Development and numerical validation of an aero-servo-elastic code for floating vertical-axis wind turbines.

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Abstract

State-of-the-art aero-servo-elastic codes fail to model the unsteady aerodynamics of floating wind turbines and of Vertical Axis Wind Turbines. To solve this shortcoming, Nenuphar has developed, in collaboration with Adwen offshore, an aero-servo-elastic code for VAWTs called PHARWEN, which couples an aerodynamic code ARDEMA 3DS to a structural solver NeSToR. ARDEMA 3DS is based on a 3D vortex panel method associated to a Beddoes-Leishman type dynamic stall model. NeSToR is an Euler-Bernoulli beam-element model. Validation of these models against numerical benchmarks is carried out on a straight cantilever wing and on a full-scale VAWT prototype, called 1HS that NENUPHAR has designed, built and operated over one year in Fos-Sur-Mer (South of France). The comparisons were found to be very satisfactory. Finally, a classical flutter test where analytical results are available was carried out with PHARWEN to validate the aero-elastic coupling. Flutter was clearly observed and its critical speed and frequency were comparable to the ones found in the literature. Several discrepancies however exist, which would require a thorough benchmark of the different aerodynamic models used for flutter detection.

1 Introduction

The offshore wind industry faces great challenges to escape from low-depth areas where the bottom-fixed technology is confined to. Floating concepts are promising to reach untapped wind resources in deep sea [1]. In order to reach market competitiveness, it is required to design light-weight floater concepts which would most probably cause greater unsteadiness levels in the aerodynamics of the wind turbines [2]. It is therefore crucial to develop reliable design tools, which are able to model this source of unsteadiness.

Vertical Axis Wind Turbines (VAWTs) are potentially interesting candidates for this development as they show several advantages for floating offshore conditions and their aerodynamics is inherently highly unsteady. Classic BEM (Blade Element Momentum) codes fail to model these complex aerodynamics [3] making floating wind turbines and VAWTs orphan of efficient and fast numerical simulation tools to design and optimize them. That is why Nenuphar has developed, in collaboration with Adwen offshore, an aero-servo-elastic code for VAWTs called PHARWEN.

Several attempts have been made to overcome the shortcomings of classic BEM codes. Madsen [4] has extended the actuator theory to a 2D cylinder which allows to more accurately reproduce the flow of a VAWT. This aerodynamic model was implemented in the HAWC 2 aeroelastic code [5]. While it indeed improves the physics of the results compared to classic BEM codes, its time-averaged formulation does not allows to fully capture the unsteady aerodynamics of floating VAWTs.

Sandia developed a free vortex model CACTUS based on the lifting-line theory [6] which can be used with the OWENS toolkit for its coupling capabilities [7]. This code uses an unsteady and instantaneous formulation which improves the physical modelling of the flow compared to the actuator cylinder. A weakness of the code is however that the lifting-line theory fails to fully capture the unsteady theory in case of complex geometry (e.g. VAWTs with swept wings) and when curvature effects are important (e.g. VAWTs with moderate to high solidity).

Dixon [8] solved this issue by developing a 3D, unsteady, multi-body, free-wake panel method which allows to capture the unsteady aerodynamics of a floating VAWT of any configuration. To speed up computation, the calculations are run on a graphics processing unit (GPU). This method was found to be the most promising and therefore chosen by Adwen offshore and Nenuphar to be the core of the PHARWEN aero-servo-elastic code.

2 Presentation of the PHARWEN aero-servo-elastic code for floating VAWTs

2.1 Aerodynamic model

The aerodynamic model called ARDEMA 3DS includes an inviscid flow solver coupled to a Beddoes-Leishman dynamic stall model. The former is based on the work by Dixon at TU Delft [8] which 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 are parts of a VAWT. The code has been rewritten by Adwen offshore in order to make it easily coupled with any structural solver and to be more computational time effective. 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 angle of attacks of their blades over one full rotation are always varying and reach moderate to high values depending on the tip speed ratio and on the rotor solidity [9].

The vortex code ARDEMA solves the Euler equation (Eq. 2) that is the Navier-Stokes equation under the assumptions that the flow is incompressible, adiabatic and inviscid which is usually a good approximation outside the boundary layer and outside the wake. In these conditions the mass conservation law reduces to Eq.1 and the velocity can be represented as the gradient of a scalar potential (Eq. 3) that satisfies the Laplace equation (Eq. 4).

$$\nabla . q = 0 \tag{1}$$

$$\frac{\partial \vec{q}}{\partial t} + \vec{q}.\nabla \vec{q} = \vec{f} - \frac{\nabla p}{\rho} \tag{2}$$

$$q = \nabla \Phi \tag{3}$$

$$\nabla^2 \Phi = 0 \tag{4}$$

Laplace equation is a second order linear partial differential equation, so any linear combination of independent solutions (sources, doublets, vortices) is also a solution. The potential velocity solution is found using the Source Doublet formulation with Dirichlet Boundary conditions on the surface and Kutta conditions at each section trailing edges. The pressure is then computed from the potential velocity solution using unsteady Bernoulli’s equation, leading to aerodynamic loads on the sections.

The Beddoes-Leishman (BL) model relies on the division of the dynamic stall phenomenon into elementary processes [10]. The assumption made is that the dynamic stall phenomenon results from the consequence of three processes weakly coupled:

- Attached flow module: Unsteady loads variation caused by the blade kinematics under inviscid flow hypothesis
- Separated flow module: Aerodynamic performance degradation caused by flow separation at the blade trailing edge
- Leading edge vortices effects module: Loads perturbation due to the blade leading edge vortices

More specifically, the model is based on the Theodorsen theory to model the unsteady aerodynamics and on the Kirchoff theory to compute the separation point.

2.2 Structural model

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. According to [11], it is based on three kinematic assumptions:

- Assumption 1: The cross-section is infinitely rigid in its own plane
- Assumption 2: The cross-section of a beam remains plane after deformation (Navier's hypothesis)
- Assumption 3: The cross-section remains normal to the deformed axis of the beam

Following [12], the structural dynamics problem is formulated in the rotor frame. To do this, the strain and kinetic energies are expressed with respect to the local kinematic values, then the Lagrange equation is derived in the rotor frame to obtain the equation of motion. This approach allows to take into account all the inertial forces linked with a moving and rotating rotor (Coriolis effect, spin-softening effect, centrifugal force, fictitious force due to time-dependent rotational speed and floater motions).

The finite element method is then used to solve the system of partial differential equations using linear basis functions for torsions and tractions and Hermitian cubic functions for bending. This method allows to compute the different terms of the classic equation of motions in the rotor frame:

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} = \{F\} \tag{5}$$

Where:

- $\{q\}$, $\{\dot{q}\}$ and $\{\ddot{q}\}$ are respectively the generalized displacements, velocities and accelerations vectors
- $[M]$ is the global mass matrix
- $[C]$ is the global damping matrix
- $[K]$ is the global stiffness matrix
- $\{F\}$ is the generalized force vector

2.3 Global coupling

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: PHARWEN architecture flow-chart.

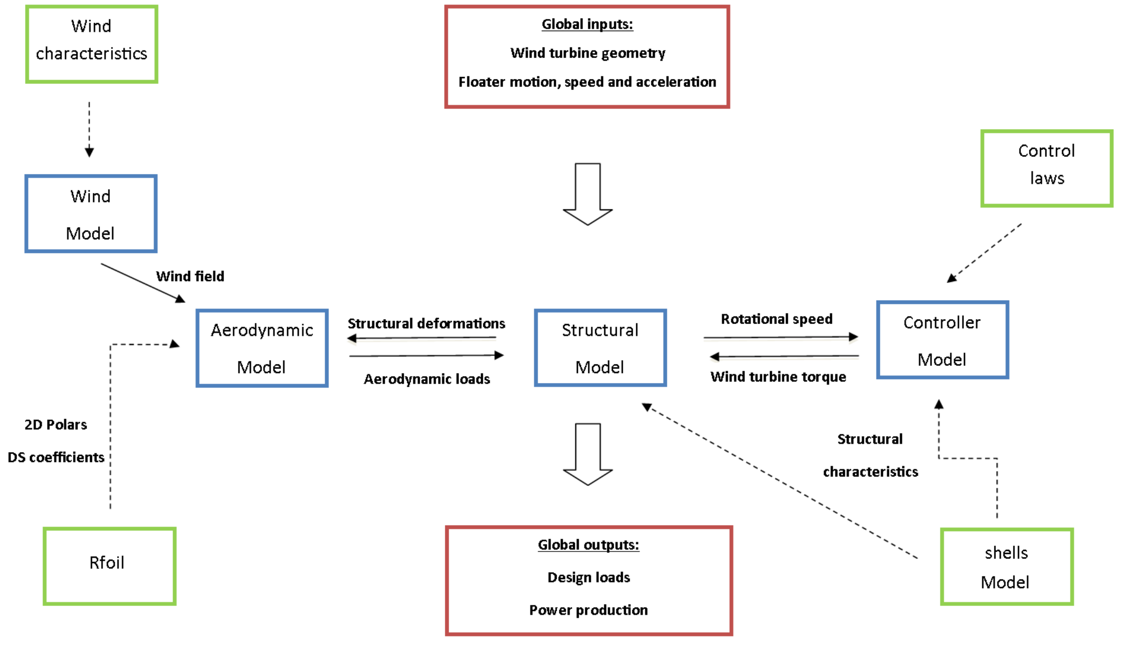

Figure 1: PHARWEN architecture flow-chart

This code is intended for vertical-axis wind turbine design. It can therefore handle the input cases and data described below.

- Geometry and structural properties: any H-type VAWT.
- Wind: any wind condition required by [13]. It includes wind shear, steady wind, wind turbulence, gusts in normal and extreme conditions.
- Floater motions: any rigid-body motions (6 degrees of freedom) given as time series inputs.
- Operating conditions: The code can simulate any mode (MPPT, rotational speed limitation, power limitation) and also start-up and shut-down cases.
- Standstill conditions: either with steady wind or transient events.

3 Numerical validation

3.1 Aerodynamic model

In this chapter, we consider the full-scale VAWT prototype, called 1HS that NENUPHAR has designed, built and operated over one year in Fos-Sur-Mer (South of France). Figure 2 shows a picture of the wind turbine and Figure 3 recalls its main dimension.

Figure 2: NENUPHAR VAWT prototype 1HS

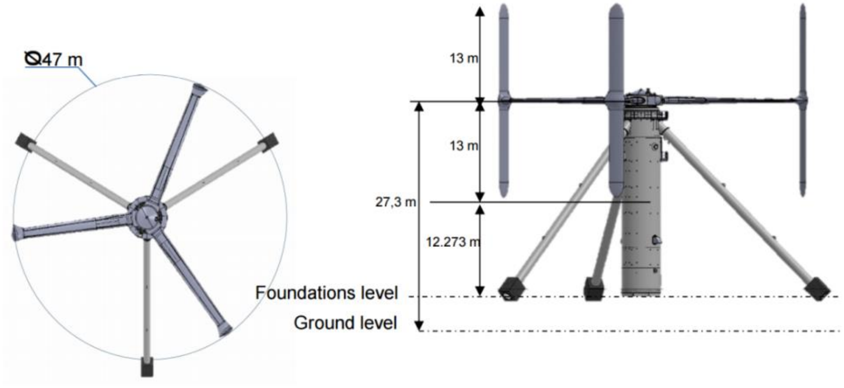

Figure 3: General dimensions of the 1HS

To validate the aerodynamics of PHARWEN, numerical comparisons are carried out with a 2D Navier-Stokes flow solver (CFD 2D). In order to have comparable results, the blade span is extended to 3000m such that the 3D effects are negligible at the blade midspan. Figure 4 and Figure 5 show respectively the normal and tangential aerodynamic coefficients of the 1HS blades over one full rotation. The models match very well at high TSR where the flow remains attached to the blades. At low TSR, flow separation and dynamic stall occur hence a decrease in the model's precision, the latter remains however satisfactory for loads calculation.

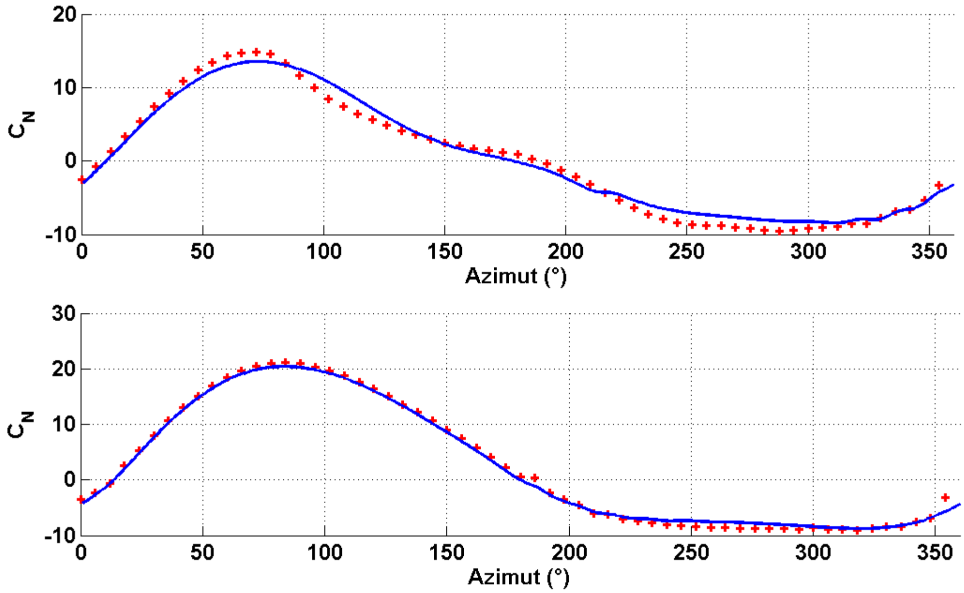

Figure 4: Normal aerodynamic coefficients of the 1HS blades over one rotation at low TSR (top) and high TSR (bottom). Comparison between PHARWEN (red cross) and CFD 2D (blue line).

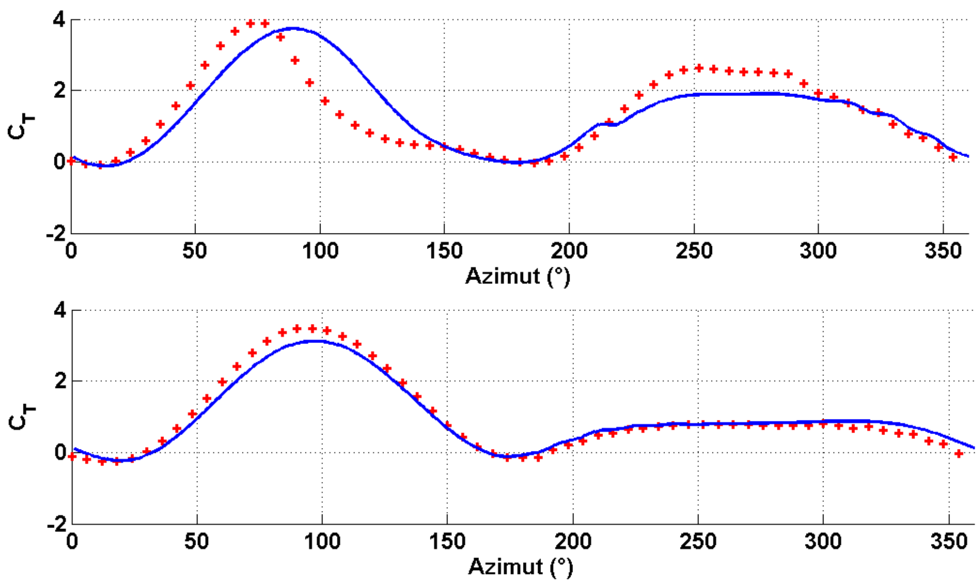

Figure 5: Tangential aerodynamic coefficients of the 1HS blades over one rotation at low TSR (top) and high TSR (bottom). Comparison between PHARWEN (red cross) and CFD 2D (blue line).

3.2 Structural model

3.2.1 Straight wing

To validate the structural tool NeSToR, a straight wing is first considered. To represent the aero-elastic behavior of a wing, it is important that the structural model computes accurately the eigen modes of the structure while taking into account the coupling between bending and torsion. We consider here the Goland wing with a length of 6.096m, a chord of 1.8288m and which structural characteristics can be found in Table 1.The beam has cantilever boundary condition.

Bending stiffness (N.m²)	Torsional stiffness (N.m²)	Linear density (kg/m)	Moment of inertia (kg.m)	Elastic axis (% of chord)	Center of gravity (% of chord)
9.77×10^6	9.88×10^5	35.71	8.63	33	43

Table 1: Goland wing's structural characteristics

The two first eigen frequencies were computed at 7.67 Hz and 15.27 Hz, which is in accordance with Banerjee [14] who solved this problem with exact explicit analytical expressions and found respectively 7.89 Hz and 15.44 Hz. The small discrepancies can be explained by a slight modification of the Goland wing characteristics in [14]. Figure 6 shows a good agreement of the two first mode shapes between NeSToR and [14]. These modes are of a particular importance are they are the ones involved in the flutter aeroelastic instability.

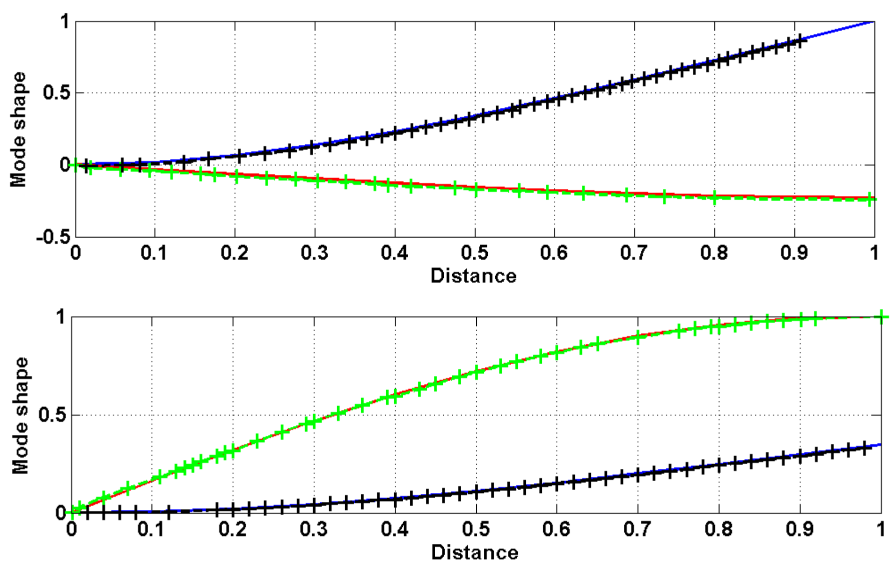

Figure 6: Comparison of the mode shapes between NeSToR (plain lines) and [14] (cross lines). Mode 1(top) shows a predominance of bending (blue and black lines) while Mode 2 (bottom) shows a predominance of torsion (red and green lines).

3.2.2 VAWT test case

PHARWEN can be used as a global design model to compute the stress in different parts of the wind turbines. These loads are then used as design values to design the components of the VAWT (blades, drive train, strut-to-blade attachment, tower,…). It is therefore important to validate the stresses computed by NeSToR. For that purpose, the same aerodynamic loads computed on the 1HS, as described in §3.1, for a wind speed of 20 m/s were injected in a commercial beam-element model and in NeSToR (without the aero-elastic coupling). The internal loads computed at the strut-to-blade junction with the two codes are shown in Figure 7 and Figure 8. Note that while NeSToR can take into account the structure dynamics, the results presented here are computed with a static resolution.

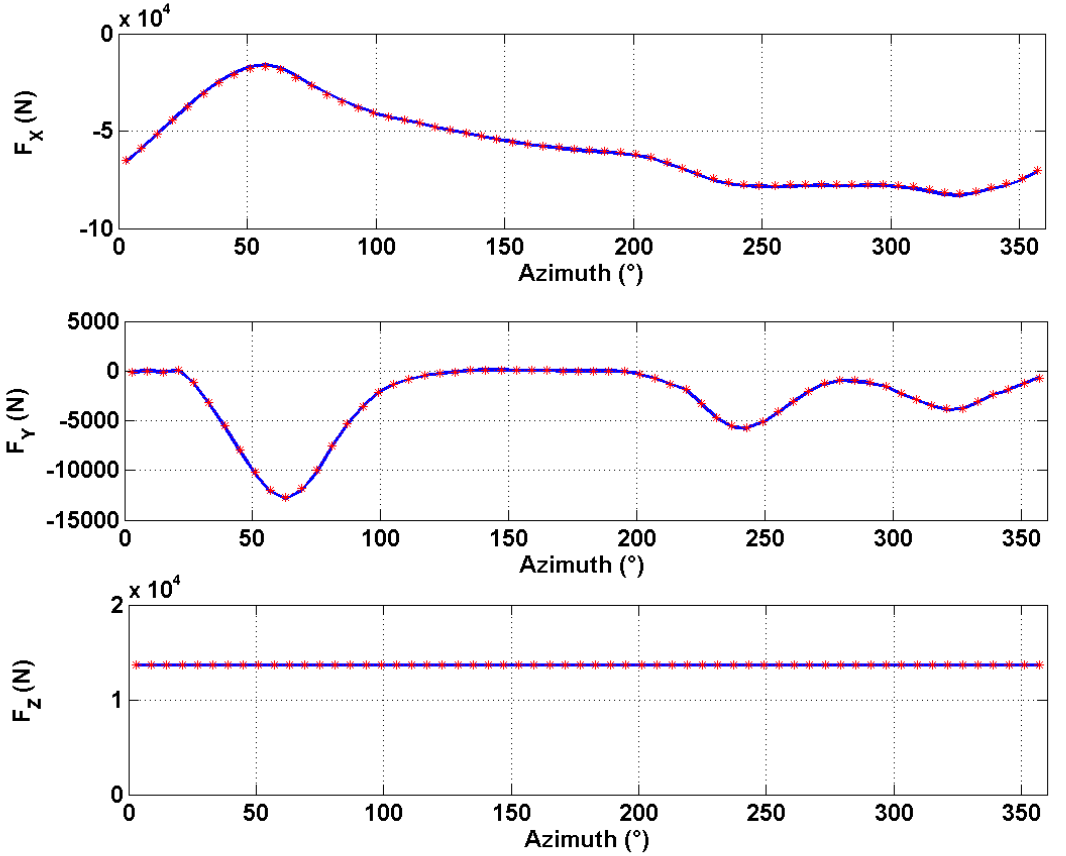

Figure 7: Comparison of the internal forces computed by NeSToR (red stars) and a commercial beam-element model (blue line). Results are presented in a cylindrical coordinate system rotating with the blade. (x: radial, y: orthoradial, z: vertical).

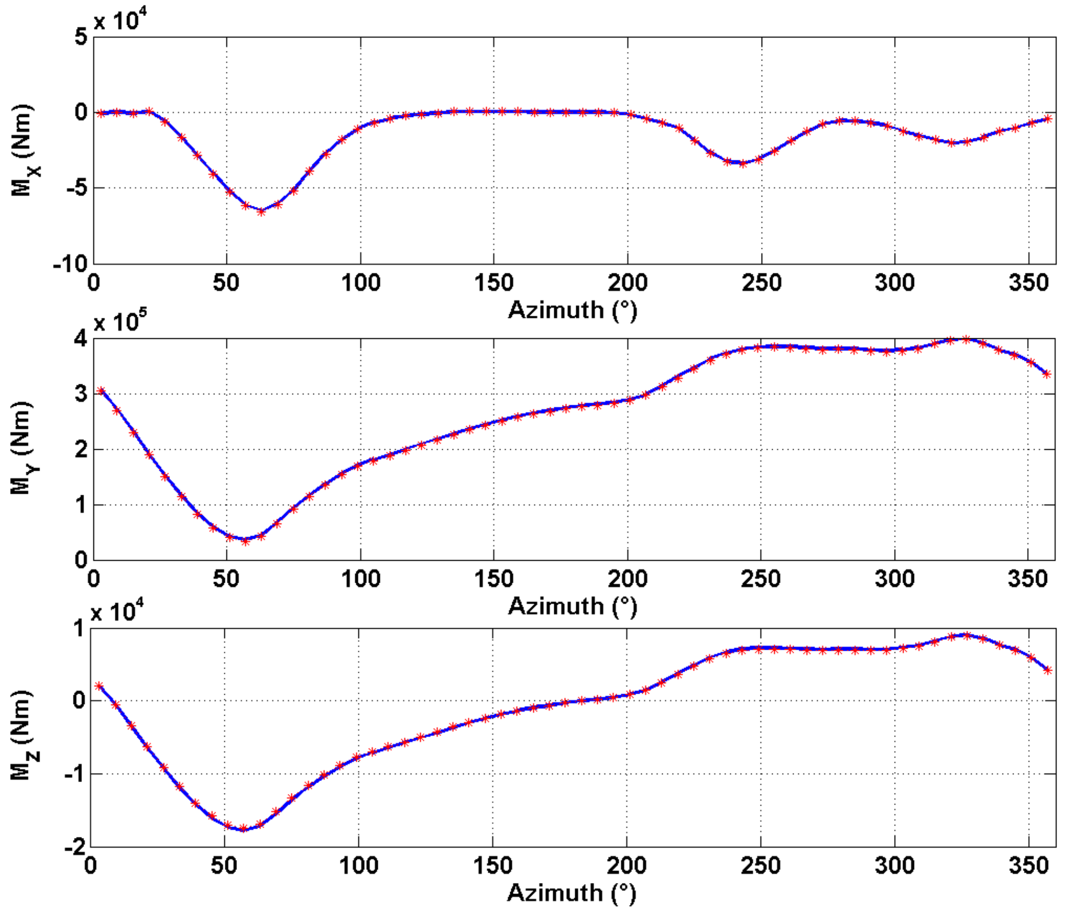

Figure 8: Comparison of the internal moments computed by NeSToR (red stars) and a commercial beam-element model (blue line). Results are presented in a cylindrical coordinate system rotating with the blade. (x: radial, y: orthoradial, z: vertical).

3.3 Global coupling

The validation of the aero-elastic coupling of the model is done in two parts. First, the Goland wing described in the previous chapters is simulated and a flutter detection test is carried out. Second, comparisons with the loads experimental measurements from NENUPHAR prototypes are carried out. This second part is however presented in another paper [15].

To detect flutter on the Goland wing, time-domain aero-elastic simulations are run with PHARWEN for different wind speeds until an exponential growth of the blade bending and torsion is observed. A flutter speed of 145 m/s and a flutter frequency of 8.8 Hz were computed which are comparable to the values presented in [16]. The discrepancies between the different sources probably come from the assumptions behind each aerodynamic model. A thorough benchmark between the different codes would be needed to understand them. More detailed results are shown at a wind speed of 150 m/s to ease the observation of flutter. Figure 9 shows the bending displacement and the torsion of the blade tip during flutter. Figure 10 shows the 3D wake computed by PHARWEN which oscillates at the flutter frequency.

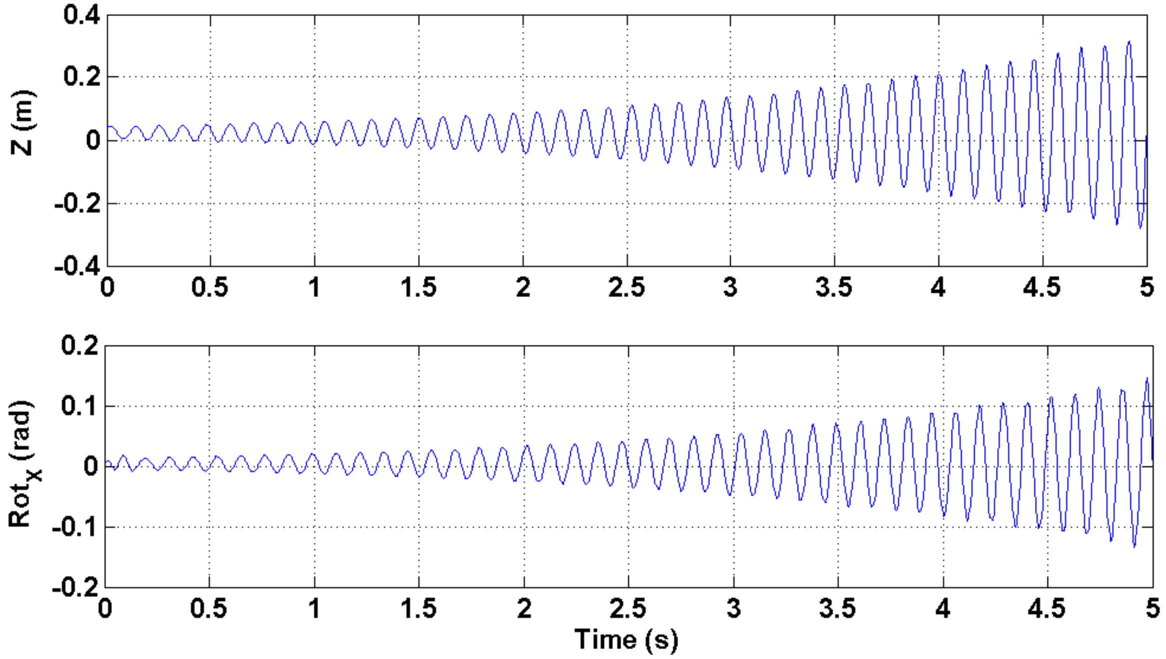

Figure 9: Bending displacement and torsion of the blade tip at a wind speed of 150 m/s

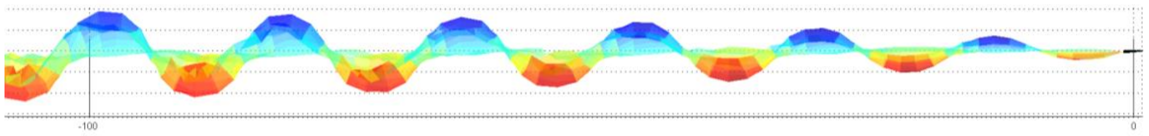

Figure 10: Wake of the Goland wing at a wind speed of 150 m/s. Side view. The wind is coming from the right.

4 Conclusion

This paper presents the development of the PHARWEN aero-servo-elastic code, which aims at simulating accurately the behavior of a floating VAWT. The model is based on an aerodynamic module ARDEMA 3DS that allows to capture the complex unsteady aerodynamics of floating wind turbines and of VAWTs. It couples a 3D vortex panel method to a Beddoes-Leishman type dynamic stall model. To compute the structure dynamics, an Euler-Bernoulli beam element model NeSToR is used. This code allows to take into account all the inertial effects linked to a rotating body moving in space.

Two cases were considered to validate the model: a straight cantilever wing and a full-scale VAWT prototype called 1HS that was designed, built and operated by Nenuphar. The structural and aerodynamic modules are first validated separately. ARDEMA 3DS is validated against a 2D Navier-Stokes model on the 1HS. On its side, NeSToR is validated against [14] on a straight wing and against a commercial beam-element model on the 1HS. The modules' results compared very well.

Finally, a flutter detection test is carried out on the straight wing to validate the aero-elastic coupling. Flutter was clearly observed and its critical wind speed and frequency were comparable to the ones presented in [16]. However, a more detailed comparison of the aerodynamic models used by the different sources would be needed to understand the discrepancies.

As there is no high-fidelity numerical benchmark to validate the aero-elastic coupling on a VAWT, PHARWEN results were directly compared to experimental measurements carried out on full-scale VAWT prototypes operated by Nenuphar. They are equipped with multiple accelerometers and strain gauges in different parts of the wind turbine allowing to capture a good distribution of the structure's stress and displacements. First results of this work are presented in [15].

Further comparisons with experimental data will be carried out by Nenuphar as its Technology Validation and Verification plan makes progress. Two wind tunnel tests have already been performed: one on a model-scaled VAWT moving on an hexapod and one with counter-rotating VAWTs. This will allow to validate respectively the unsteady loads due to rigid-body motions and the aerodynamic interactions between two wind turbines. Full-scale experimental campaigns on onshore and offshore VAWTs with Individual Pitch Control are also already planned.

Acknowledgments

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