ETUDE EXPERIMENTALE A PETITE ECHELLE D'EOLIENNE FLOTTANTE DANS LA VEINE FLUIDE DE LUMINY

SMALL SCALE TESTS OF FLOATING WIND TURBINES IN THE WIND AND WAVE FLUME OF LUMINY

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Résumé

L'avenir du monde éolien semble voué à l'offshore et, à l'exception de la mer du Nord qui offre des conditions exceptionnellement propices à la pose d'éoliennes sur fondations fixes, des zones très venteuses présentant des profondeurs relativement faibles (moins de 50 mètres), les éoliennes flottantes sont attendues comme la seule solution technico-économique viable pour aller chercher des vents de plus en plus intéressants avec la distance aux rivages.

L'efficacité économique de ces projets influence énormément les choix dans le design pour des réductions de coûts impactant directement le prix de l'énergie. Dans ce domaine, le manque d'expérience impose la conduite de tests en bassin onéreux sur des modèles réduits avant la phase du prototype à échelle réelle. Ce papier présente les essais opérés sur un modèle 1/100e d'une éolienne de 5 mégawatts sur une fondation flottante de type Dutch Trifloater dans la veine fluide de Luminy.

Summary

The future of wind turbines is expected to be offshore and, except for the North Sea which provides exceptional conditions for bottom-fixed wind turbines with very good winds in rather shallow depths (less than 50 meters), floating wind turbines are expected to be the technical and economical solution to catch the high winds further away from the shore.

The financial effectiveness of such project is drastically driving the choices in the design toward the cost reductions and the lack of experience in this domain requires expensive tank tests and prototypes. This paper presents the tests carried out on a 100th-scale 5 megawatt turbine on a floating foundation in the wind and wave flume of Luminy.

I) **Introduction**

The facility in Luminy, first built to study wind and wave interactions, provides a good quality of wind and, with the wave generation system recently up-graded, the possibility to test at a limited scale the behaviour of floating windmills under the coupled actions of wind and waves. The limits of model scale, in the case of wind turbines, are driven by the range of wave generation and water depth, but also by the height of the wind tunnel.

The experimental campaigns carried out between February and May 2014, are a 100-th scale of a five megawatt turbine, similar to the AREVA M5000-M116, on a semi-submersible platform of the type Dutch Tri-Float, adapted to the characteristics and the requirements of stability of the M5000.

The aim of the tests is to prove the possibility of making very small scale experimental campaigns capable of giving clues about the feasibility of a floating wind turbine before making larger scale model tests or a prototype. The tests also aim at validating numerical models used to design the devices.

II) **Test facilities**

II - 1) Luminy wind and wave flume presentation

The facility in Luminy is operated by MIO and PYTHEAS. The installation comprises the main wind and wave flume, which has for internal dimensions: length 40 m, width 2.7 m, water depth 0.70 m to 0.90 m, height above free surface: 1.7 m. The facility provides a wind of high quality in a wide range of speeds, up to 14 m/s; wave generation with a brand new wave maker installed beginning of 2014, capable of providing waves with periods in-between 0.5 and 2.5 seconds and amplitudes up to 10 cm; and current generation up to 10 cm/s.
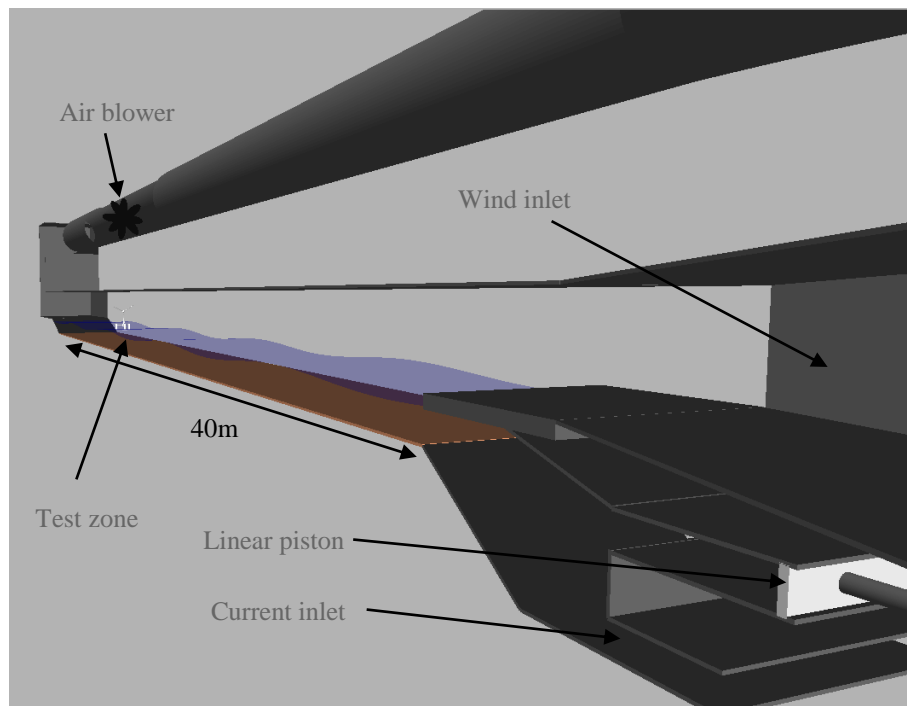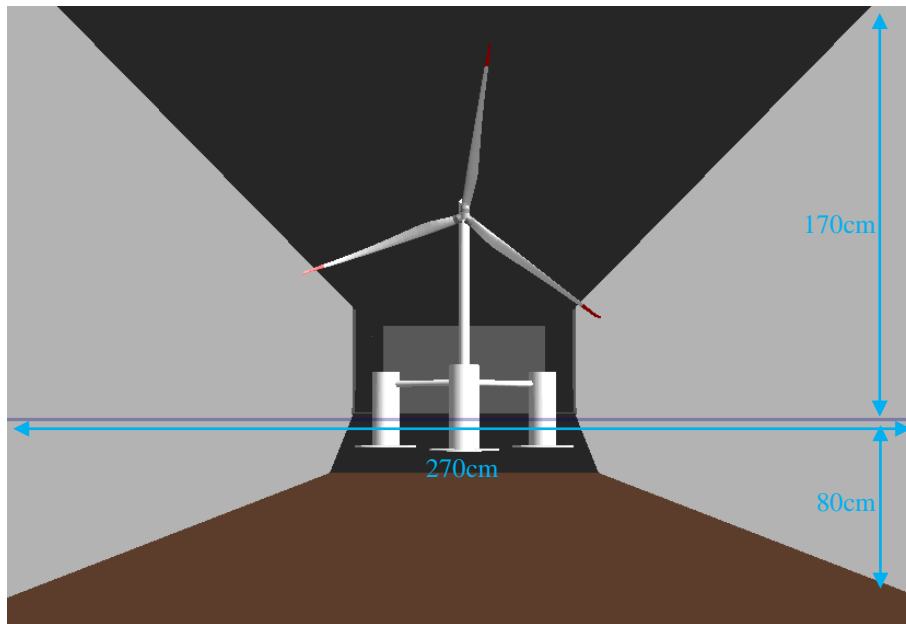
Figure 1 Main characteristics of the installation

The wavemaker, in order not to disturb the wind inflow and its quality, is under water. The wind meets, after many honey combs with different porosity ratios to break down the turbulence, the water at a point where the waves have already been generated. Over the distance (about 30 meters to the test zone), wind and waves interact as they would do in real life. This is the main difference with other facilities that have been used to perform tests on wind turbines.

II - 2) Wave generation

The wave generation was formerly made with a hydraulic flap but to improve the range of amplitudes, it was changed for a hydraulic piston with more than three times the displaced volume of the flap (meaning at least three times the amplitude of the waves generated).
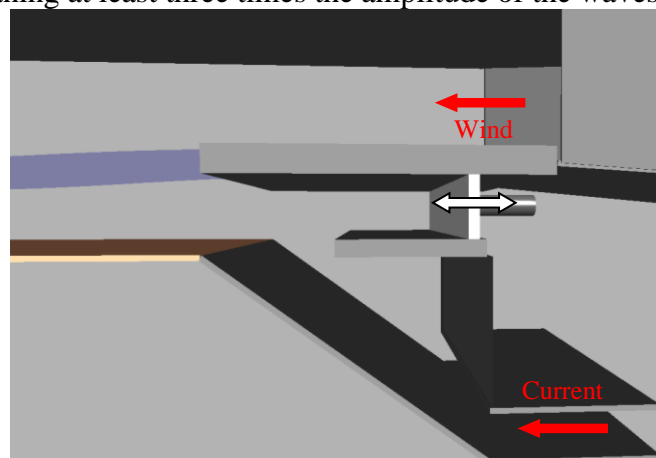

Figure 2 Wave generation schematics

The transfer function of the new wave maker has been calculated through linearized potential flow theory, assuming the piston to be at the far end of a rectangular channel. Results are shown in figure 3, compared with measurements, made close to the wavemaker (red symbols) and at the test zone, 30 m down the tank (blue symbols). The curve labelled "fluid piston" is for zero draft of the plate at the free surface. The other curve is accounting for the limited, but not negligible, draft of the plate (9 cm).
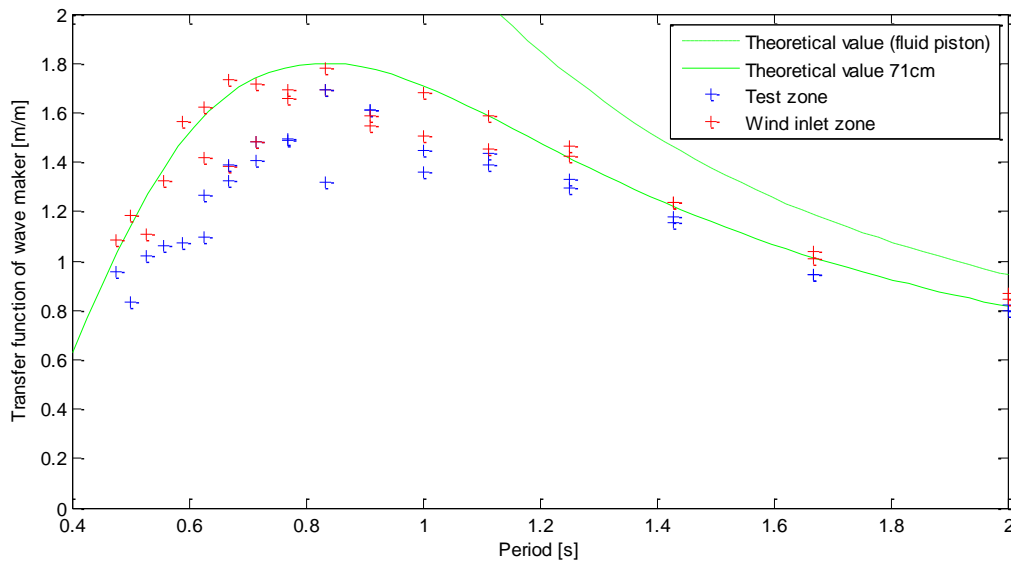
Figure 3 Wave maker transfer function

III) __Turbine modeling__

III - 1) Scaling laws

The floating wind turbine comprises two sources of excitation for which the scaling laws generally used are not compatible: the aerodynamics for which the importance of the viscosity over the inertia must be respected following thus the Reynolds similarity, and the hydrodynamics involved in the sea-keeping analysis mainly driven by the ratio between the gravitational forces and the inertia.

	Length	Time	Velocity	Acceleration	Mass	Force	Pressure	Moment
Froude	λ	$\lambda^{0.5}$	$\lambda^{0.5}$	1	λ^3	λ^3	λ	λ^4
Reynolds	λ	λ^2	λ^{-1}	λ^{-3}	λ^3	1	λ^{-2}	λ^3

Table 1 Comparison of scaling laws

The choice made here is to follow Froude's scaling law being the main driver of the sea-keeping analysis. At scale 1/100th 1 meter is 1 centimeter, 1 second is 0.1 second and 1 ton is 1 gram. This is a driving constraint for the pieces of equipment to be installed in the nacelle. For instance the top head mass of the M5000 is about 340 tons all included (Rotor and Nacelle Assembly, a.k.a. RNA).

III - 2) Manufacture of the model

III-2-i) Blades

One challenge was definitely the blade manufacturing. The real blades are more than 55-meter long and weigh between 16 and 20 tons meaning at 100th scale 55 centimeters for 16 to

20 grams. The blades were thus made of a single-layer carbon sheets to have a thin shell and meet the weight constraints. Axial reinforcements were set along the blades and a biaxial carbon layer was added at the blade root to ensure the structural integrity of the system
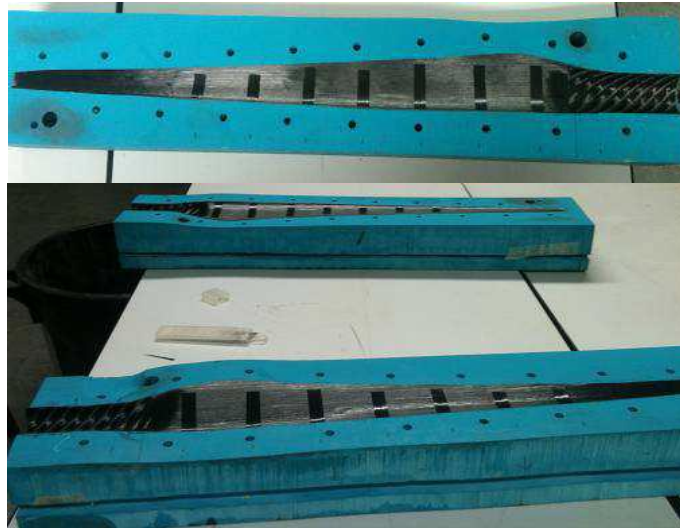

Figure 4 Blade manufacturing

The manufacturing being fully handmade, cautious attention must be paid to try and have the highest repeatability and avoid too high imbalances of the rotor. The process was carried out respecting entirely the original design of the blade (distribution of twists, chords, thicknesses, profiles). The last complexity of the rotor assembly was the pitch alignment (blade orientation around its root axis). Since 1° difference represents already an important aerodynamic influence, one cannot ensure perfect pitch position at this scale. The imperfection of the rotor assembly is a bit higher than at full scale, but since the model has fixed pitch angle it is not a big issue. Full scale wind turbines often have single pitch regulation meaning that pitch angles are not aligned at all times (mainly to reduce the loads on the structure).

III-2-ii)   Floater

The floater was designed to have a maximum 3-degree pitch angle under nominal thrust of the wind, and to have pitch and roll natural periods out of the wave range (>20 seconds at full scale). The Dutch Trifloater[1] has large heave plates providing the system with a very high added mass in heave and large added inertias in roll and pitch, and also a large damping in those degrees of freedom.

IV)   <u>Numerical model</u>

IV - 1) Hydrodynamic data base

Most hydrodynamic softwares (Diodore, Aquaplus, Hydrostar, etc.) are based on the boundary integral equation method (BIEM). The structure is discretized in panels on which the density of singularities sources usually follows a chosen distribution (generally constant).

Another approach is the finite element method. Use is made here of the software COREV[3], initially developed at IFP in the early seventies. An advantage of using finite elements is that, at variance with BIEM codes using source distributions, no problem results from dealing with thin structural elements such as the heave plates.

COREV assumes vertical axisymmetry, so the hydrodynamic data base generated is for

only one column. To simulate the Trifloater, the hydrodynamic data bases of each pile are combined to compute the behaviour of the assembly. The main trick of the operation is the proper phase shift between all hydrodynamic databases. In this approach hydrodynamic interactions between the three columns are not accounted for but, due to the smallness of their diameters and to the deep submergence of the heave plates, they are not believed to be significant.

IV - 2) Formulation of the hydrodynamic viscous loads on the heave plates

The use of large skirts at the bases of the piles has two main functions, in the one hand bringing an important added mass and in the other, adding a high damping to vertical and rotational motions. COREV computes the linear radiation damping but an additional quadratic viscous damping is needed to fit the real behaviour of such systems.

The quadratic damping is introduced via a stochastic linearization of the drag term in the Morison equation. The sensitivity analysis made on the drag coefficient to fit with experimental test ended in choosing a drag coefficient equal to 10, somewhat larger than the Cd values usually found in literature[2]. The results shown hereafter are for a configuration of the moored system giving natural periods of 4.52s in surge, 1.71s in heave and 2.16s in pitch.
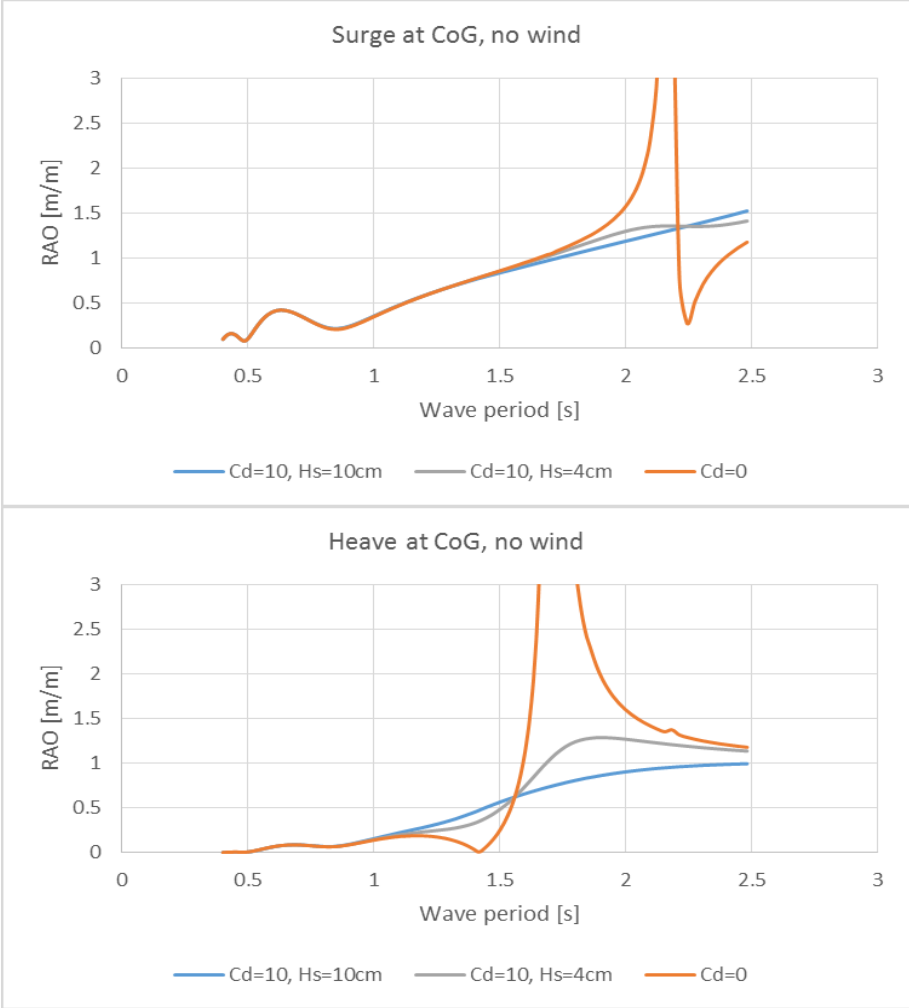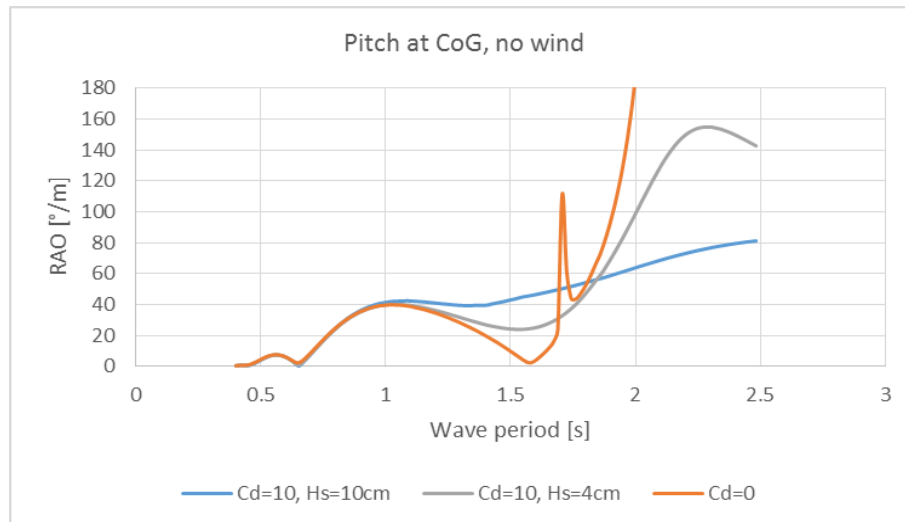
Figure 5 Float motions with and without viscous damping

IV - 3) Formulation of the aerodynamic loads on the rotor

To account for the aerodynamic damping due to the rotor, one has to consider the thrust curve of the turbine. Below the rated wind speed, the pitch orientation of the blades is constant and in an optimal position to try and be more efficient at power extraction from the wind. Over this wind speed range, the thrust coefficient has more or less a constant value.
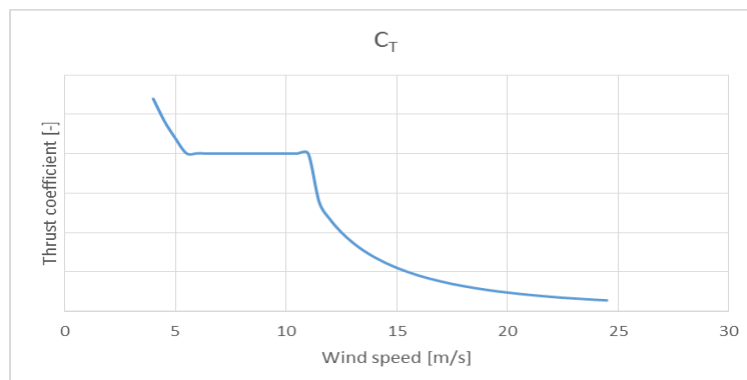

Figure 6 Thrust coefficient curve of a wind turbine

Once the rated power reached the thrust coefficient is rapidly decreasing due to the new orientation of the blades to limit the power extracted from the wind. The thrust force on the rotor has the form of a quadratic damping acting on the relative motion at the center of the hub.

Given the very high inertia of a wind turbine rotor and the shape of the CT curve, the thrust coefficient is chosen to be constant other the whole wind spectrum (in the case of turbulent wind) and the whole wave spectra, meaning that the relative wind speed seen by the blades may be out of the boundaries of constant CT when the wave induced response of the support becomes large.
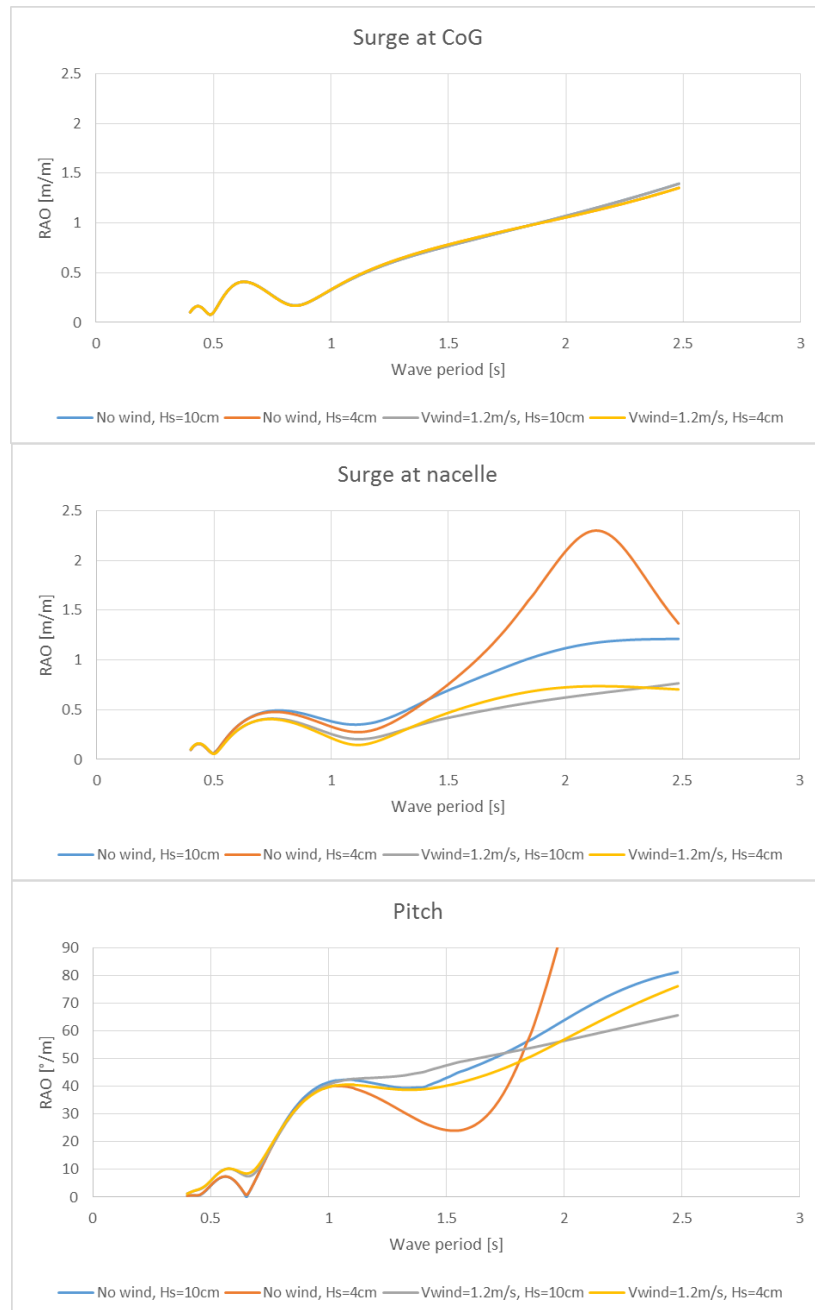
Figure 7 Numerical surge and pitch RAOs, in 4 cm and 10 cm HS, with and without 1.2 m/s wind

Figure 7 shows the obtained surge and pitch RAOs, with and without wind. The response in surge at the center of gravity of the floater is almost unaltered by the introduction of the wind action, but the pitch changes a lot. The composition of the floater motions produces a high relative speed at the rotor center that introduces a high damping on the pitch motion of the float. The surge RAO of the floater does not depend on the significant waveheight while the pitch is quite sensitive to its value.

V) <u>Experimental campaign</u>

V - 1) Rotor characterization

The rotor is the main unknown of the problem since the Reynolds numbers are not

respected. The ratio of the Reynolds numbers is $\lambda^{1.5}$ thus 1/1000. The real blade operates in ranges of Reynolds numbers over 1 million, whereas the model is in the range of thousands (<10000). The blade element momentum theory is not applicable to this rotor since the oscillations of drag on the blades make the instantaneous thrust unpredictable unless performing CFD analysis. It is then critical to perform a full analysis of the rotor to know the mean thrust level and oscillations.

Figure 8 Setup for rotor analysis

To perform this analysis, the whole RNA (Rotor Nacelle Assembly) has been put on a tower fixed on a 6-dof force sensor and put at the same place as the float. The results are, not surprisingly, quite far from the real machine performance in terms of thrust for a given wind speed. Nevertheless, without control on rotation speed it is possible to obtain the thrust level required by increasing the wind speed (not following thus Froude scaling).

V - 2) Floating turbine

Due to the configuration of the wind and wave flume (long enough but only 2.7 m wide), a subsurface mooring could not be used. The model was moored by an aerial assembly of 4 cables and springs, as can be seen in figure 9.

**Figure 9 Floating wind turbine in the wave and wind flume with the trajectometry cameras**

In the tests different configurations, for the mooring lines, the draft of the model, its orientation, etc., were considered. The results presented here were measured on a system with the following main characteristics:

Ballast	1500	[g]
Pile diameter	11	[cm]
Pile height	30	[cm]
Skirts diameter	25	[cm]
Skirts thickness	0.6	[cm]
Pile center to tower center	37	[cm]
Draft in operation	17	[cm]
Draft without ballast	12	[cm]
Center of gravity (LAT)	1.2	[cm]
Center of buoyancy (LAT)	-10	[cm]
Mass (all included)	5740	[g]
Inertia in pitch (Iyy)	6942238.7	[g.cm²]
Transition piece lowest point (LAT)	10	[cm]
Hub center (LAT)	90	[cm]
Mooring line stiffness	48.6	[g.cm^{-1}]
Surge natural period	**5.33**	**[s]**
Heave natural period	**1.73**	**[s]**
Pitch natural period	**1.90**	**[s]**

Table 2 Properties of the model

V-2-i) Tests in waves only (no wind)

The first tests with the floating configuration aimed at validating the results from the program based on COREV and the system properties (mass, inertias, stiffnesses). In order to better appreciate the nonlinear effects associated with the quadratic viscous loads on the heave plates, tests were performed in irregular waves with 4 different significant waveheights (4, 6, 8 and 10cm) and 2 peak periods (1.5 and 2s). Results presented hereafter are for the endmost significant waveheights (4 and 10cm) at the peak period of 1.5s.
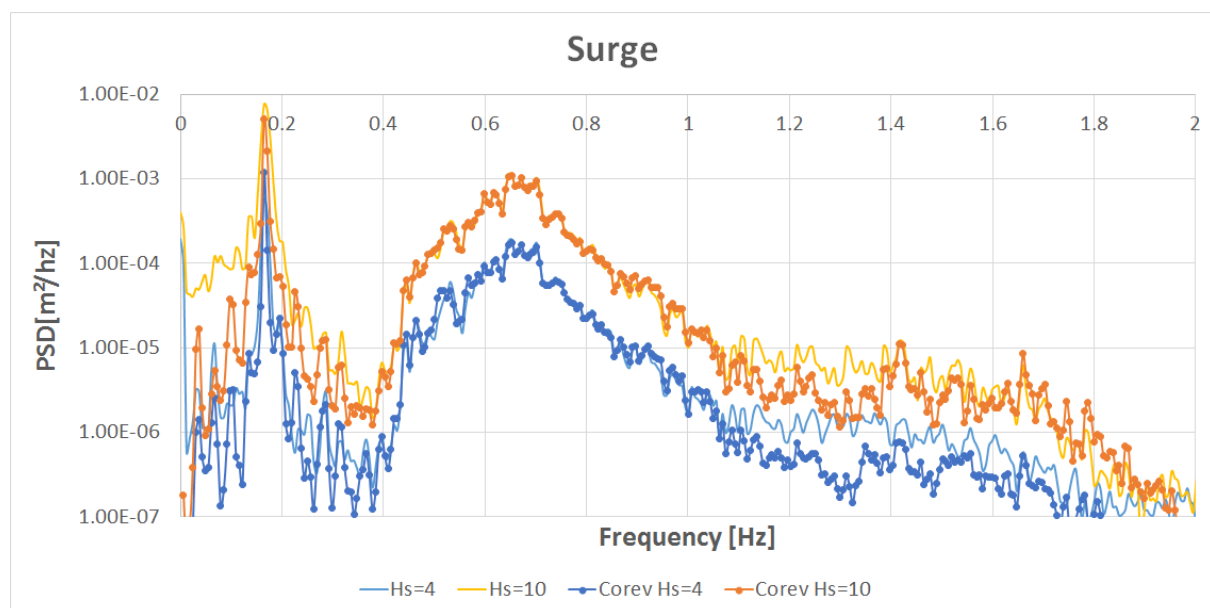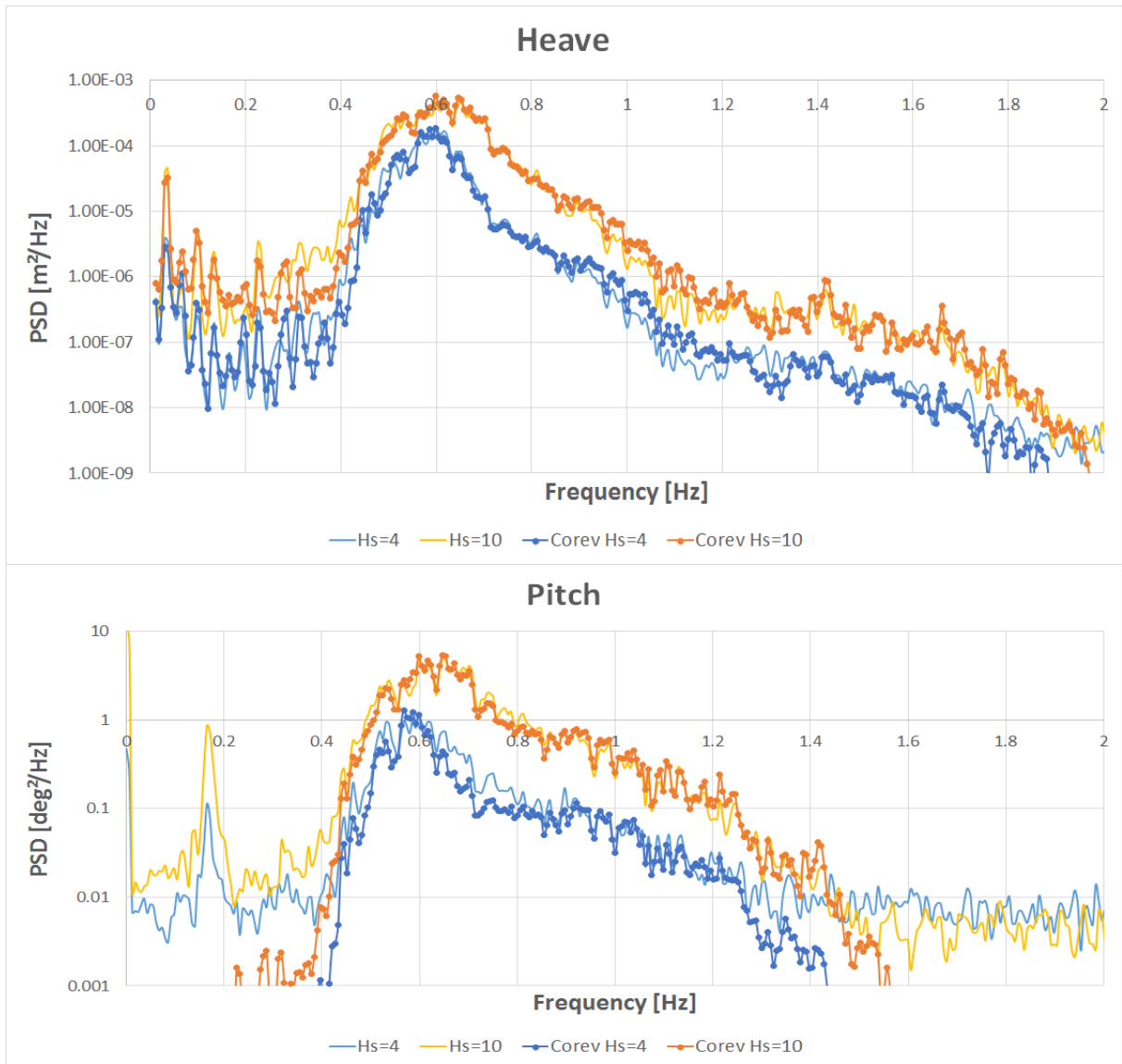
Figure 10 Measured and calculated power spectra of the floater response (wave only, no wind)

Figure 10 shows the experimental and calculated spectra of the surge (at center of gravity), heave and pitch responses, for the two sea states. The experimental wave spectrum, as measured during the calibration tests, was used in the computations. The heave and surge motions are very well predicted over a very large range of frequencies whereas the low frequency component of the pitch response is quite underestimated by the numerical model. Figure 11 shows the associated RAOs in the 10 cm HS sea state.
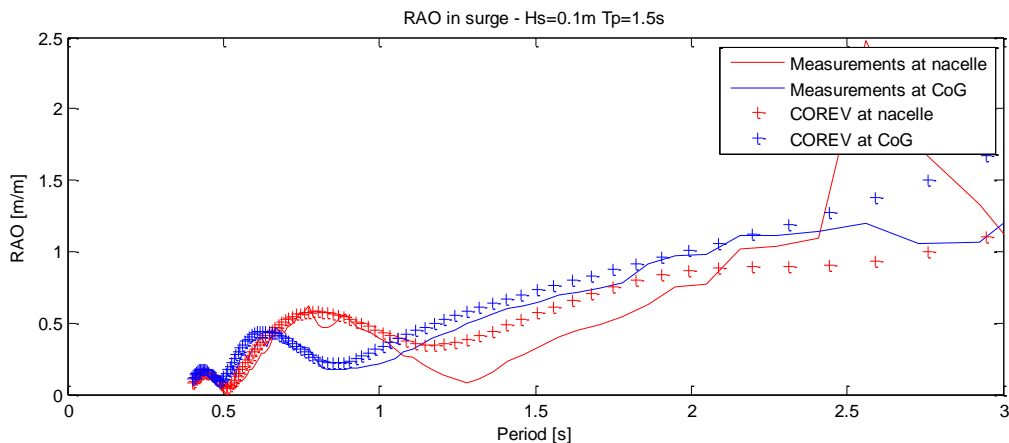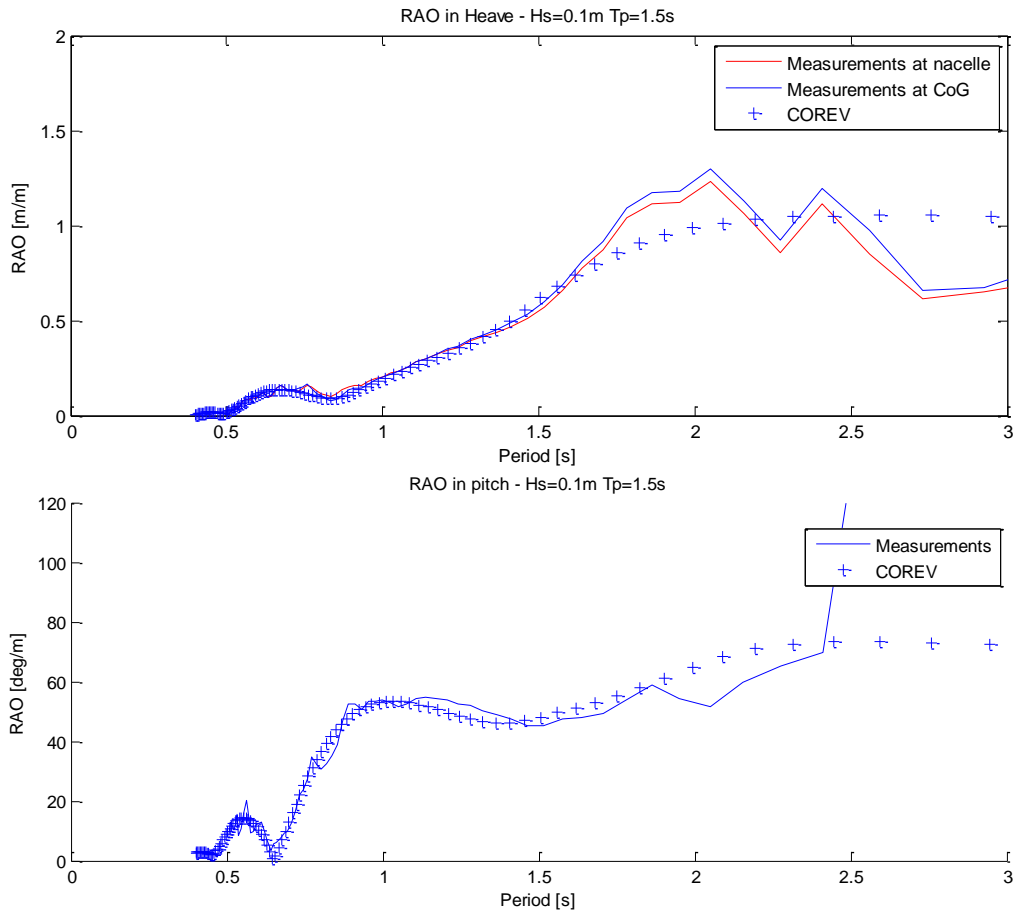
Figure 11 RAOs in surge, heave and pitch (no wind)

The phase between the pitch motion and the surge, and the high distance between the center of gravity of the system and the center of the rotor hub, give an important difference between the nacelle and the float relative motion, which is crucial for the turbine manufacturer. The pitch motion and surge are well predicted at float CoG but at hub center there appears to be some discrepancies.

V-2-ii) Tests in waves and wind

The introduction of linearized aerodynamic damping in COREV, under the assumption of constant thrust coefficient, presents a real interest of taking the aerodynamic damping into account while taking a look at the top head mass motion.

As aforementioned the introduction of aerodynamic damping in the computation of the motion at the CoG gives quite no differences in surge but in pitch it gets really different with the increasing wind. While the pitch motion is a bit amplified, the relative motion at the hub center is actually damped.

In the tests this influence has been investigated to try and validate the implementation of aerodynamic damping in the code. The results were not very conclusive. The RAOs present no major changes between the different wind speeds.
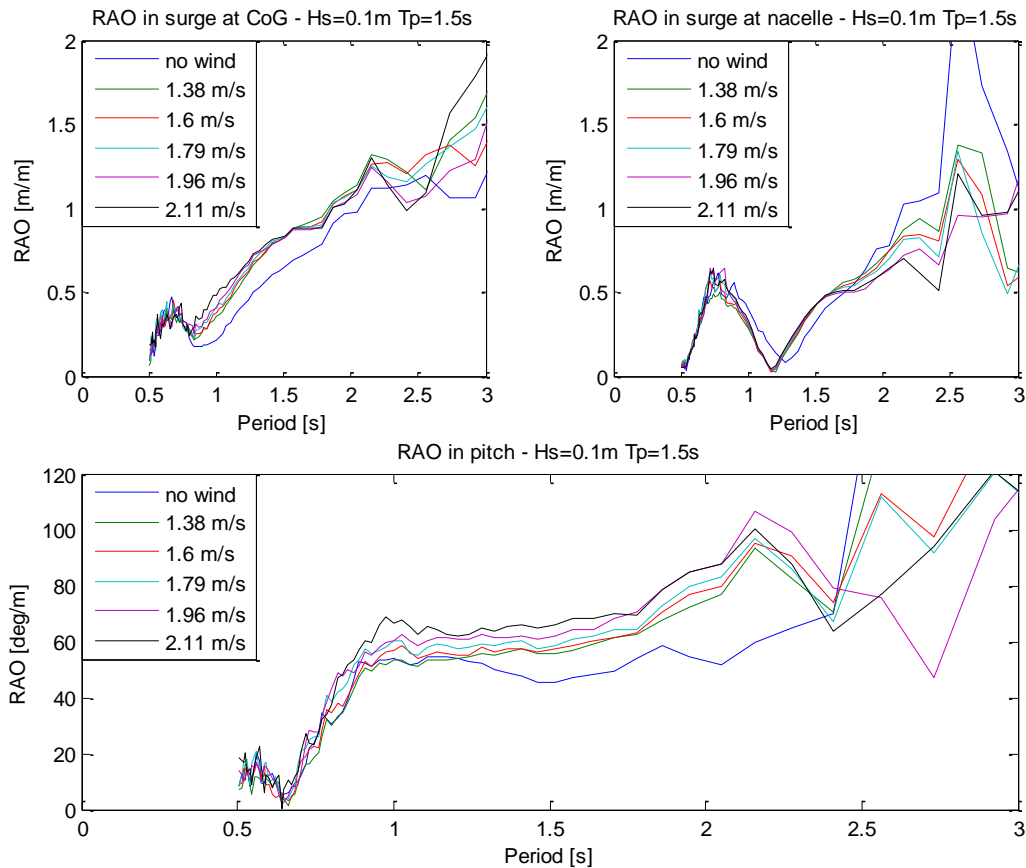
Figure 12 Experimental RAO in waves and wind

The aerodynamic loads tend to stabilize the nacelle increasing in the same time the pitch motions. In these tests, the rotor speed was not controlled because of the weight constraint on the nacelle. The mean offset of the float due to the wind and the monitoring of the rotor speed have shown that the mean thrust was as predicted in the rotor qualification. Nevertheless the free accelerating rotor does not provide a constant thrust coefficient. The rotor inertia is too low, not to respond to the induced relative wind speed due to the float motions. The thrust coefficient at these Reynolds numbers changes significantly when changing the rotation or the wind speed. It is believed that these effects are responsible for the discrepancies.

VI)   Conclusion

Tests of floating wind turbines at very small scale have been proved to be feasible. They may be a great asset in early phases of a project and/or to validate numerical simulations. Nevertheless, working at such scales requires cautious modelling skills and a good knowledge of the downscaling problems on a system requiring two contradictory scale factors. The work here highlighted the lack of verification on coupling effects because of the limitations put at early phases of the project (no mass at the nacelle except rotor). The command of rotation speed would have been an important asset the platform could not afford in the current configuration.

The analysis of a floating vertical axis wind turbine will follow the present work.

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