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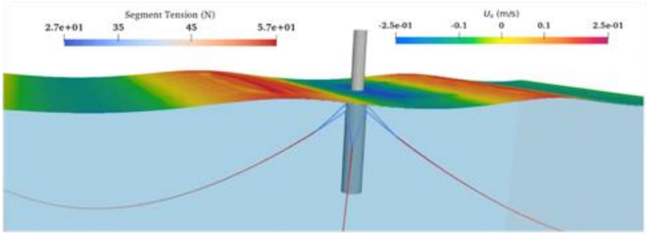

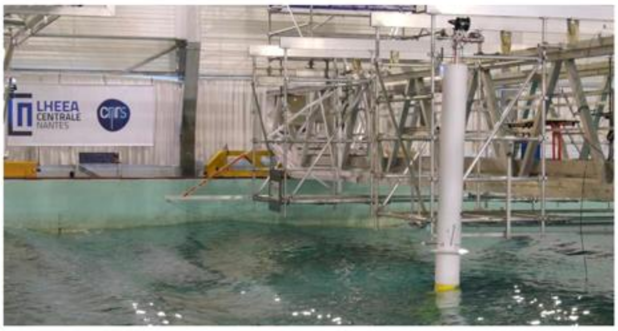

ON THE DEVELOPMENT OF SOFTWARE-IN-THE-LOOP METHOD TO TEST FOWT CONCEPTS IN THE 'SOUTH FRANCE - OCEAN BASIN'

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Résumé

La modélisation physique des éoliennes flottantes en bassin est nécessaire à leur développement afin de répondre aux problématiques d'optimisation de la conception et de réduction des coûts. Réaliser des tests sur une éolienne flottante en générant un champ de vent dans le bassin présente certaines limitations et difficultés. Premièrement, ce type de modélisation est limité à une petite échelle, telle que 1/60, en raison du volume limité couvert par les ventilateurs dans lequel le champ de vent est pertinent. Deuxièmement, la nécessité de traiter différentes lois de similarité, Froude pour l'hydrodynamique et Reynolds pour l'aérodynamique, conduit inévitablement à des compromis de modélisation. Le software-in-the-loop (SIL) s'impose donc comme la solution la plus adaptée à la modélisation du vent en bassin océanique. Dans cette publication, l'outil de SIL développé par la société Océanide, qui opère le « Bassin de Génie Océanique - Sud France», est présenté.

Summary

Physical modeling of floating wind turbines in a basin is necessary to address design optimization and for cost reduction issues. Conducting tests on a floating wind turbine by generating a wind field in the basin presents certain limitations and difficulties. Firstly, this type of modeling is limited to a small scale, such as 1/60, due to the limited volume covered by the fans in which the wind field is relevant. Secondly, the need to deal with different similarity laws, Froude for hydrodynamics and Reynolds for aerodynamics, inevitably leads to modeling compromises. Software-in-the-loop (SIL) thus emerges as the most suitable solution for wind modeling in oceanic basins. This publication presents the SIL tool developed by Océanide, which operates the "South France - Ocean Basin" test facility.

I - Introduction

The engineering of Floating Offshore Wind Turbine (FOWT) concepts requires the accurate modelling of each part of the system and their interactions when subjected to the environmental conditions (wind, wave and current). It includes floater hydrodynamics, wind turbine aerodynamics, wind turbine control and structural mechanics. One way to solve this multi-physics problem is to combine in real-time a physical model of the floater and a numerical model of the wind turbine.

Basically, the hydrodynamics of the floater is simulated thanks to the physical model installed in the wave tank, the aerodynamics of the wind turbine is solved thanks to the numerical software (Orcaflex or DeeplinesWind can be used), the natural frequency of the tower is integrated in the physical model, the turbine controller is integrated in the numerical model and a control loop, developed in Python, makes the communication in real-time between the physical model and the numerical model allowing to couple all the physics. This hybrid modelling (physical and numerical) is called the Software-In-the-Loop (SIL).

Océanide has developed this technique since 2019 (first application on the TLP floater of Provence Grand Large project). An upgrade has been performed during the last 2 years with the BEEFORE project, a project supported financially by the French Environment and Energy Management Agency (ADEME) through the FRANCE 2030 investment plan.

The VolturnUS semi-submersible platform equipped with the IEA 15MW wind turbine was tested at scale 1/40 in the “South France - Ocean Basin" operated by Océanide, see Figure 8. The thrust load was emulated with a single ducted fan to generate the wind turbine thrust load or a dual ducted fans system including a controlled heading to generate the thrust load, the RNA yaw moment and a change in the nacelle’s direction. Océanide has developed several levels of numerical model. The first level consists of applying directly the aerodynamic loads without any coupling with the platform motions, it is called the SIL-C for “command”. The second level consists of using an analytical model to emulate the hydro-aero coupling and the aero-damping, it is called the SIL-A for “analytic”. The last level uses a numerical model to calculate the aerodynamic loads knowing the 6DOF RNA motions and is called SIL-O or SIL-D for “Orcaflex” or “DeeplinesWind”. Extensive qualifications were conducted. First, tests in air were performed on a dedicated bench to qualify the whole system. Then, tests in basin were carried out with the floater based on a step-by-step approach including open-loop (SIL-C), simplified-loop (SIL-C) and finally complete software-in-the-loop (SIL-O) qualification.

In this paper, we will first present the global SIL system with the wind loads emulation device and the numerical aerodynamic modelling. Then we will present the system qualification tests in basin including, the physical floater, the wind turbine numerical model and the campaign description. Finally, we will focus on the main results, conclusions and future developments.

II - System description

The SIL system developed and presented in this paper is an upgrade of the previous developments achieved by Océanide [Ref. 1]. The main enhancements performed since 2022 were to develop a plug-and-play interface, adding a popular turbine software (Orcaflex) and some functionalities in the model like modelling more accurately parked turbine wind loads and measuring the tower bottom 5D loads instead of bending moments only.

II - 1 SIL system

The SIL system consists of performing basin tests with numerical simulation interactions. To accurately model FOWT in oceanic basins, it is essential to integrate complex wind load modelling. In the past, only the mean constant wind load was modelled with a cable, a pulley and a suspended mass linked to the model. Then, big fans blowing a constant or a changing wind field in the basin were used, this technology involved adapting in air screen like circular plate reproducing the mean drag or changing the blade shape to have more accurate wind loads. Nowadays, turbine numerical software can provide accurate wind loads on FOWT reproducing complexity of the wind fields (vertical profile and turbulences). This kind of complexity is far from being achievable with blowing fans in oceanic basins. Besides, numerical calculations allow to have a very good estimation of the wind loads from a wind turbine, not only considering the 6DOF loading but also providing high frequencies excitations provided from wind field turbulence and flexibility of the model (mainly tower and blades). Last but not least, the numerical calculations enable the inclusion of the turbine controller, which can significantly influence the wind loads experienced by a FOWT under the effects of wind and waves. Going to this last enhancement of wind load modelling in oceanic basins imposes three main developments: wind load actuators to accurately reproduce the complexity of the wind load, simple and fast enough numerical turbine model and finally real-time interaction between the physical and numerical models. All these aspects are further detailed below.

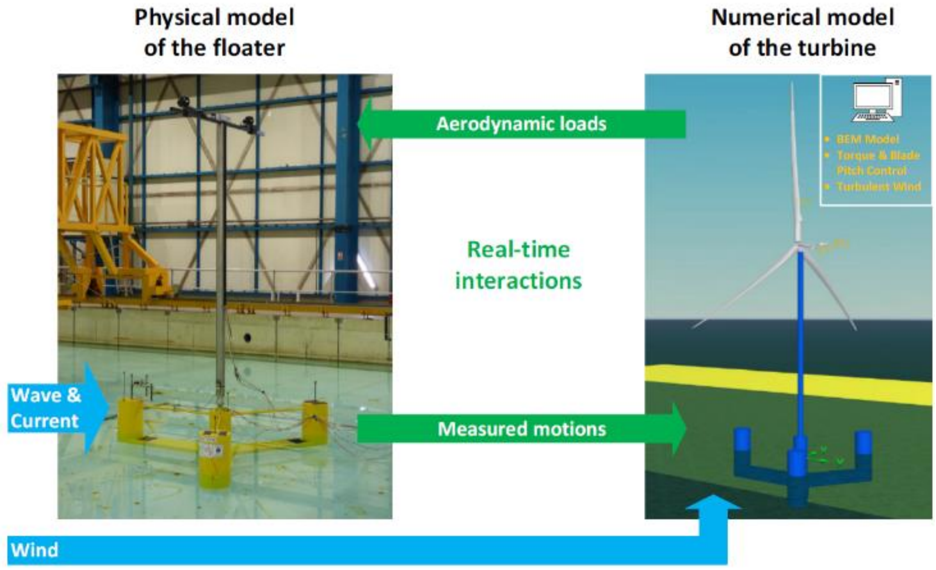

Figure 1. Schematic drawing illustrating the principle of the SIL developed by Océanide in the "South France - Ocean Basin"

II - 2 Wind load emulation system

Complex wind load emulation systems can be of several types. We can pull on the model with one or several piloted winch(es) using a PID system. We can also use one or several actuators acting as an inverse turbine and blowing to generate the required wind load. These blowing actuators can be of 2 types: ducted fan or propeller (see Figure 2). Since 2015 Océanide has made the choice of using ducted fans as wind load actuators. The main advantage of this type of actuator is that it effectively avoids any coupling with the floater's motions. The wind generated is significantly faster than the floater's movements, ensuring that the induced load remains unaffected by those motions. A propeller type can have some advantages like providing a better efficiency and so reducing the electrical consumption, however by reducing the generated wind flow velocity the independence of the floater motion is not as clear as with ducted fan solution.

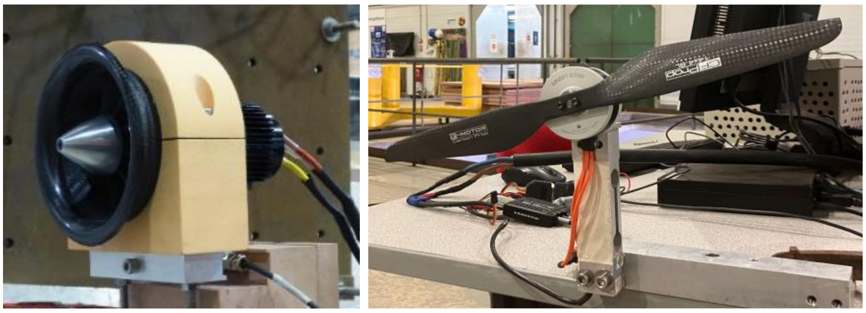

Figure 2. Schematic drawing illustrating the principle of the SIL developed by Océanide in the "South France - Ocean Basin"

In the SIL system developed by Océanide, the wind load is emulated using one (see Figure 3) or several actuators (see Figure 5) according to the level of complexity of modelling required.

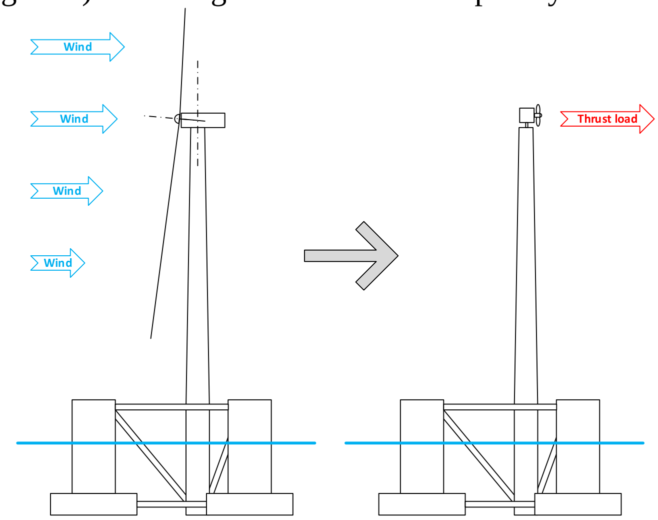

Figure 3. Thrust load emulation

Regarding the wind load complexity, some numerical investigations have been performed on previous project [1] to evaluate which are the DOF of interest to be emulated in the basin among the complex tensor wind load that the numerical software can provide, with the objective to capture the physics of FOWT. This numerical study compared the motions on a typical semi-submersible FOWT under colinear wind and wave sea-state with several wind load modelling approximations: thrust only, thrust and yaw moment and finally full 6-DOFs wind load (see Figure 4). The conclusions from this study are detailed hereafter:

- surge and pitch DOFs are mostly influenced by the thrust load,
- heave motions are governed by the waves with a negligeable impact from the wind loads,
- thrust only modelling is not a good approximation if the objective is to investigate the sway, yaw and roll motions of the floater. These 3 DOF motions are of second order regarding the floater motions, but to have a better modelling of these motions, adding the yaw moment induced by the turbine will provide the greatest part of these motions.

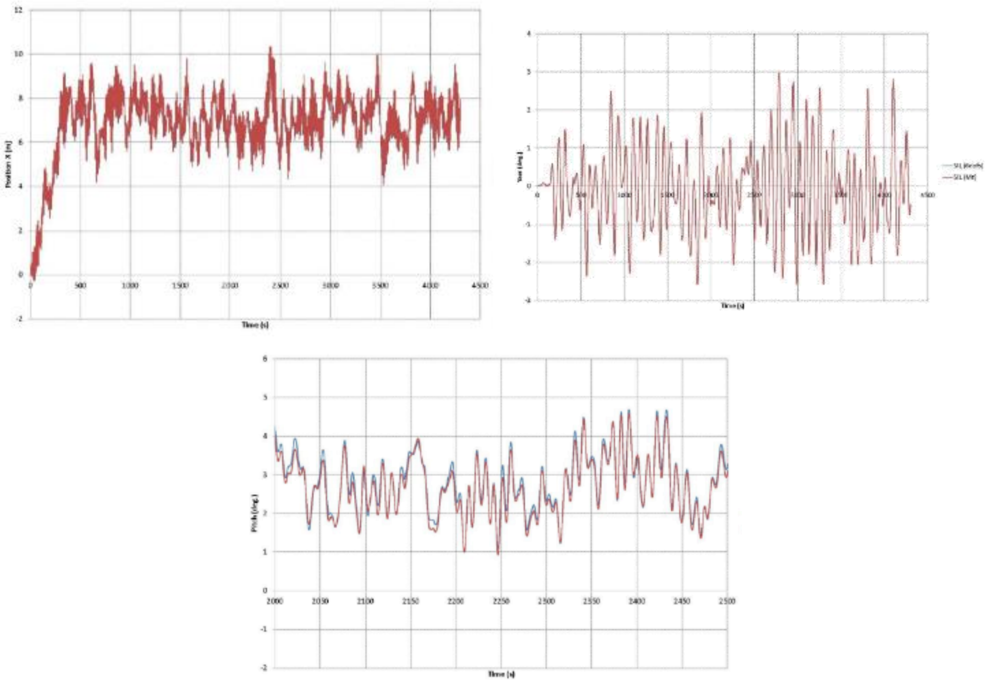

Figure 4. Surge, Pitch and Yaw comparison between a 6DOF SIL numerical model (blue) and a 2DOF (thrust+Mz) SIL numerical model (red)

Finally, for an engineering design point of view, the best fit-for-purpose wind load actuator selected by Océanide is a 2 ducted fans setup fixed on an steerable carbon beam. This setup allows the emulation of thrust load, yaw moment and wind direction change by rotating the setup.

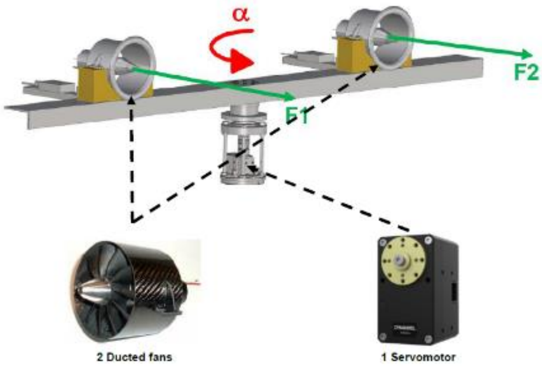

Figure 5. Wind Load Actuator Device

The actuators are located at the wind load application point elevation. For operating conditions, the turbine thrust load is the prevailing wind load, imposing a wind load application point at the hub level. For parked conditions, the application point changes drastically and is generally located along the tower (due to influence of tower and floater wind screens). To accurately model the wind loads for these two design conditions, two sets of two ducted fans are installed on the model: 2 at hub level are used for operating load cases, 2 others for parked conditions including tower and floater wind screen in the wind load calculation (see Figure 6).

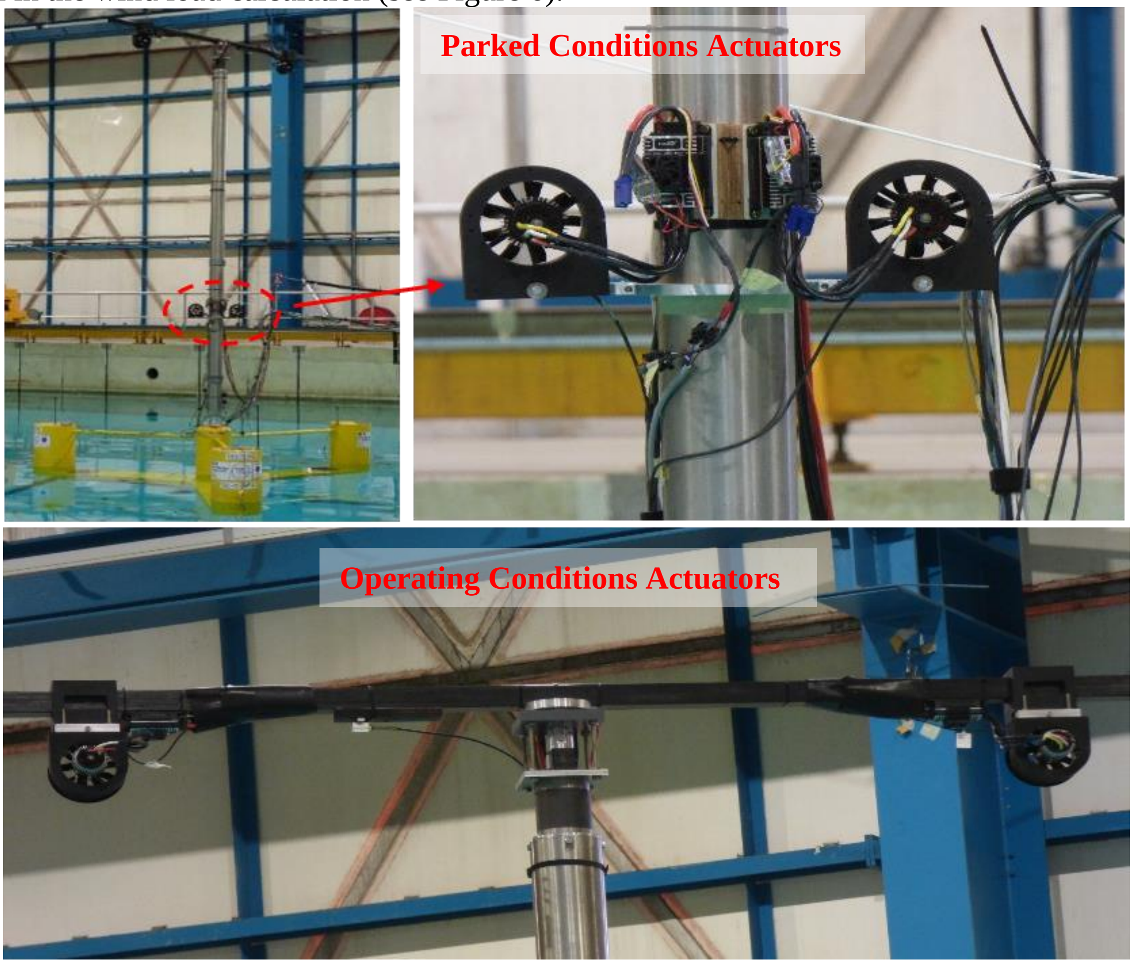

Figure 6. Pictures of the physical model in the “South France - Ocean Basin"

II - 3 Aerodynamic modelling

The ducted fans used have a maximum thrust capacity of 3 000kN full scale (48N model scale). The emulated loads have been imposed through a control system. Three levels of control system have been developed:

- SIL-C for command SIL: the thrust noted *F_fixed* and torsion moment are computed before the tests considering the RNA has no motion and then applied to the physical model during tests. In this mode the turbine model developed by the Client is used (no software limitation).
- SIL-A for analytical SIL: the thrust and torsion moment are computed before the tests considering the RNA has no motion. This mode allows the use of the turbine model developed by the Client (no software limitation). Then a correction is applied to the thrust load to include the real time hub motions and so the aerodynamic damping. This correction is based on a simplified equation considering that the thrust is proportional to the square of the relative velocity and that the wind velocity is larger than the hub velocity:

$$F_{thrust(t)} = F_{fixed(t)} - \beta * V_{hub(t)} \qquad (1)$$

With

$$\beta = 2 * \frac{\overline{F_{fixed}}}{\overline{V_{wind}}^2} \overline{V_{wind}} \qquad (2)$$

with $\overline{F_{fixed}}$ the average thrust considering a fixed RNA and $\overline{V_{Wind}}$ the average wind velocity.

- SIL-O or SIL-D for SIL using Orcaflex or DeeplinesWind: a complete loop mode where the thrust load and torsion moment are calculated in real time with Orcaflex or DeeplinesWind considering the hub motions from the model in the basin. This calculation includes the aerodynamic damping and the turbine controller real time actions (rotor torque and blade pitch control).

It is to be noted that direct access to the turbine data (electrical power production, rotor torque, blade pitch, rotation velocity) is available in case of use of the complete loop using the numerical model. This is a real benefit for FOWT behavior understanding during basin tests.

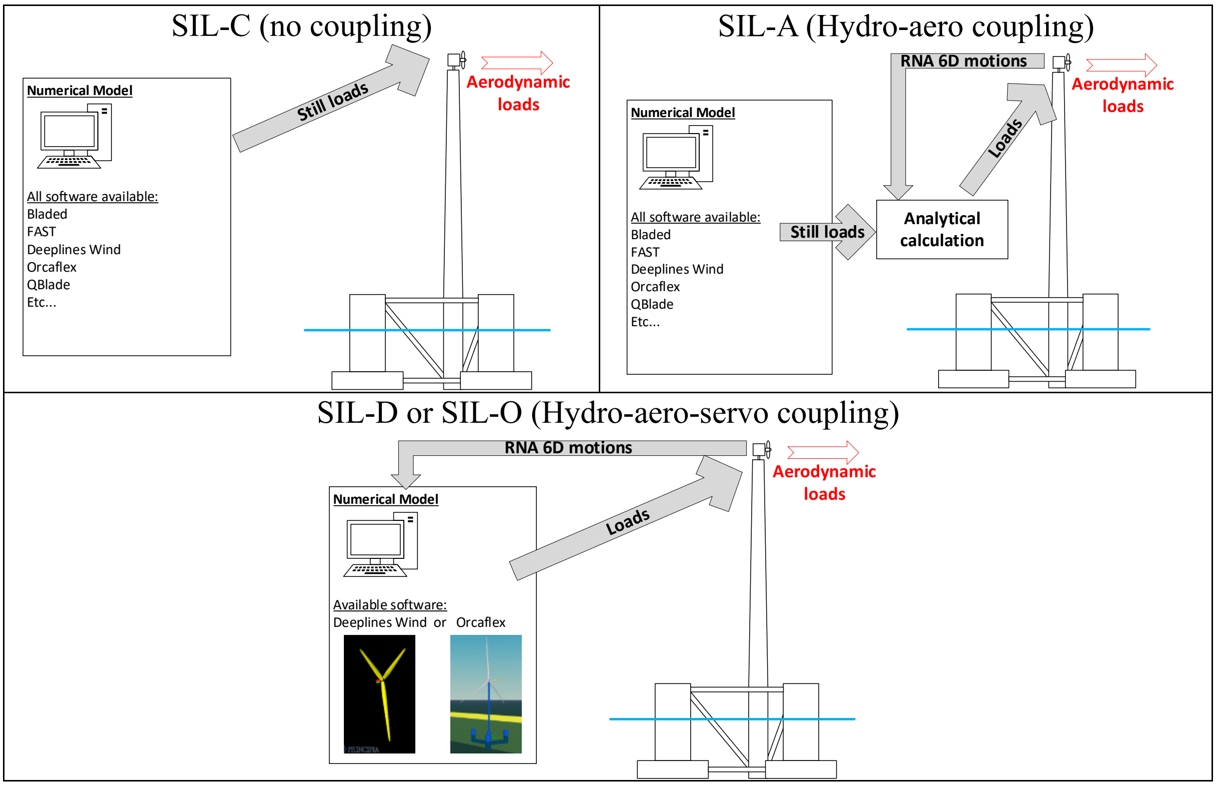

Figure 7. Control System Levels developed by Océanide

III - Qualification tests in basin

The experiments were carried out by Océanide in its wave, current and wind basin named 'South France – Ocean Basin', shown in Figure 8. The tank is 16m wide and 40m long. Thanks to a movable floor, water depth can be varied from 4.8m down to a few centimeters.

The experiments were performed at 1/40 scale, in Froude similitude. The water depth was set to 130m full scale. By default, data are provided at full scale in the present paper.

Figure 8. South France Ocean Basin (left) and VolturnUS floater with 15MW turbine (right)

III - 1 Floater physical model

The model was fabricated by Océanide and composed of:

- The VolturnUS semi-submersible floater made of columns and bracings
- The tower as a rigid aluminum pipe, plus a transition piece at the floater/tower interface used to adjust the tower first bending natural frequency
- An equivalent RNA (Rotor and Nacelle Assembly), including two ducted fans to generate thrust and yaw moment (see Figure 6)
- Two additional ducted fans located at parked conditions wind loads application point for extreme wind load modelling (see Figure 6)
- A specific setup to measure the tower bottom 5D loads
- A mooring composed of three horizontal mooring lines with springs

The dual ducted fan system was also used for modeling change of wind direction as the whole system is able to be controlled in rotation.

Each model component has been adjusted in mass, COG and inertia.

Decay tests without wind nor active turbines are performed. The measured natural frequencies of the model are then: 0.009Hz for surge, 0.017Hz for yaw, 0.036Hz for pitch and 0.52Hz for mast bending. It was submitted to waves with energy in the range of 0.05Hz to 0.2Hz and to wind (calculated numerically) with energy from low frequencies up to about 0.37Hz (the 3P frequency).

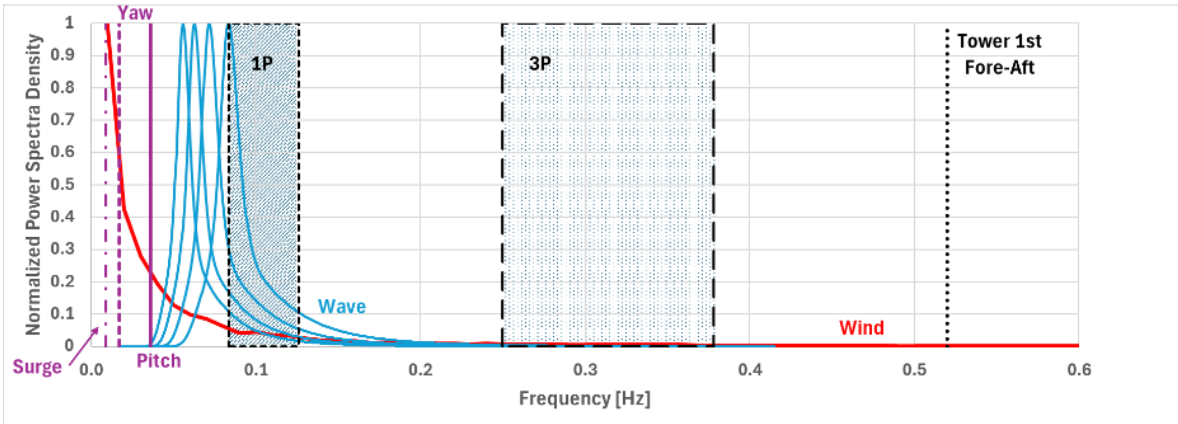

Figure 9. VolturnUS with 15MW IEA turbine excitation frequencies

III - 2 Wind Turbine numerical model

A model of the IEA 15MW turbine [2] is built in Orcaflex software. The model consists of three blades, connected to the hub and shaft. The shaft itself is connected to the nacelle. The motion of the nacelle is provided by the basin model test, and in return the numerical model provides the aerodynamic load tensor.

The choice of Orcaflex for the turbine numerical modelling has been performed based on the observation that it is the most popular software for wind turbine modelling used by engineering companies. Moreover, Orcaflex has developed a complex Python interface that eases significantly the interface with the basin.

In the turbine model the blades are considered rigid to reduce the computing duration. The aerodynamic loads acting on the blades are dynamically computed with BEM theory. The hub and the nacelle are modelled as rigid bodies without mass (all masses are modelled physically in the basin). The blades are connected to the hub and their relative pitches are controlled. The shaft is a beam element connected on one side to the hub and on the other side to the generator; it is also controlled to produce the required moment. At last, the nacelle is connected to the tower top. In this campaign, two control types are used:

- NREL, which controls only the torque of the turbine and the pitch of the blades according to the wind speed. It corresponds to the initial 5-MW NREL controller adapted to the 15-MW with a gain detuning [4].
- ROSCO, which controls the torque and the pitch of the blades as the NREL but the pitch is also looped with the inclination of the floater and the tower [5].

Constant wind and turbulent wind are used (generated by Turbsim [6]). The files are generated over 4300s for the tests in basin. The prescribed velocity is the hub height velocity. A 250x250m grid is used. The vertical profile is a power law profile with an exponent of 0.14. The turbulence model is a Kaimal spectral model with a 15% turbulence intensity. The full field turbulent file where the wind velocity and direction is provided on a mesh of the grid (referred to as “turbulent” wind). Interpolations in space and time are then performed to obtain the velocity at any point and time.

A first campaign “in air” with the actuator fixed to a pendulum setup has been performed to check the full SIL system capabilities to work in real-time. The pendulum setup was tuned to represent a typical pitch natural frequency of a FOWT. This preliminary “in air” campaign allowed to check the full loop and to confirm that real-time (including time scaling effects) are fulfilled.

With the pendulum setup, the negative damping can also be modelled. A test has been developed for this objective: a constant ramp test. This test consists of increasing slowly the wind speed (homogenous wind speed in space is used), starting below rated speed (in area 2) up to cut-out speed (area 4). The wind change is slow (quasi static). This test allows to characterize in one test the control stability in transition phase between area 2 & 3 and in area 3, see Figure 10.

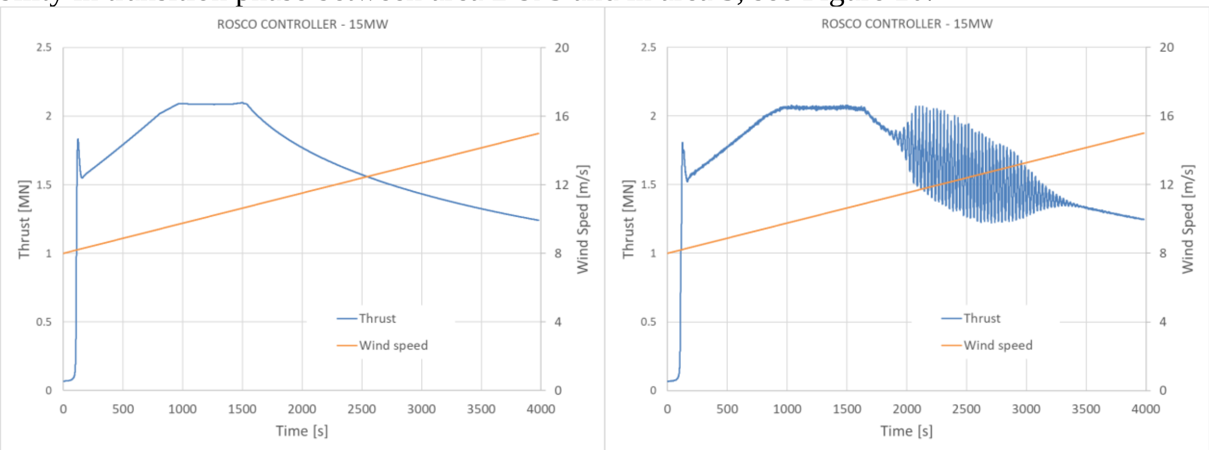

Figure 10. Measured ROSCO thrust on a constant wind ramp stable (left), unstable (right)

III - 3 Campaign description

Capabilities and performances of the system were qualified outside basin. However, at the final stage of development of any product, it is always recommended, as far as practicable, to test it in the same conditions than it will be used in the future. That is why basin tests were conducted with the developed software-in-the-loop system. As a secondary objective of the Project, this campaign also allowed to quantify the influence on the hydro-aero-servo coupling on a given FOWT, and to evaluate the level of complexity of the wind load modelling that could be used for basin tests of a FOWT concept, depending on the stage of the project.

The ducted fans are installed on the floater model for basin tests. Tests include wave only, wind only and finally wave plus wind together. Three different wind and wave environmental conditions (below, rated and above) and an extreme condition have been tested. For extreme environmental conditions the wind turbine is parked and the wind load is applied on the tower.

- Below: Hs=2m/Tp=12s; wind of 8m/s turbulent
- At rate: Hs=4m/Tp=14s; wind of 12m/s turbulent
- Above: Hs=6m/Tp=16s; wind of 16m/s turbulent
- Extreme: Hs=8m/Tp=18s; wind of 45m/s turbulent

This step-by-step procedure is used to assess the impact of each phenomenon on thrust loads and FOWT motions. First, wave only and wind only were tested. Then the combination of both conditions with the three different control modes (SIL-C, SIL-A and SIL-O).

IV - Main results and conclusions

Few results from the qualification basin tests campaign are presented below:

1. First, the capability of the ducted fans to reproduce the command (thrust and moment around Z) is checked. Some statistics, plot samples and frequency investigations are provided,
2. Then the capability of the system to act in real time is verified by comparison of basin tests results using the SIL system with full numerical calculation (using hydrodynamics calibration from basin tests),
3. Finally, the SIL modes described above are used in basin and their impact on floater behavior is characterized.

IV - 1 Ducted fans capabilities

Before the basin test campaign some qualification tests were performed outside basin. An air test campaign using a similar system but highly simplified (such as a pendulum using only 1 DOF) is realized to evaluate the capacity, the accuracy and the response time of the ducted fan and of the three software modes described above to reproduce the wind loads at hub.

During the basin test campaign, the wind loads calculated and the applied loads from actuators (Fan 1 & Fan 2 below) are measured to verify for each test the accuracy of the system to reproduce the real-time calculations physically in the basin.

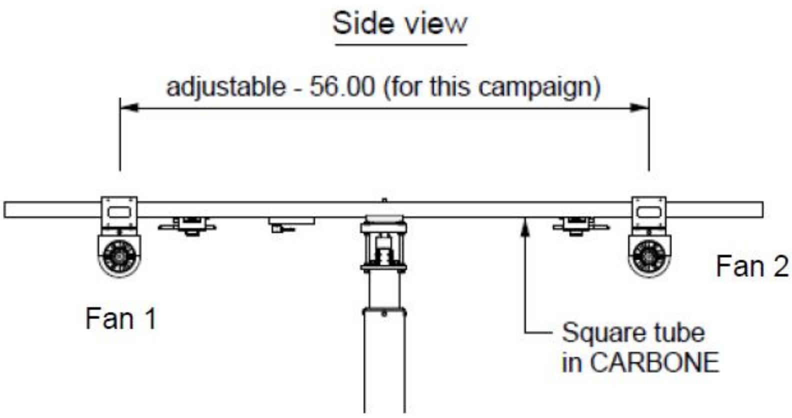

Figure 11. Actuators used for thrust load and wind Mz moment emulation

These qualifications tests have shown that the system is able to emulate the wind load with a very good accuracy for frequencies up to the 3P frequency. An illustration of the measured generated load (red, called 'Measured') and of the specified load (blue, called 'Command') time series and spectra for the 12m/s wind speed is shown on the Figure 12.

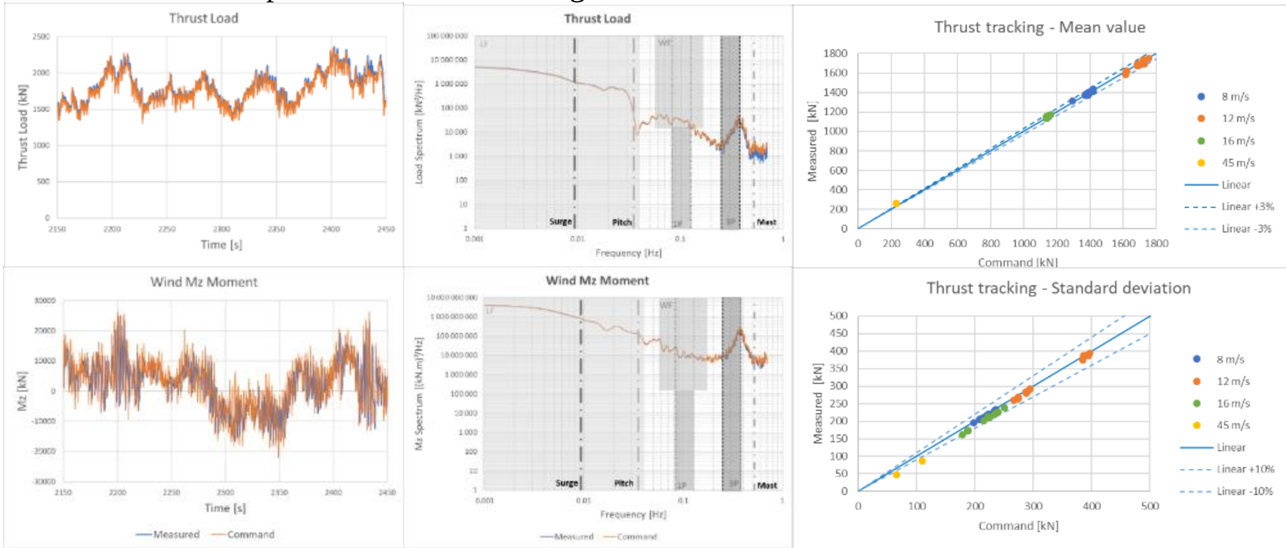

Figure 12. Aerodynamic modelling qualification tests: Time series, spectra and wind loads statistics

These capabilities are far enough to model the aero-hydro-servo coupling during FOWT basin tests. Nevertheless, if the objective is to study high frequency behavior up to tower first bending natural frequency (0.50Hz here), a methodology has been developed with SIL-C and SIL-A modes by increasing the command for these specific frequencies. This method allows to compensate the reduction of the transfer function of the ducted fans for high frequencies.

IV - 2 Numerical model comparison

A full numerical model using Orcaflex has been developed. This model was first calibrated by adjusting the GM, the added mass and the damping to fit with basin characterization tests (decay, hammer). Then, the tests performed during the qualification tests campaign using SIL-O were compared to the results from the same simulations using the full numerical model. The emulated wind loads (thrust and Mz) are very similar, showing that the SIL tests provide the correct wind load estimation during the basin tests.

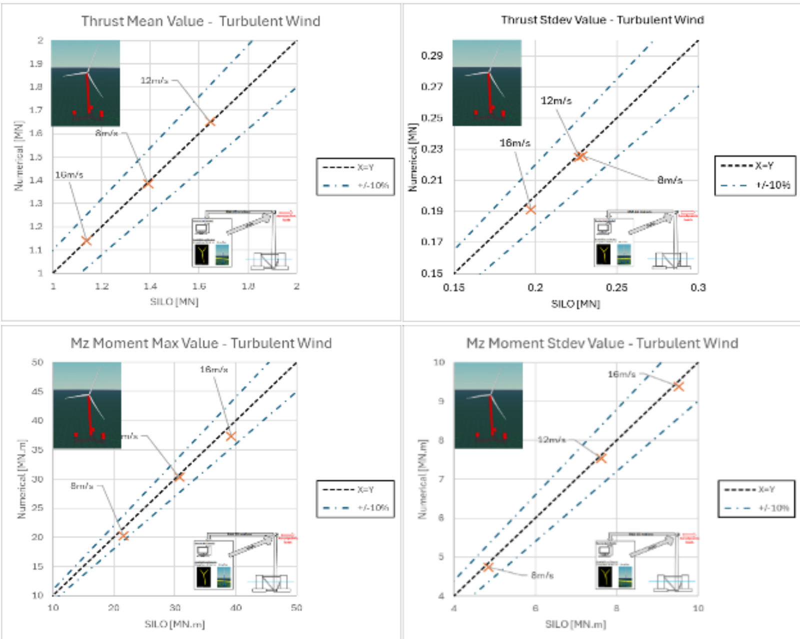

Figure 13 : Thrust and Mz moment from SIL-O and from full numerical

IV - 3 Modelling level

During the basin tests campaign, the three SIL modes developed by Océanide have been compared to evaluate their impacts on the floater behavior. A focus is put here on the pitch motion that is the DOF most impacted by the turbine.

The SIL-A mode, which considers an analytical model to include the impact of floater motions on wind velocities seen by the RNA, provides similar behavior than the SIL-O mode. The SIL-A mode is thus a suitable alternative to account for aerodynamic damping on floater behavior, at early stage of floater design when no or few information on the wind turbine is available.

On the contrary, the SIL-C level of model consisting in applying wind load time series directly at tower top seems to show some limits. Indeed, for high power wind turbines of 15 MW / 20 MW, currently developed by the industry, this technique tends to increase the motions at floater natural periods as the aerodynamic damping is neglected. It is therefore strongly recommended not to consider the direct application of wind load time series as this could lead to unrealistic response of the floater (see Figure 14). The influence of SIL-A and SIL-O on pitch in the wave frequency range is also capture in the insert in the bottom right corner.

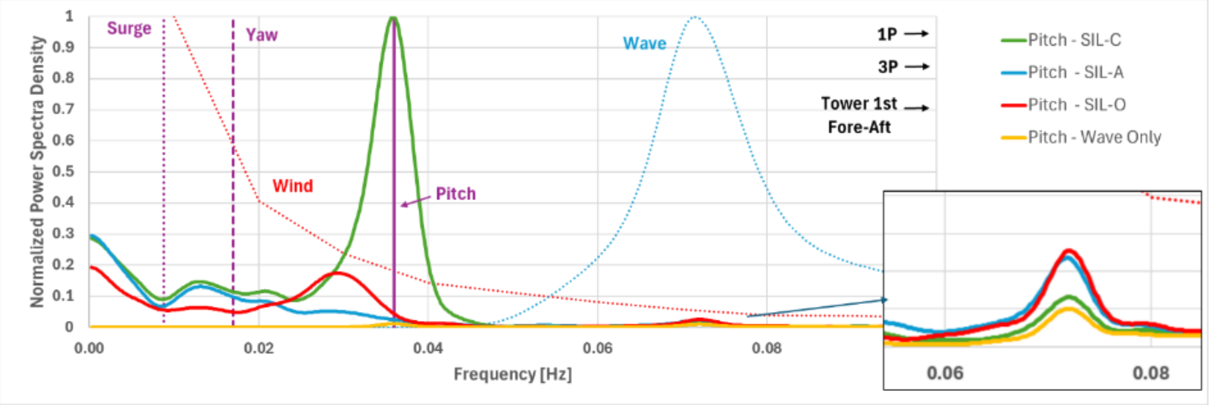

Figure 14. Spectral densities of pitch motion for the three different SIL levels (wind 12m/s)

V - Conclusions

During this project, a SIL method was developed to simulate behavior of FOWT concepts during basin tests campaign by coupling in real-time a physical model of the floater and a numerical model of the wind turbine. This SIL was developed to emulate the wind induced loads (thrust and moment around vertical axis) and the wind heading changes through to 3 different levels of complexity. Finally, this development was qualified during an extensive basin tests campaign. Main conclusions of this campaign are listed below

- Thrust and moment around vertical axis are emulated with a very good accuracy up to the 3P frequency
- The way to simulate the wind heading change has been validated
- The SIL-A mode provides similar behavior than the SIL-O mode. The SIL-A mode is thus a suitable alternative to account for relative wind velocity impact on floater behavior at the early stage of the project when no or few information on the WT is available to build a complete numerical model
- This development was successfully used to tune the parameters of the controller and then to compare to different controller settings, by comparing their power productions and damage levels
- Finally, the use of a numerical model of the physical model allows to add some confidence on the results obtained during the model tests campaigns

At early stage of a design, when few/no wind turbine information is available SIL-A is a very good approximation to investigate aero-hydro coupling without including controller uncertainties that can be extensively investigated numerically through Integrated Load Analysis (ILA).

Main ways forward to improve Océanide SIL system are listed below:

- Decrease the delay to increase the method capability in terms of frequencies that can be emulated. At this time, signal prediction method has been found as the most promising solution to reduce this delay by predicting the motion signals and thus calculating the wind loads 'in advance'. Signal prediction method and other methods, such as the implementation of a PID on the actuators command loop, will be investigated and developed in the future to further optimize our system.
- Increase the library of the SIL-A analytical equations to account for other phenomena or other turbine types. Some developments have been done by Océanide recently in parallel to the present work to include analytical formula to simulate a vertical axis wind turbine.

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However, the present paper only reflects the opinion of the authors and does not imply endorsement by these Companies.

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