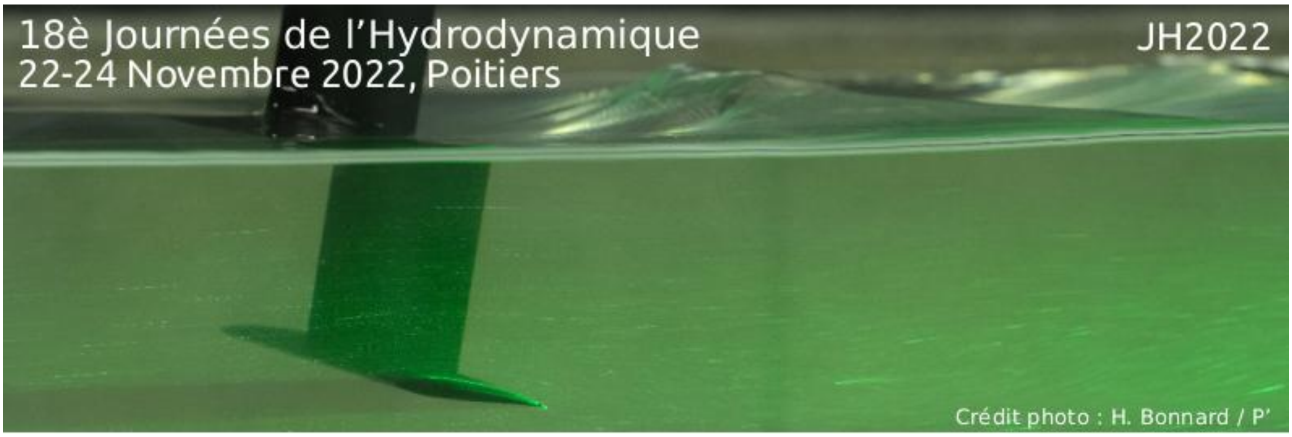
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LES DEFIS DE LA MODELISATION DES EOLIENNES FLOTTANTES A AXE VERTICAL

CHALLENGES IN MODELLING FLOATING VERTICAL AXIS WIND TURBINE

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Résumé

Les éoliennes à axe vertical sont une solution intéressante pour récupérer l'énergie du vent bien que moins développées que les éoliennes à axe horizontal. C'est pourquoi lors de la conception détaillée du système, certains points font l'objet d'une attention particulière pour pouvoir correctement représenter les caractéristiques spécifiques de ce type d'éolienne.

Cet article détaille le modèle réalisé avec DeepLines Wind de l'éolienne S2 de 1MW développée par SeaTwirl. La turbine est constituée de trois pales montées sur un flotteur de type spar. La turbine et le flotteur sont tous les deux en rotation, connectés avec un palier au générateur qui est maintenu en position par les lignes d'ancrage. Le premier point étudié est la représentation du chargement aérodynamique sur les pales. Trois méthodes ont été testées : « Multiple Streamtubes », « Actuator Cylinder », et méthode vortex 2D (tranches horizontales). L'approche de type « Actuator Cylinder » a été choisie comme un bon compromis entre la représentation des efforts et le temps calcul. Le second point est la définition du contrôleur basé uniquement sur le moment appliqué à l'axe de la turbine, les pales étant fixes par rapport à la turbine. Un modèle de la turbine seule a été développé pour optimiser la vitesse de rotation et les différents paramètres de contrôle avant de tester sur le système complet. Séquences de démarrage (en utilisant l'énergie venant du réseau), zones d'exclusion ainsi que procédures de sécurité pour l'arrêt de la turbine ont été mises au point basé sur les recommandations du DNVGL. Le flotteur est modélisé par des éléments finis poutres avec une formulation de Morison. Les propriétés structurelles (poutre équivalente) des pales ont été obtenues avec le logiciel NuMAD de Sandia National Laboratories. Comme le flotteur est en rotation dans l'eau, un effet Magnus est ajouté en présence de courant, basé sur des essais en bassin réalisés par SSPA. Il en résulte des efforts supplémentaires de traînée et de poussée fonction du rapport de vitesse (vitesse structure au rayon externe de la spar divisée par la vitesse de courant). Un moment de frottement est également appliqué car il peut influencer la production électrique.

Le modèle complet a été testé sur différents environnements représentant le vent, la houle et le courant ainsi que des procédures d'arrêt de la turbine. L'objectif de ces calculs est de fournir des données pour vérifier l'intégrité des différentes parties du système ainsi que la production électrique. Ainsi des données globales sont obtenues (mouvements et accélérations du flotteur, performance de la turbine) mais aussi des chargements, contraintes et déformations le long des pales, de la tour, du flotteur et des lignes d'ancrage. Ces post-traitements génèrent de l'ordre du gigabyte de données par cas.

Summary

Floating vertical axis wind turbines (FVAWT) are an interesting solution to harness wind power but are not yet as widely developed as horizontal axis wind turbines (HAWT). Therefore, for detailed design of the system, there are some challenging points to represent numerically because all the specificities of the VAWTs must be included in the global model.

This paper introduces the modelling of SeaTwirl 1MW S2 VAWT in Deeplines Wind. The turbine is a three-bladed VAWT mounted on a spar. The turbine and spar are both rotating together, connected with a bearing to the generator housing that is held in place by mooring lines. The first issue was the representation of the aerodynamic loading on the blades. Three methods were tested: multiple streamtubes, actuator cylinder and 2D (horizontal slices) vortex method. The actuator cylinder method was selected as a good compromise between load representation and computational time. The second issue was to incorporate a control system, based on the applied torque on the shaft as the blade pitch is fixed. A model of the turbine alone was used to optimize the rotational speed and controller's parameters before testing on the full model. Start-up (with grid energy), exclusion zone and a complete safety system based on DNVGL's guidelines for shutdown procedures were also included in the controller. The floater itself was represented by beam elements with hydrodynamic loading provided by Morison's formulation. The structural properties of the blade were obtained with NuMAD from Sandia National Laboratories. As the spar is rotating in the fluid, a Magnus effect was added when current is present, according to results from tank tests performed by SSPA. The resulting lineic drag and lift forces are a function of the speed ratio (velocity at spar outer radius divided by current velocity). Furthermore, a hydrodynamic friction torque was applied as it can influence electrical production.

The global model was tested on various environments (wind, wave, current) and shutdown procedures. The objective of the simulations is to provide data for assessing the integrity of the whole system as well as to check the performance in terms of electrical production. Therefore, global data were processed (floater's motions and accelerations, turbine performance), but also loads, stress or strains at all stations in the blades, struts, tower, shaft, and mooring lines. Those post-treatments generate approximately one gigabyte of data per case.

I - Introduction

SeaTwirl is proposing an original concept of a vertical axis wind turbine with the tower directly connected to a spar. The floater is therefore rotating with the turbine and is kept in position by the generator housing that supports the mooring lines. The present paper focuses on the global model that was developed to provide information on the turbine production, floater behaviour, and internal stresses or strains in the mooring line, spar, tower, struts, and blades. The model investigated is a 1MW S2 prototype.

Some specific issues of the system are investigated. In general, Floating Offshore Wind Turbines (FOWT) are coupled systems with aerodynamic and hydrodynamic loadings. A global model of the system must be built to capture the interaction between the turbine, floater and mooring system. In the case of a vertical axis turbine, the aerodynamic representation of the forces is more complex than the standard Blade Element Momentum (BEM) method used for the horizontal axis turbine. One of the main differences is that the blades are crossing their wakes. Several methods can be used. In the present case, an actuator cylinder method was selected as it was compared to measurements on the Nenuphar prototype [1] in the INFLOW project. It makes it possible to run a large number of simulations compared to more advanced methods that require large computer time. Another topic is the control of the turbine. Several algorithms were tested to define rated speed, torque control as well as start and shutdown procedures. Finally, due to the rotation of the floater, the Magnus effect has to be incorporated as an external force since it influences mooring loading. The friction moment must also be incorporated as it acts in parallel with the controller torque to slow down the rotation of the turbine.

II - Global model

II - 1 Concept overview

The S2 VAWT will be moored on a location east of Karmøy, on the south-west coast of Norway.

Figure 1: Mooring site location

The water depth on-site at the position of the spar is around 110m. The overall system shown in Figure 2 is about 135m in height with a draft of 80m. The hull diameter is 5.5 m. The turbine has a 50m diameter with three 40m long blades. Blade profile from the NACA family was chosen. There are three mooring lines with two bridles at the top for each line. The lines hold the generator housing in position, while the spar, tower and turbine are rotating in a counterclockwise direction (top view).

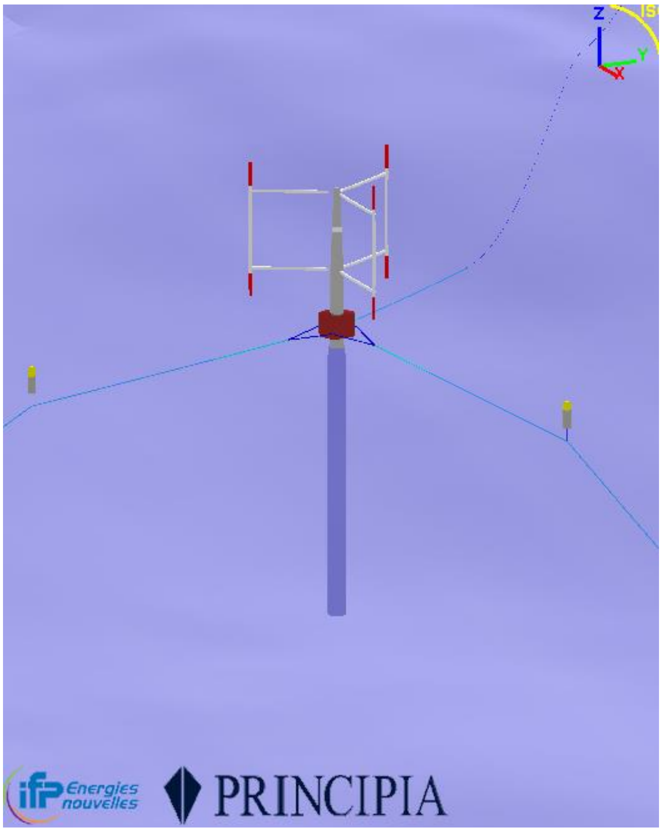


Figure 2: Global system

II - 2 Numerical model

The spar as well as turbine blades and struts, are represented with beam elements while the mooring lines are modelled by bar elements. Contact with the seafloor is considered as well as friction effect. To properly reproduce the two struts and blade assembly, a detailed ANSYS model is built with the different material layers (Figure 3).

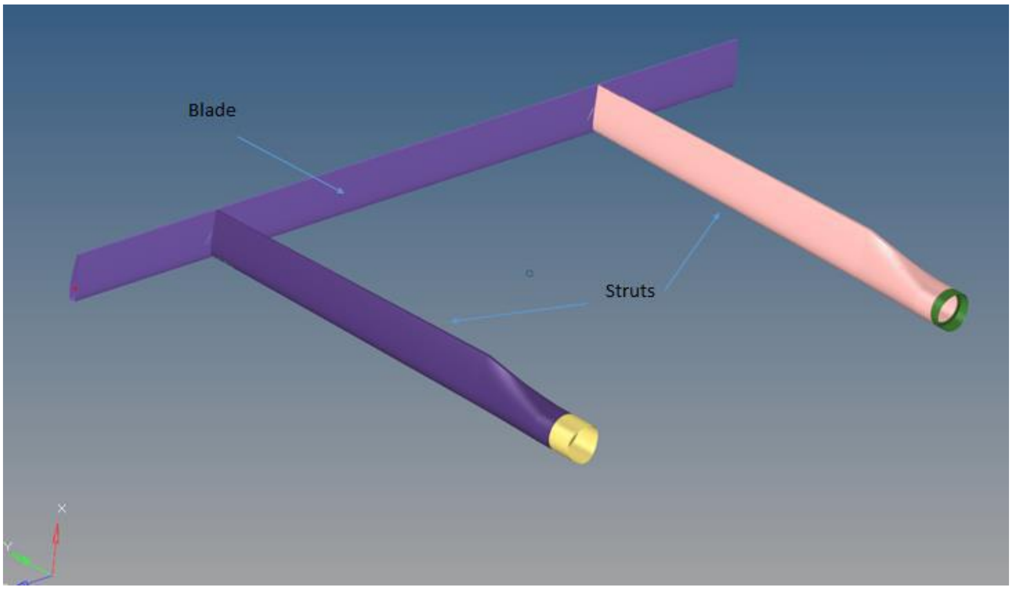


Figure 3: Detailed model of the assembly blades/struts

This detailed model has two objectives:

- First, equivalent properties of the varying sections are obtained in order to have an equivalent beam section. Besides the section weight, the model defines the centre of gravity, the elastic centre and the stiffness matrix of the element.
- Secondly, the model is used to check the implementation of the beam element model by comparing the response of the assembly to simple static loadings, as well as the resulting modes. There is a special emphasis on properly defining the stiffness of the blade/strut connection.

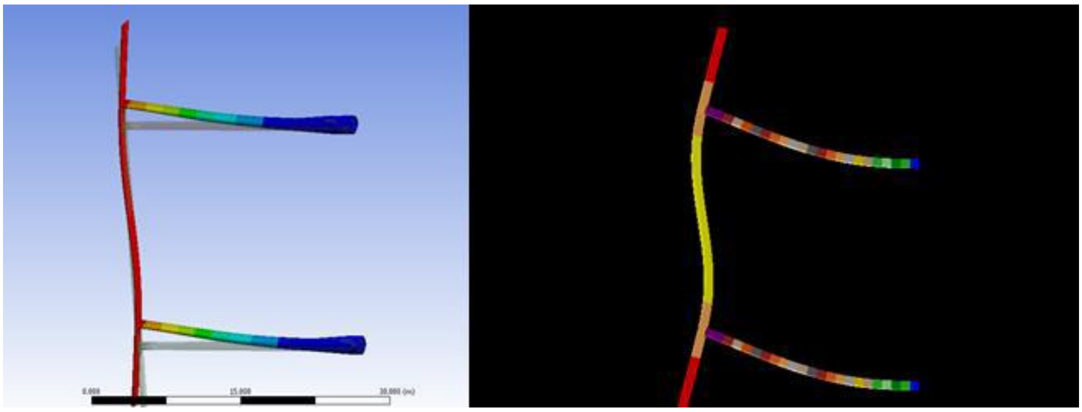


Figure 4: First Mode of the assembly: detailed versus beam model

III - Specific issues

III - 1 Aerodynamic model

In DeepLines Wind [6], the coupling between the mechanical solver and the aerodynamic library has two main steps as described in Figure 5:

- At the beginning of the simulation, the mechanical solver provides general information to the aerodynamic library, namely the number of blades, the number of communication points (one node per blade element at mid-element), and the location of two .xml files that provide the aerodynamic description of the blades and the general data to be used (wind file, air density and viscosity, aerodynamic model and options).
- At the beginning of each time step:
    - The mechanical solver provides positions, velocities and accelerations for all the communication points at the end of the previous time step;
    - The aerodynamic library provides the lineic forces and moments;
    - If a controller is present, the mechanical solver also calls the controller, and the controller provides the torque to be applied to reach the target rotational velocity (in the present study there is no pitch control);
    - The mechanical solver then computes the new blade position based on aerodynamic forces and moments.

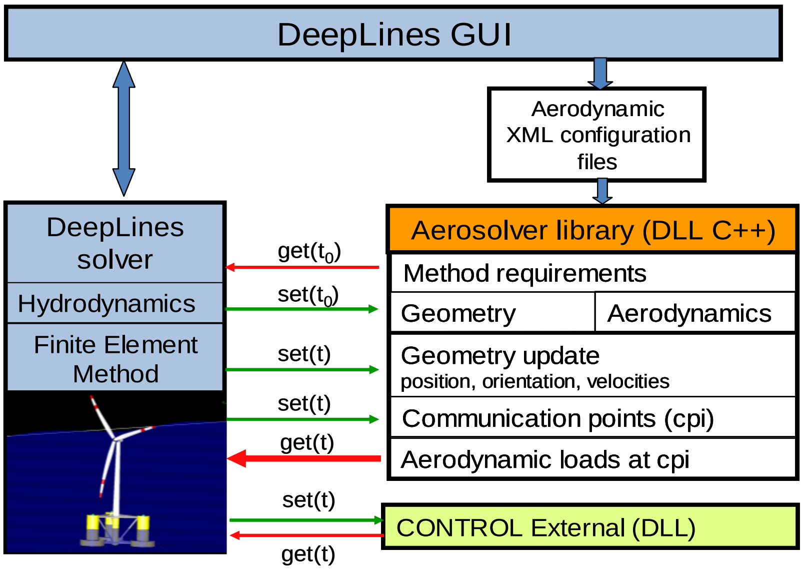


Figure 5: Aero/Mechanical coupling

Three models are available for the study [2]:

- The Multiple Streamtube Model (MSM) uses a BEM-type method. The wind turbine is divided into several adjacent streamtubes, and, similarly to the BEM model for horizontal wind turbines, an induction factor is computed for each streamtube: an equation system based on an expression for the thrust coefficient from actuator disk theory and another expression from blade element theory is solved for to obtain the induction factor. This method was not kept as no distinction is made between the upwind and downwind positions for the calculation of the force on the blades (see also [1]).
- The actuator cylinder (AC) method is based on simplified Euler equations, neglecting the second-order terms. It uses an actuator surface coinciding with the swept area of the 2D VAWT. In the AC model, the normal and tangential forces Qn and Qt resulting from the blade forces are applied to the flow as volume forces perpendicular and tangential to the rotor plane. The velocity induced by the normal and tangential forces Qn and Qt can be computed analytically.
- A 2D Vortex model is also coupled with Deeplines Wind (DLW). Calculations are more CPU-intensive using this model. The vortex solver is based on a bound vortex model of the wind turbine blades and a freely deformable vortex wake made of inviscid vortex blobs. It solves the unsteady, inviscid, incompressible Navier-Stokes continuity and momentum equations (under the form of the vorticity transport equation) in a Lagrangian manner. At each time step, vortices are released from the blade elements into the wake. All these vortices interact with each other, through the Biot-Savart law, allowing the deformation of the wake. The blade/wake interactions can be captured using such a model. To calculate blade forces, the influence of all the vortices is accounted for (Figure 6). The effective velocity at the blade nodes, including the induced velocity due to the wake vortices, is computed. Based on this velocity, the angle of attack is obtained. Then, the circulation is calculated from the airfoil lift coefficient (drag from airfoil polar is not accounted for here; however, the vortex system induces a downwash velocity contribution, that is closely related to drag), and new vortices are released in the wake. A fixed point algorithm is used, since the newly released vortices induce a change in the effective velocity, and thus a change in the angle of attack. Once this fixed point algorithm has converged, the attack angle at every blade point is known. Based on this attack angle, normal and tangential forces are computed, using both lift drag and moment coefficients. An example of the particle is shown in Figure 6 where the interaction blade wake can be observed.

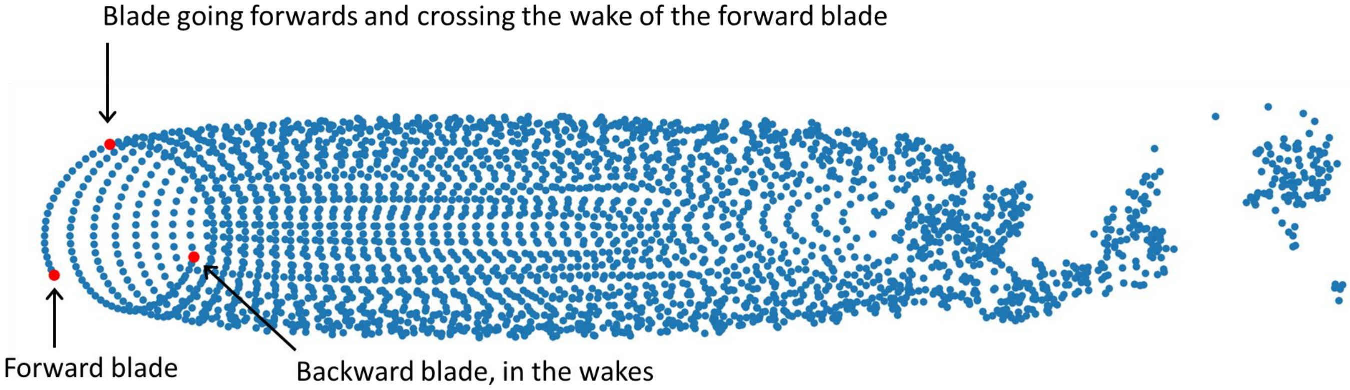
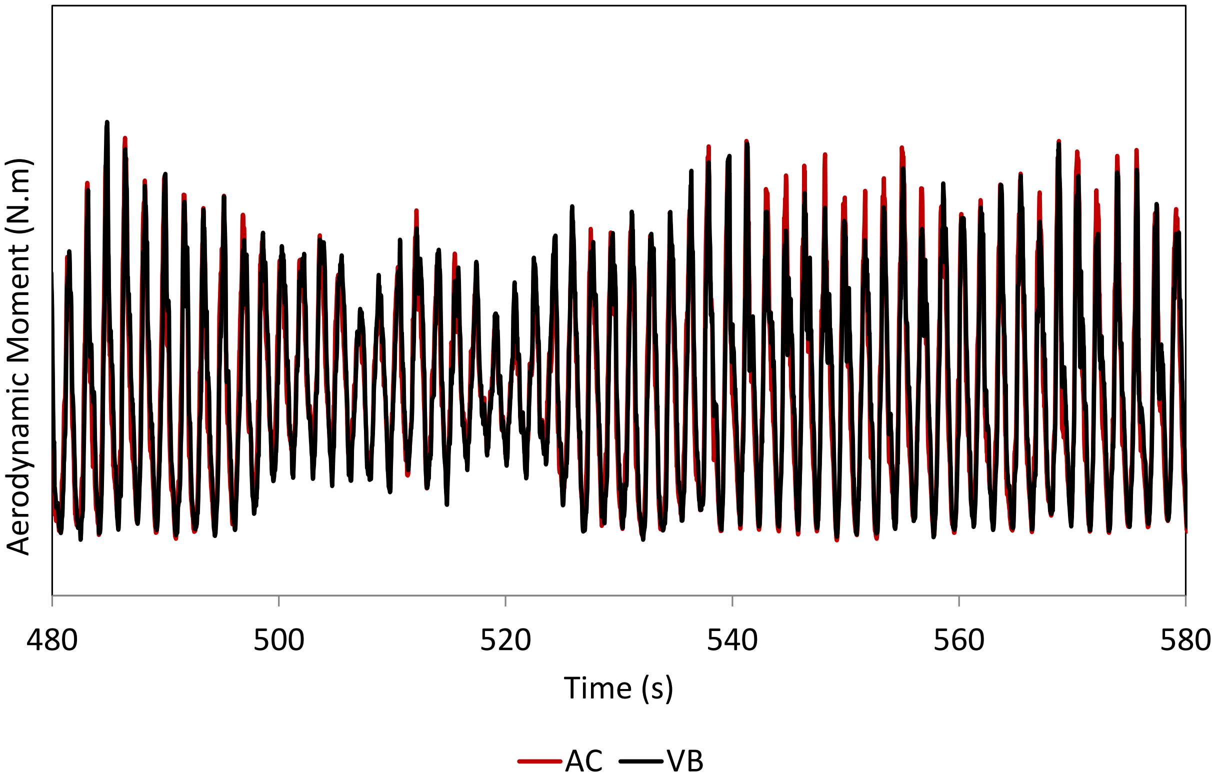


Figure 6: Example of vortex field crated by the Vortex Blob method

In order to validate the AC methods for turbine modelling, a comparison is performed in Figure 7 between AC and 2D vortex approaches. The case is a fixed turbine foundation with a 21.6m/s turbulent wind and an imposed rotation of 11.7rpm. The check is performed on the aerodynamic moment and power as well as on the bending moment in a blade, 9m above the bottom tip. The AC model can well reproduce the variation in aerodynamic loading as well as the resulting internal moments.



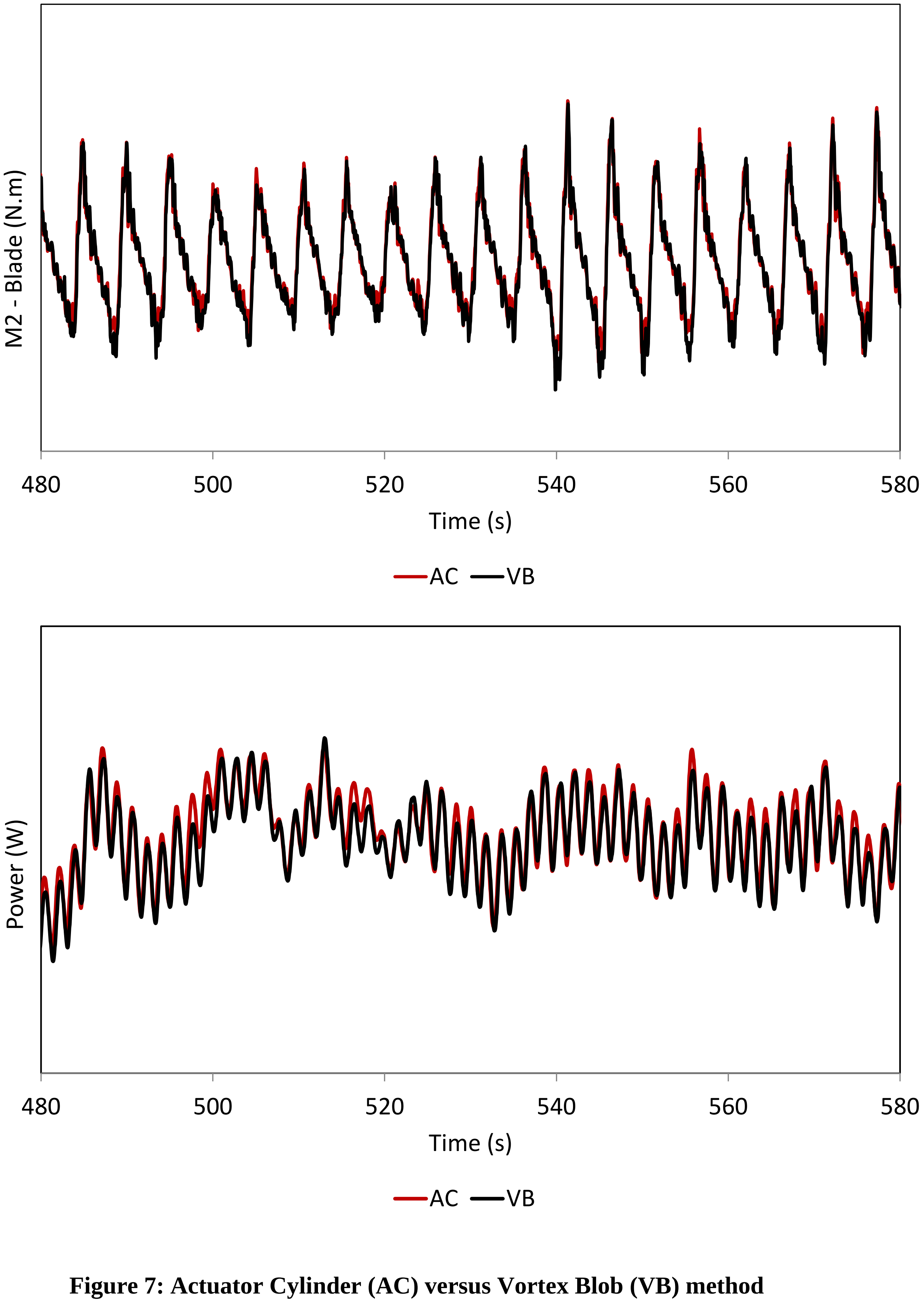


Figure 7: Actuator Cylinder (AC) versus Vortex Blob (VB) method

A second comparison is performed with HAWC2 (Horizontal Axis Wind turbine simulation Code 2nd generation) developed by DTU [4]. Again, this is a fixed foundation case with a constant wind at 13m/s and imposed rotation of 11rpm. The tangential and normal forces on one blade section are compared over one turbine rotation. Again, the agreement is acceptable as shown in Figure 8.

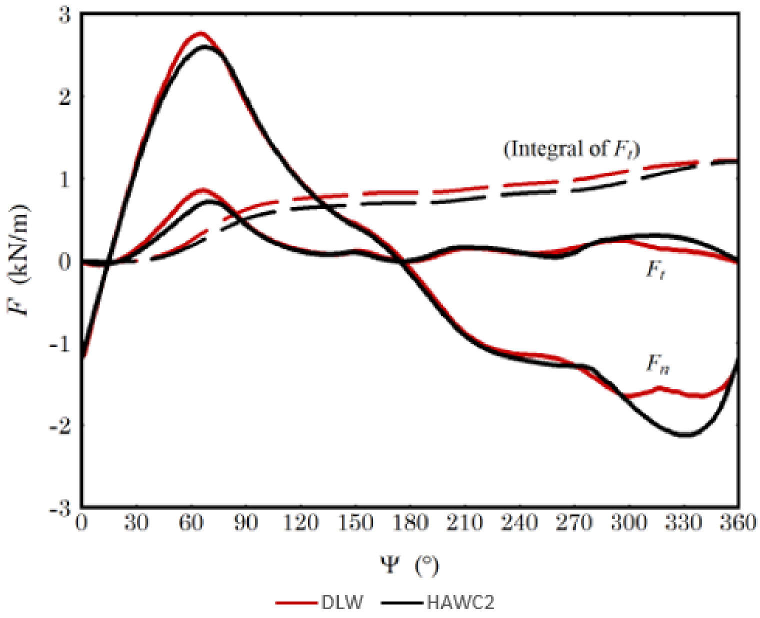


Figure 8: Comparison HAWC2/DLW on the force acting on the blade in one rotation [5]

III - 2 Controller

The controller logic was developed by SeaTwirl (Nieto [7]) and checked on a simplified model. The control is based on the filtered rotational velocity including a notch filter on the 3P mode. Based on the turbine performance, a lookup table linking the torque to the rotational velocity is defined as well as the maximum torque that can be imposed on the turbine. A target torque to extract power can then be obtained as the turbine rotates below rated wind velocity. Finally, a PI (Proportional-Integral) layer is added above rated wind velocity to the torque target signal to define the torque applied on the shaft and avoid any discontinuity. A region corresponding to low wind velocity is also defined to help the turbine starting up by providing energy. This can be seen in Figure 9: for a 4m/s wind velocity average, when the turbine slows down too much due to a lull in the wind, it is reaccelerated to avoid a complete stop. On the other hand, for large wind velocity, the turbine is maintained around a constant rotation speed.

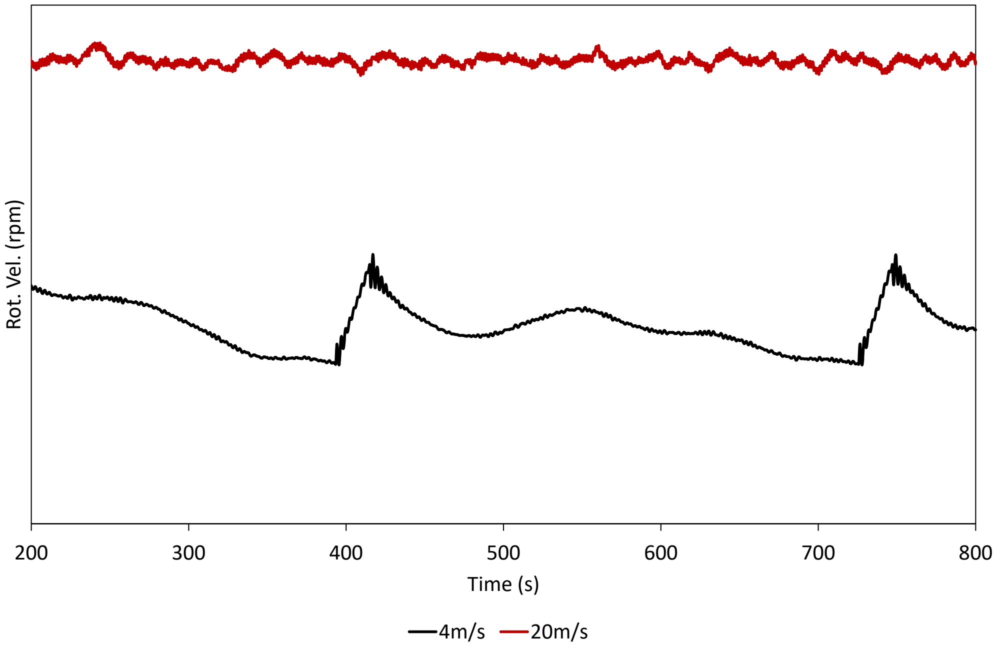


Figure 9: Turbine rotational velocity for a mean wind velocity (35m from sea level) of 4m/s and 20m/s

An exclusion zone algorithm (Rosander et al. [8]) was also implemented to avoid potential resonant frequencies from the system. The exclusion zone strategy is based on increasing the torque as the turbine velocity increases and is coming closer to the velocity to be avoided. Then the torque is decreased creating an acceleration of the turbine that quickly bypasses the excluded velocity region. It can be seen in Figure 10 around 440s when the turbine slows down before reaccelerating.

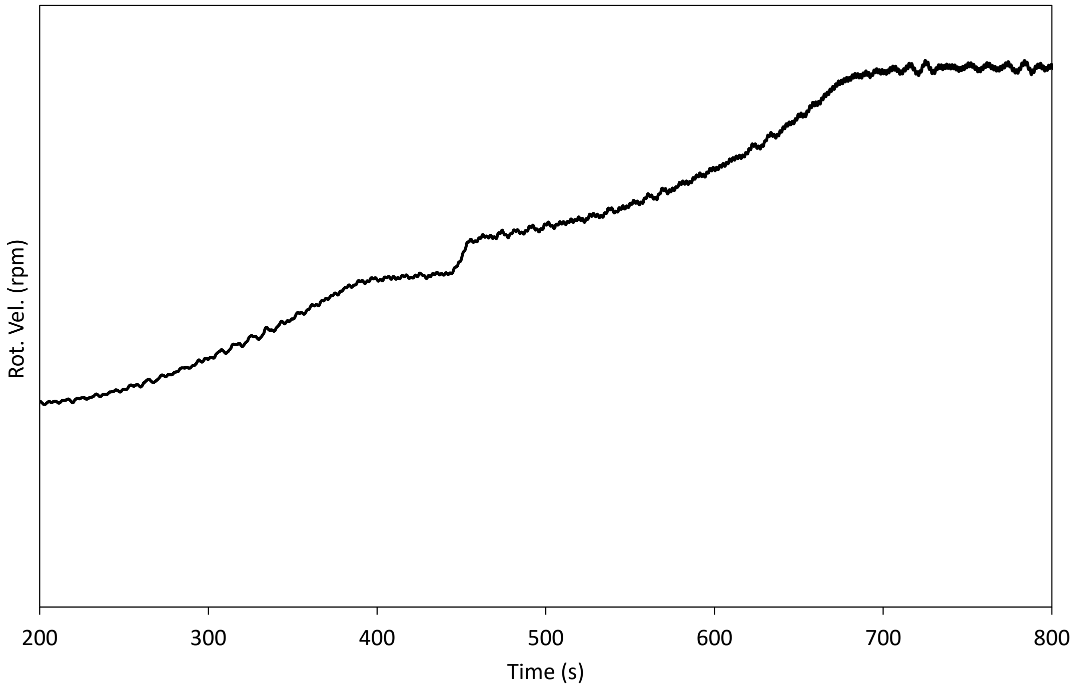


Figure 10: Example of effect of exclusion zone (starting at 440s) on the rotational velocity

Finally, some shutdown procedures are put in place for normal shutdown or emergency shutdown (for instance in case of high rotational velocity). As shown in Figure 11, stopping the turbine creates a torque that is counteracted by the mooring lines and therefore it creates some yaw motion in the floater. It is therefore an important design case.

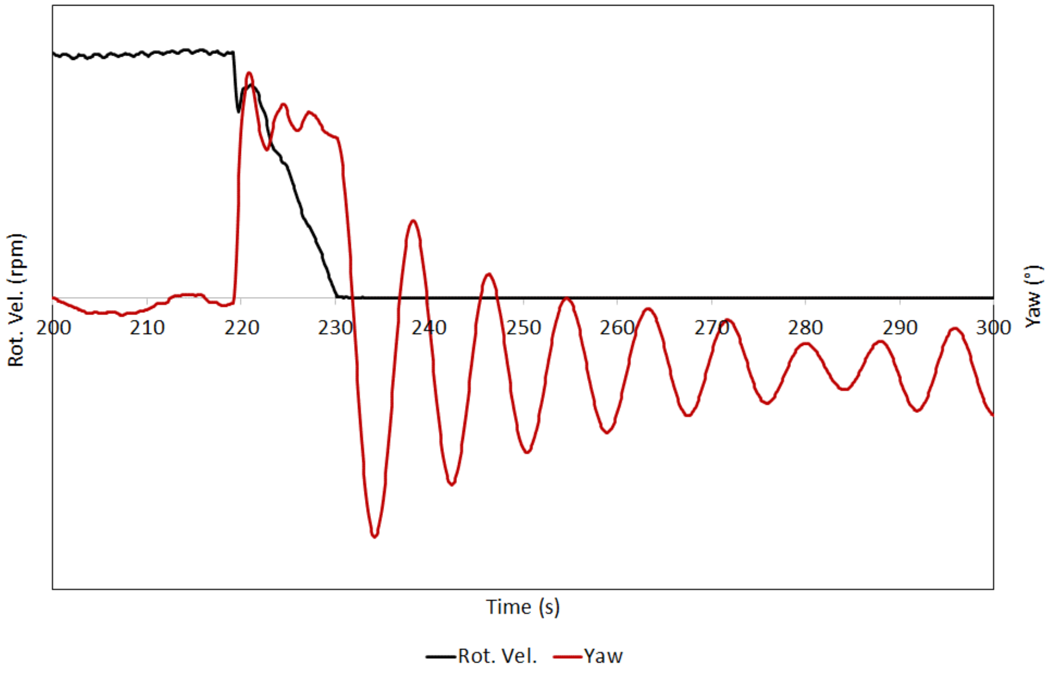


Figure 11: Effect of shut down on floater's yaw

III - 3 Magnus effect

The Magnus effect [3] is accounted for in an external dynamic link library. For the present study, the Magnus effect creates a drag force (in-line with current), a lift force (based on the cross product of current velocity and rotational velocity) and some friction loss (moment along the shaft direction). The reference fluid velocity is the current velocity; the wave velocity is not taken into account.

For the drag and lift force the following formulation is used:

- At the beginning of each time step, DLW provides to the library the position (translation and rotation), velocity (translation and rotation) and acceleration (translation and rotation) of each element along the spar in the global frame together with the current velocity and diameter.
- The library evaluates the velocity ratio based on the current velocity projected in a plane perpendicular to the spar axis (U), the radius of the element R and the rotational velocity along the spar axis ω as $\alpha = R\omega/U$.
- Linear interpolation in a table drag coefficient (or lift coefficient) as a function of velocity ratio provides the drag (Cd) (respectively the lift Cl) along the spar and then the lineic force to be applied in the current direction (respectively perpendicular to the current). The lift and drag coefficients are extracted from model tests.

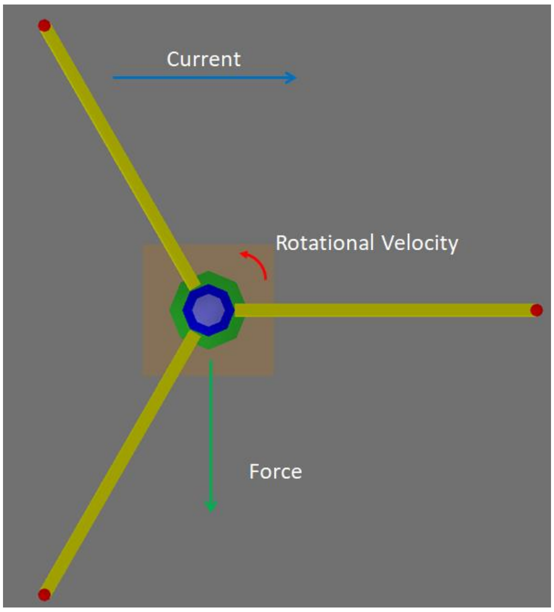


Figure 12: Direction of application of the lift force

A friction moment [9] is applied along the immersed part of the shaft is characterized by a friction coefficient *Cf*. The Reynolds Number is defined as $Re = R^2\omega/\nu$ with ν the kinematic viscosity. Then, for smooth cylinder, $Cf = 4/Re$ at low *Re* and at higher Reynolds it is defined by:

$$\frac{1}{\sqrt{Cf}} = -0.6 + 4.07 log_{10}(Re\sqrt{Cf}).$$

The moment per unit length is then:

$$M = \rho \pi R^4 \omega^2 Cf.$$

Finally, a moment is applied at the bottom of the spar. The moment is defined as follows:

$$M = \frac{1}{2} 0.0728 R^5 \omega^2 \rho \left(\frac{\nu\omega}{R^2}\right)^{1/5}.$$

For an average wind velocity of 14m/s, a surface current of 0.22m/s and mild wave environment, the offset increases from 2.8m to 4.0m due to Magnus effect.

IV - Conclusion

A global model of a floating vertical axis wind turbine (VAWT) was developed in DeepLines Wind. The model is used to obtain extreme loads and fatigue of all the components from mooring lines to blades. The aerodynamic loading was calibrated by comparing different numerical methods and tools with feedback from measurements performed in the frame of the INFLOW project. The controller was then developed to produce the required 1MW but also to provide start and stop sequences. For the Magnus effect, data from the DEEPWIND project were first used but then specific model tests were performed to extract the extra lift and drag induced by the spar rotation. The design is then based on the best available methods and data. As the S2 is a pilot project, extensive instrumentation will be deployed to further improve the model prediction.

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