prototypes: different rotor configurations were tested (twisted and canted blades and straight vertical blades), both for a period of approx. 1 year

The test site as well as both VAWT prototypes were heavily instrumented with high-quality, calibrated sensors (strain gauges, accelerometers, temperature probes, meteorological mast, temporary Lidar setups [2], etc.) thus providing a large set of data covering a wide range of wind conditions and rotational speeds. The code is able to simulate the onsite conditions in order to numerically compute 10 minutes time-series which are compared to the equivalent measured 10 minutes time-series (also called "bins" hereafter) used for the validation. Code input values (such as structural eigen frequencies, mass, dimensions etc.) were verified through dedicated measurements.

Two types of comparison are carried out. On one hand, statistical data (mean value, standard deviation, max, min) of the sensors' measurements and simulation results are compared over a large amount of bins. On the other hand, measured and simulated power spectrum density and loads variation over one rotation are compared in details for specific bins. The present paper focuses on the latter as they offer a good overview of VAWT aerodynamics that is crucial for the validation of a code to be used for the design of industrial VAWTs.

*NeSToR : Nenuphar Structural Tool for Rotor

3. Comparison between numerical and experimental results of large-scale VAWT prototypes

At a given operating point (constant wind speed and rotational speed), loads vary periodically with the rotation of the rotor. Measured and simulated loads over several wind turbine revolutions occurring during 10 minutes time series are compared.

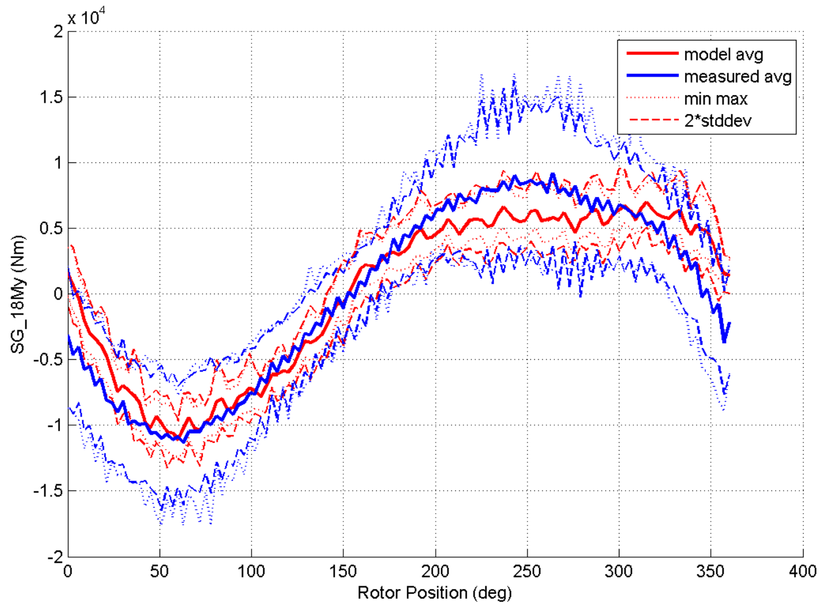

Figure 2 : Blade flap bending moment (SG_18My) variation as a function of rotor azimuthal position.
Comparison between simulated (red) and measured (blue) data.
Rotational speed: 5 rpm, wind speed: 3.4 m/s
Plain curves: average value. Dotted curves: minimum, maximum values. Dashed curves: standard deviation.

Figure 2 shows the typical variation of the blade flap bending moment over a complete rotor revolution. The rotor position is given relatively to the average wind direction. The blade bends inwardly towards the rotor vertical axis under the aerodynamic loadings when it passes upwind (in the 0° to 180° range), and outwardly when it passes downwind (in the 180° to 360° range).

On such a figure, the average curve can be interpreted as the load that would be theoretically measured in "steady" (as opposed to "turbulent") wind conditions and a rigid (not prone to dynamic amplification) structure. The curves corresponding to standard deviation and extreme moment values represent the variation ranges of the load at a given rotor position over several rotations. Loads variations, that are characterized by their minimum, maximum and standard deviation value, are mainly due to the turbulent nature of the wind (which leads to varying aerodynamic loadings at each rotation) and to the dynamic structural response of the structure. To achieve a good agreement between numerical results and measurements, the variation of the wind speed both in time and in space needs to be correctly modeled in the code. A structural simulation module able to accurately model the eigen modes of the wind turbine and the associated damping coefficients is also necessary in order to properly simulate the aero-elastic behavior of the rotor.

In the particular case presented in Figure 2, the average value of the bending moment matches very well, whereas a significant difference on the standard deviation can still be observed. This is because the simulated results were produced considering a steady wind. Additional cases, including comparisons with numerical results generated with a turbulent wind, will be presented and discussed in the full paper.

Other comparisons are carried out to analyze the wind turbine loads and vibrations: power spectrum comparisons, operational modal analysis, comparisons performed on particular transient events and statistical analyses. The different analyses allow validating independently different parts of the code in order to reach a full code validation.

4. Conclusion

The paper presents comparisons of the numerical modeling of a large-scale VAWT with the measurements acquired on-site during a 2-year long measurement campaign on two different full-scale prototypes operating at high Reynolds numbers. The acquired data enable to validate the PHARWEN3D simulation tool, showing that it can predict correctly the wind turbine behavior over one rotation.

5. Learning objectives

Measurements made on both NENUPHAR full-scale prototypes provided valuable information to validate experimentally the numerical simulation tool and associated models, thus improving confidence in PHARWEN's predictions. To obtain accurate simulations over a complete revolution of the rotor is crucial for the design of VAWTs because the BEM codes commonly used for the design of HAWTs cannot properly model the behavior of VAWT especially with regards to the complex aerodynamics and wake patterns affecting the downwind path of the VAWT rotors.

Next steps of PHARWEN development and validation include the integration of hydrodynamic aspects and aero-servo-hydro coupling, as the ultimate goal is an integrated and optimal design of a floating offshore VAWT.

References

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[2] Nenuphar, DTU Risoe, Adwen, 2015, Modelling of Wake Flow Around a Full-scale Prototype VAWT, EWEA