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

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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 the BEM (Blade Element Momentum) codes [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 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. The acquired data enabled to validate the PHARWEN3D simulation tool, showing it can predict correctly the wind turbine behavior over one rotation as well as simulate aerodynamic loading of the structure and predict wind turbine performances.

Objectives

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 model (DMST) [4] and the second one eliminates DNS or LES simulations. Vortex methods are a good solution to meet both these objectives. The first vortex code was based on the lifting-line theory but a more advanced 3D vortex panel method, first developed by Dixon [5], is used in PHARWEN3D.

Methods

PHARWEN3D 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 PHARWEN3D, NENUPHAR undertook to experimentally validate the code by using measurements collected on its 600kW VAWT onshore prototypes operated on a test site near Fos-sur-Mer.

Fig.1: NENUPHAR's 600kW onshore large scale (height=42m,diameter = 50m) prototypes: 1H (left), 1HS (middle), view of the site showing 54m met-mast and 1HS prototype (right).

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. 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 [6] 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 rotation as it offers a good overview of VAWT aerodynamics, crucial for the validation of the code to be used for the design of VAWTs. Statistical analysis of the results was also performed. Measurement results of NENUPHAR's "1H" prototype (3-bladed rotor with canted and twisted blades) are presented as those of the second prototype, "1HS" (3-bladed rotor with straight non-twisted vertical blades) are still ongoing.

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. For the purpose of comparison, 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 on the right.

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

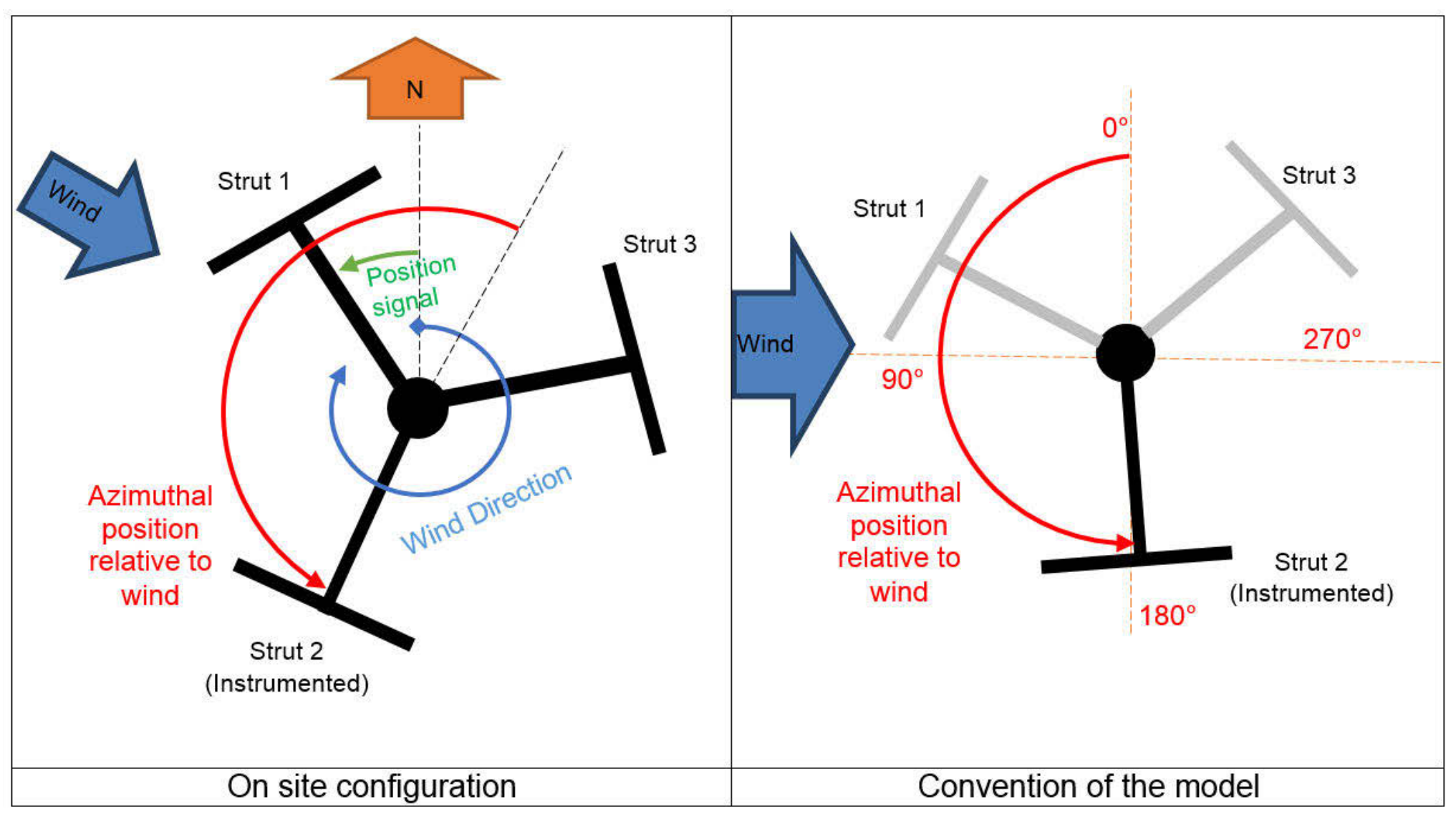

Fig. 3: Azimuthal position relative to wind

Results

Figure 3 shows the flapwise bending moment at a point on the blade over one rotation as measured by the strain gages and as computed by PHARWEN3D for the three bins:

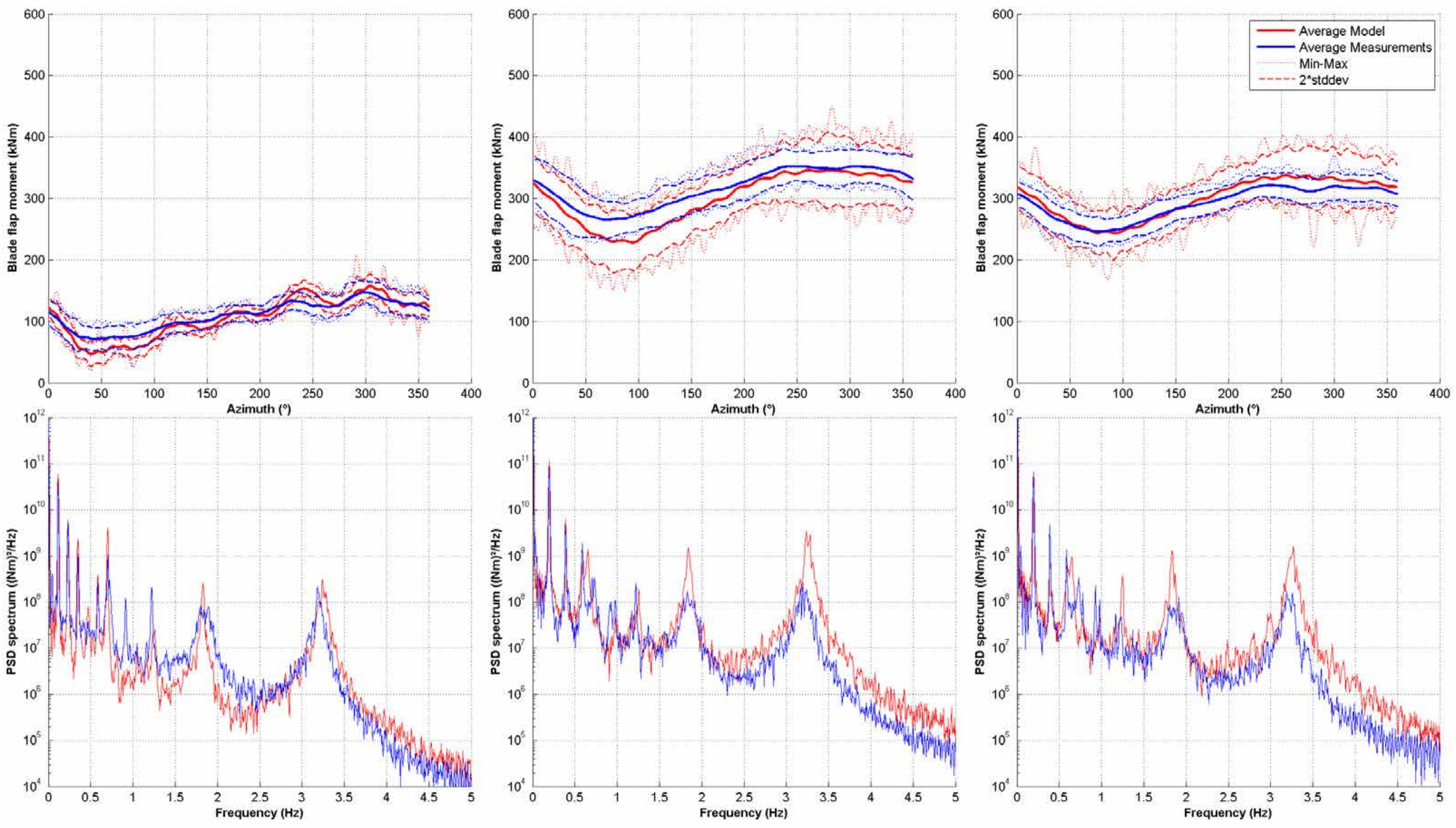

Fig.3: Blade flap load variation as a function of azimuthal position (top) and signal's power spectrum density (bottom). Comparisons between simulated (red) and measured (blue) data for three TSRs: low (left), optimal (middle) and high (right). Plain curves: means values, dotted curves: max and min.

The rotor position is given relatively to the average wind direction as shown on Figure 2. The blade bends inwardly towards the rotor center 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 rotation) and are further amplified by the dynamic structural response of the structure

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 the Figures 2 and 3 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 270° of azimuthal position when the blades are impacted by the tower wake. In general, the code is slightly conservative when considering extreme (min, max) values.

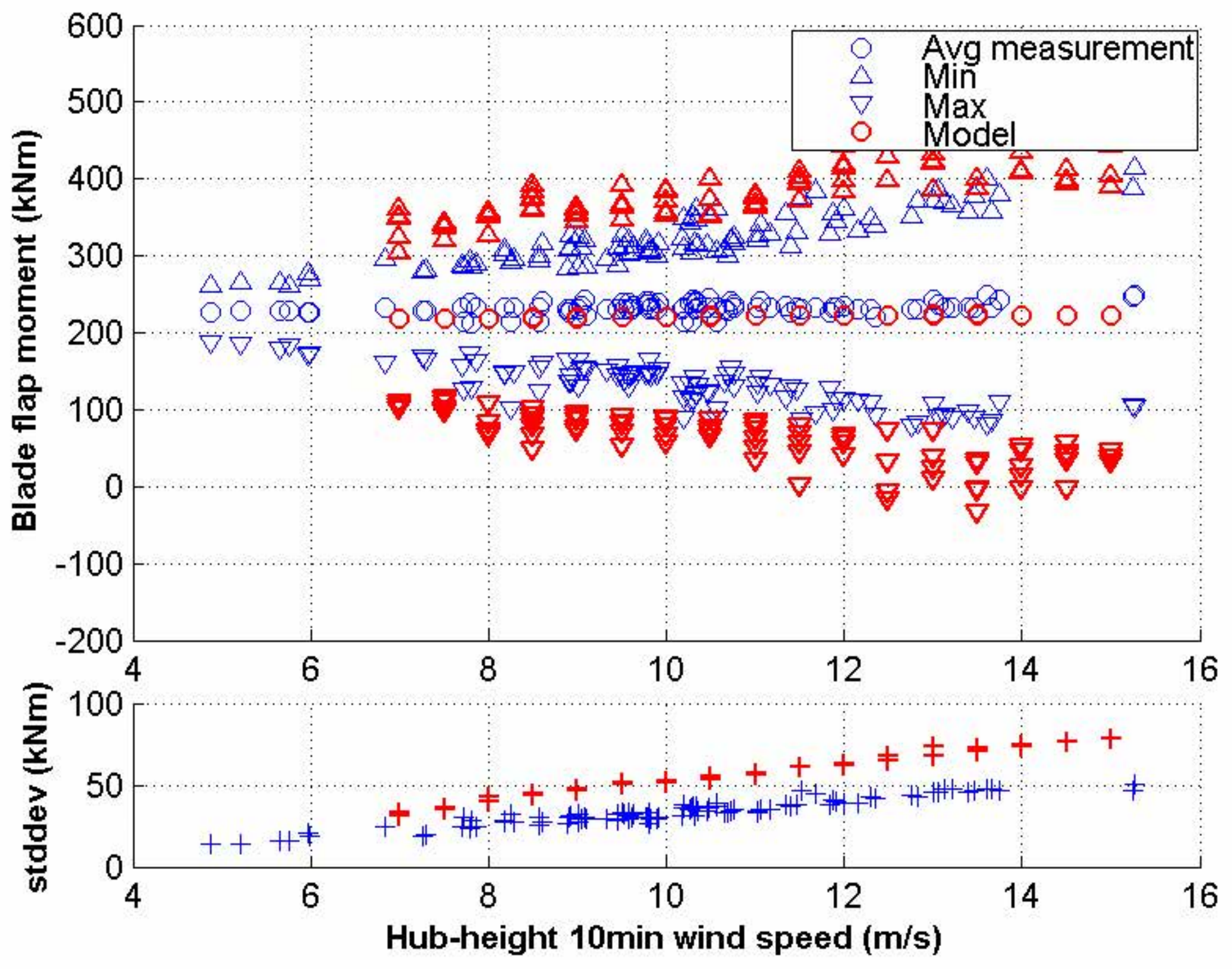

Fig. 4: Blade flap bending moment as a function of wind speed. Comparison between simulated (red) and measured (blue) data.

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 power, including cases of rigid-body motions, useful for floating VAWTs applications. Improvements of the code, including simulation of the turbine tower influence as well as simulations of blade pitching and different turbine configurations (e.g. NENUPHAR's "TWINFLOAT"® design for FOWT) are currently in development.

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