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

Denis Pitance, Simon Horb, Joanna Kluczewska-Bordier, Alexandre Immas, Frederic Silvert

NENUPHAR, Campus de l'Institut Pasteur de Lille, 1, rue du Professeur Calmette, 59000 Lille, France

Paul Deglaire

ADWEN offshore France, Tour Le Guillaumet - 60, Avenue du Général de Gaulle- 92046 La Défense Cedex

1. Abstract

Modelling of Vertical-Axis-Wind-Turbines (VAWTs) behavior is a great challenge, as their aerodynamics is highly unsteady [1] and interactions between VAWT structure, controller and external environment cannot be correctly simulated with BEM (Blade Element Momentum) aerodynamic modules [2] that are commonly used for Horizontal-Axis-Wind-Turbines (HAWTs). Nenuphar has developed, in collaboration with Adwen Offshore, the PHARWEN3D code, where the aerodynamics are modelled 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 have been used to validate the code. The acquired data enabled to validate the PHARWEN3D simulation tool, showing that it can correctly predict the wind turbine behavior over one full rotor revolution, simulate the aerodynamic loading of the structure and predict wind turbine performances.

2. Keywords

Vertical Axis Wind Turbines; Numerical Modelling; Site measurements; Load measurements; Wind Turbine Prototype, Aero-servo-elastic modelling.

3. Introduction

The offshore floating wind sector offers great perspectives in terms of offshore wind development, enabling to reach high-wind, large-depths areas, inaccessible to the bottom-fixed-technology. Floating offshore wind turbines (FOWTs) face however an issue of high LCOE costs, which is an obstacle to their development on industrial level. VAWTs offer great perspectives to solve this issue, as they are particularly adapted for floating technology, enabling a significant cost reduction.

The main objective of the work presented is to compare the numerical simulations of VAWTs behavior with a large amount of experimental data. Ultimately, the goal is to improve numerical models, in order to obtain tools that can be used to design and optimize large-scale VAWTs as such wind turbines are considered as a promising solution for floating offshore wind energy applications [3]. The models must therefore be physically realistic and be able to provide fast simulations. The first objective eliminates the Double Multiple Streamtube models (DMST) [4] and the second one eliminates DNS or LES simulations. Vortex methods are a good solution to meet these two objectives. An advanced 3D unsteady vortex panel method, first developed by Dixon [5], is used in PHARWEN3D.

4. Methodology

Numerical vortex models were used to simulate the behavior of Nenuphar wind turbine prototypes. Results of the simulations were compared to field measurements, performed using the instrumentation installed on the prototypes. The process of validation focuses mainly on the following topics: loads experienced at points that are critical for the wind turbine design, rotor dynamic behavior, VAWT aerodynamics and power performance. In this paper, the results of the comparisons between simulated loads and loads measured on the wind turbines are presented.

4.1. Numerical Modelling

PHARWEN3D code couples an aerodynamic three-dimensional unsteady vortex code (ARDEMA 3DS), 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.

The aerodynamic model called ARDEMA 3DS includes an inviscid flow solver coupled to a Beddoes-Leishman dynamic stall model. The inviscid flow solver is based on the work by Dixon at TU Delft [5] who developed a 3D vortex panel method that allows modeling any lifting surface in 3D within the inviscid hypothesis. It is thus very suitable for the discussed application as the code can model the unsteady flow around the blades and struts that constitute the rotor of a VAWT. The code has been rewritten by Adwen offshore in order to make it easy to couple with any structural solver and to be more efficient in terms of computational time. The dynamic stall model, developed by Nenuphar, allows correcting the aerodynamic results of the panel method for viscous effects: skin friction and pressure drag. It is particularly important to have a realistic dynamical stall model for VAWTs because the angles of attack of their blades over one full revolution keep on varying and reach moderate to high values depending on the operating tip speed ratio [6].

NeSToR (Nenuphar Structural Tool for Rotor) has been developed in-house by Nenuphar and allows modeling a rotating structure under the assumptions of Euler-Bernoulli theory. The latter is particularly well suited to model VAWTs as the tower, blades and struts are elongated parts and can therefore be described as beams.

The full aero-servo-elastic tool PHARWEN couples ARDEMA 3DS, NeSToR and a wind turbine controller model. The interactions between the different models and the model's inputs are described in Figure 1.

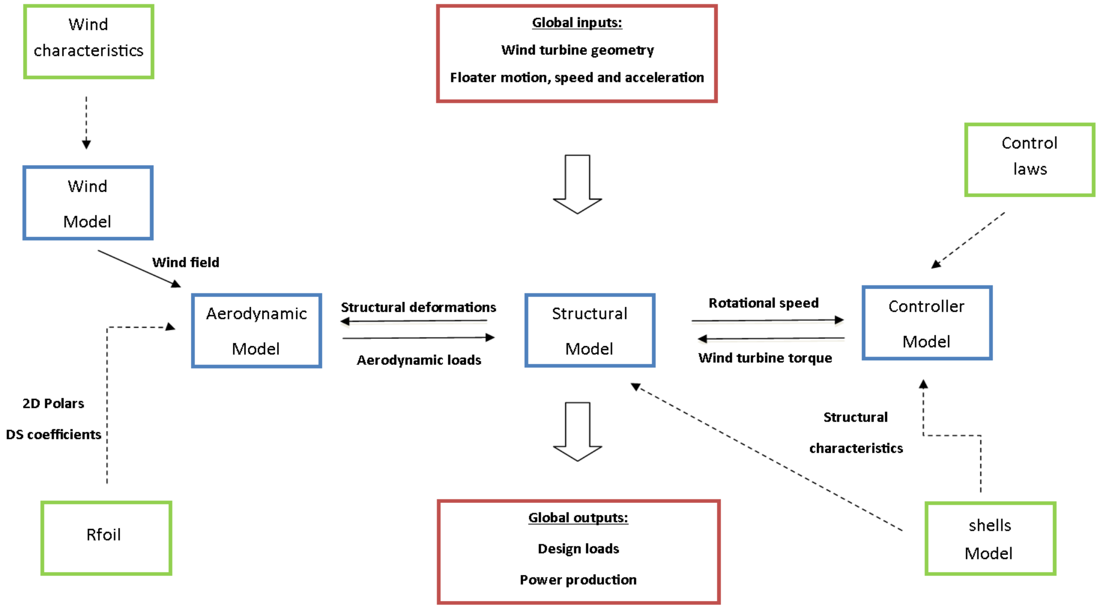

Figure 1: PHARWEN architecture flow chart

4.2. Field measurements

Nenuphar operated a 600kW, large-scale (42 m tall and 50 m wide) VAWT prototype at an onshore test site near Fos-sur-mer for over a year (see Figure 2). The prototype's hub-height is of 27m. This prototype, called "1H" enabled Nenuphar to test and develop VAWT design for its offshore floating wind turbine concept currently under development. Also, measurements from this prototype are used for numerical modelling validation.

In 2015, the "1H" prototype was replaced by the "1HS" prototype, on which blades were changed to straight vertical blades as shown on Figure 3. This latter prototype is still in operation and measurements on this prototype are ongoing at the time when this article is written.

Both prototypes were fully instrumented with high-quality calibrated strain gages, accelerometers, power and electrical measurements as well as other numerous sensors used for wind turbine control and monitoring. All signals are synchronized and recorded in a common database.

The test site is well-exposed to the strong Mistral winds and is equipped with a 52-m meteorological met mast. The meteorological met mast is equipped with anemometers (at 3 levels), wind vanes, pressure and temperature probes as well as rain sensors. All instruments are of high-quality and were calibrated prior to meteorological mast installation. The photograph of the meteorological mast is shown on Figure 4.

The present paper focuses mainly on the load measurements from the "1H" prototype. The load measurement system is described in the following chapter.

Figure 2: Photograph of the "1H" prototype

Figure 3: Photograph of the "1HS" prototype

Figure 4: Photographs showing site meteorological mast

4.3. Load measurements on the 1H wind turbine

The tower structure, three bracings as well as one strut and one blade are instrumented with foil strain gages for load measurements. Bending (one or two directions), torsion and/or traction/compression (depending on the measurement point) are measured. Over 30 main channel signals are available. There are also redundant strain gauges installed on critical measurement points.

Strain gauges were installed:

- Inside the blade and strut structures, on their composite inner skin, during the manufacturing process.
- On tower and bracings (tower supporting structures) on site after the wind turbine erection.

The different measurement points on the structure are shown on Figure 4 here below. Most of the strain gages are installed in full-bridge configuration.

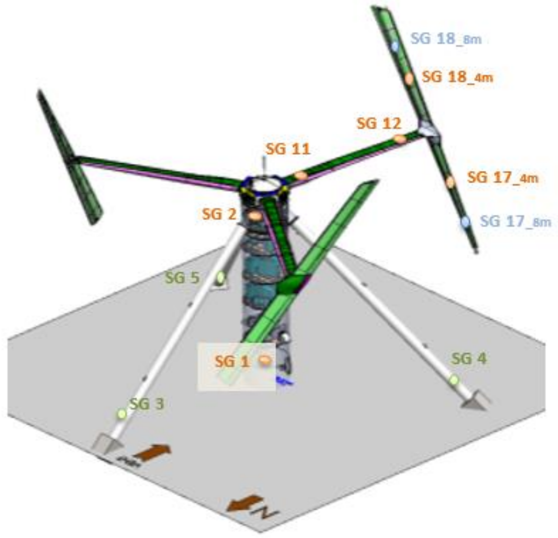

Figure 5: Measurement points on the structure: in orange: 3 axis (flap/edge bending moments and torsion); in green: 1 axis (traction/compression); in blue: 1 axis (flap bending moment)

Due to accessibility constraints and for protection of measurement points against the external environment, the strain gages in the blade and in the strut were installed inside the structures, as shown in the pictures below.

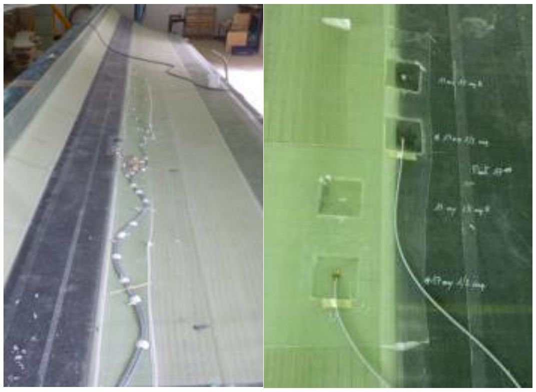

Figure 6: Installation of the strain gages inside the blades during manufacturing

Strain gages installed in the blade and in the strut were calibrated using external calibration method as recommended by the IEC 61400-13 [7]. This calibration was performed using dedicated test rigs, load cells and devices for the application of external moments on the structure.

Figure 7: Photograph showing blade calibration

Figure 8: Photograph showing strut calibration

4.4. Measured data selection

The sensors' measurements collected as 10-min bins are post-processed and checked. The data are ranked according to 3 levels of quality depending on the wind sector, the wind trend, the wind direction variation and the rotational speed variation.

Since the strain gauges were zeroed on the completely assembled prototype at standstill and at "zero wind" conditions, the gravitational loads (due to the own weight of the structure) do not appear in the measurements. In order to properly compare the results of the numerical simulations and the measurements, the gravitational loads have to be computed using the structural model of the prototype. They are then added to the measurements for the comparison purposes. It should be noted that the gravitational loads are constant and do not depend on the rotor azimuthal position.

For the purpose of detailed comparisons of azimuthal variations, three representative bins were selected from measurements at low, medium (close to optimal) and high tip-speed ratio (TSR) and steady-state operation as shown in the Table 1 below.

10min data bin type	Mean 10min Wind speed at hub-height (m/s)	Turbulence Intensity at hub height (%)	Wind direction at hub height (deg)
Low TSR	10,4	13,9	346
Optimal TSR	8,9	17,5	321
High TSR	7,9	17,6	315

Table 1: Selected measured 10min bins at different TSRs

4.5. Numerical simulation results post-processing

In order to carry out the experimental validation of the code, a post-processing routine was added to PHARWEN to be able to compare the numerical simulation results to the measurements. PHARWEN is able to compute loads and accelerations at the nodes specified in the prototype beam model. So to compare the numerical simulation results and the measurements, the loads and accelerations calculated by PHARWEN are linearly interpolated between the beam model nodes in order to get their value at the exact location of the sensors placed on the prototype.

5. Results

As seen in the previous chapter, 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 [8] etc.) thus providing a large set of data covering a wide range of wind conditions and rotational speeds. Code input values (such as structural eigen frequencies, mass, dimensions etc.) were verified through dedicated measurements. The present study focuses on measured and simulated power spectrum density and loads variation over one full rotor revolution as it offers a good overview of VAWT aerodynamics, crucial for the validation of the code to be used for the design of VAWTs. A statistical analysis of the results was also performed.

5.1. Comparisons of azimuthal load variations

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 ("bins") are compared. The results follow the azimuthal angle convention as explained in Figure 9.

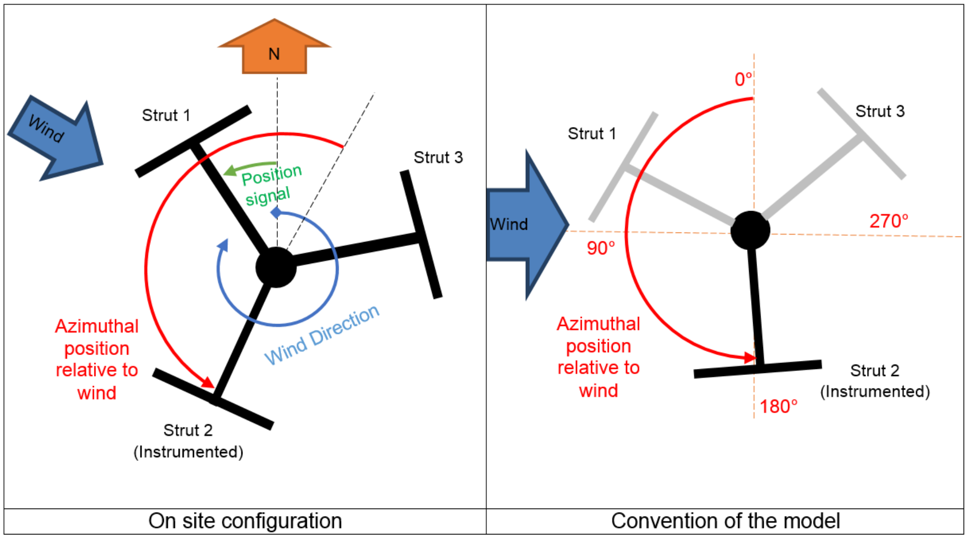

Figure 9: Azimuthal position relative to the wind as used in the graphs in the "Results" section

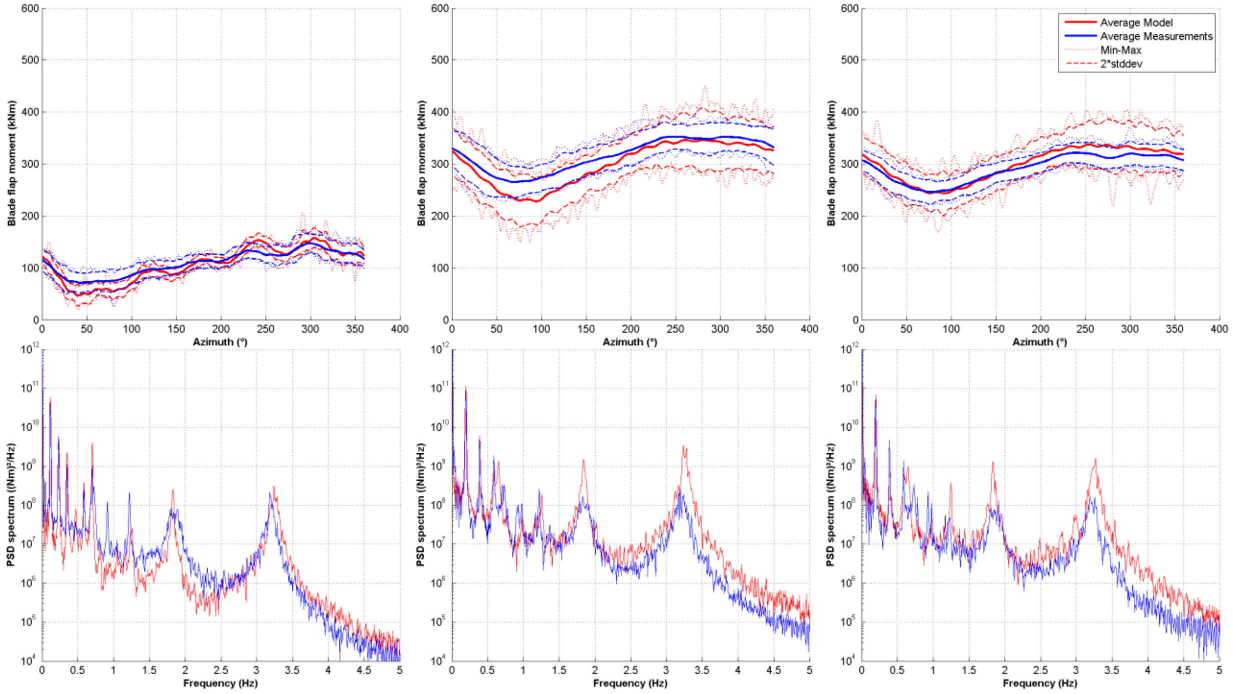

Figure 10: Blade flap load variation as a function of azimuthal position (top) and signal's power spectrum density (bottom). Comparisons between simulated (red) and measured (blue) data for three TSRs: low (left), optimal (middle) and high (right). Plain curves: means values, dotted curves: max and min.

Azimuthal comparisons for different TSRs were performed for all the measurements points on the rotor structure. Results presented in Figure 10 show a particular case of blade flap load variations, that is SG17 measurement point, interesting from the blade design point of view.

The rotor position is given relatively to the average wind direction as shown in Figure 9. The blade bends inwardly towards the rotor 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). The average curve can be interpreted as the load that would be theoretically measured in “steady” (as opposed to “turbulent”) wind conditions and with “static” (not prone to dynamic amplification) response of the structure. Loads variations that are characterized by their minimum, maximum and standard deviation values, are mainly due to the turbulent nature of the wind (which leads to varying aerodynamic loadings at each revolution) and are further amplified by the dynamic structural response of the wind turbine.

It can be observed that there is in general a good agreement between the measured and simulated data. It should be noted that the blade flap bending moment shown on Figure 10 was measured on the lower part of the blade. The PHARWEN3D code does not take into account the presence of the wind turbine tower yet, which explains the discrepancy of the results around the 270° azimuthal position when the blades are impacted by the tower wake. In general, the code is slightly conservative when considering extreme (min, max) values.

5.2. Statistical comparisons

Large number of 10min simulations for different operating conditions were performed using PHARWEN3D tool. Results were compared to operational data from the prototype.

These comparisons were done for all rotor measurement points. In Figure 11, a particular case of blade flap bending moment (SG17 measurement point) is shown.

The statistical load comparisons are related to the azimuthal load comparisons in terms of average value and standard deviation. For these two points, the statistical load comparisons are in agreement with the azimuthal load comparisons.

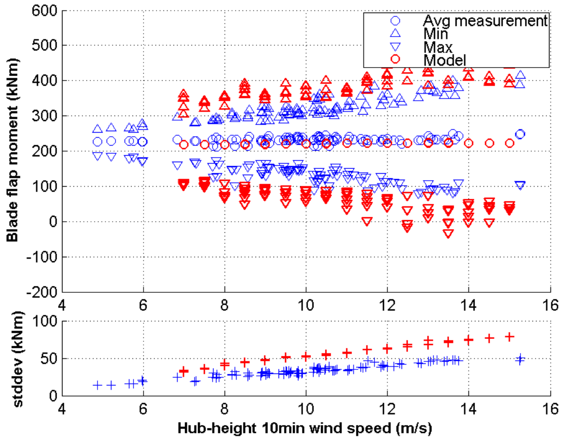

Figure 11: Blade flap bending moment as a function of wind speed. Comparison between simulated (red) and measured (blue) data.

It can be seen that the model is slightly conservative in the evaluation of load ranges, while the agreement on the average value is very good.

6. Conclusions

A good agreement was found between loads computed by PHARWEN3D and loads measured on the 1H VAWT prototype. The code is currently undergoing a thorough validation process, aiming at validating its outputs in terms of loads, dynamic behavior and generated power, including cases of rigid-body motions, useful for floating VAWTs applications. Improvements of the code, including modelling of the wind turbine tower influence as well as simulations of blade pitching and different wind turbine arrangements (such as the counter-rotating arrangement of the Nenuphar’s TWINFLOAT$^{®}$ concept for FOWT) are currently in development or under validation.

7. References

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