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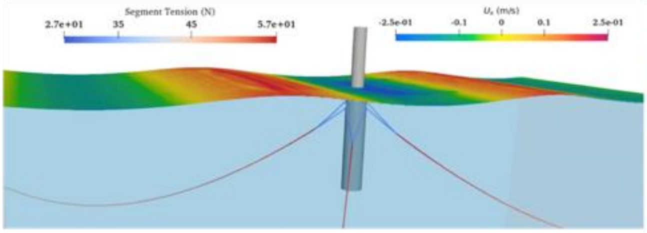

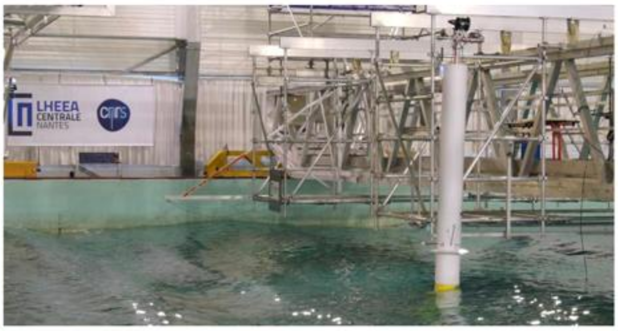

# *Modélisation CFD d'une éolienne flottante à l'aide d'une méthode de forçage discret*

# *CFD numerical approach based on a discrete forcing method for FOWT*

**W. BENGUIGUI(1,2), C. PEYRARD(1,3)**
william.benguigui@edf.fr ; christophe.peyrard@edf.fr

(1) EDF R&D, 6 Quai Watier, 78400 Chatou, France
(2) IMSIA, 7 boulevard Gaspard Monge 91120 Palaiseau, France
(3) LHSV, 6 Quai Watier, 78400 Chatou, France

## Résumé

*Une méthodologie basée des frontières immergées en forçage discret est proposée au sein d'un code CFD multiphasique (Euler-Euler à une pression) pour l'étude de flotteurs à géométrie complexe en appui aux outils utilisés pour le dimensionnement des éoliennes flottantes : les modèles aéro-hydro-servo-elastic Une validation est réalisée à échelle 1 sur un modèle réduit issu de la littérature traitant d'un flotteur à base carré avec une jupe l'entourant ainsi qu'une piscine au centre du flotteur. Les résultats sont encourageants et montrent les capacités de cette méthode à reproduire le mouvement à 3 degrés de liberté du flotteur retenu par ses lignes d'ancrage (modélisées par une approche quasi-statique). Une analyse de l'effet de la jupe est proposée qui montre un effet d'amortissement du mode de pitch avec la jupe. Une étude approfondie reste cependant nécessaire pour mieux comprendre les interactions entre les franchissements, la jupe et les possibles effets de sloshing au sein de la moonpool.*

## Summary

*A methodology based on immersed boundaries with a discrete forcing is proposed inside a multi-phase CFD solver (eulerian eulerian with a single pressure) to study FOWT with complex geometry in support to the "aero-hydro-servo-elastic" models used for the structural design of Floating Offshore Wind Turbines. A validation is performed at full scale on a reduced model from literature of a square base structure with a skirt and a pool. Results are satisfying and attest of the ability of the method to reproduce 3 degrees of freedom motion of an FOWT with mooring lines (here modeled with a static approach). An analysis is then performed on the role played by the skirt, it highlights a complementary damping of the pitch mode pool when using a skirt. A dedicated study is then required to better understand the interactions between overtopping water, the skirt, and possible sloshing in the moonpool.*

# I – Introduction

The design of Floating Offshore Wind Turbines (FOWT) has been studied through physical models ([6][10][13]) and numerical simulations. The so-called “aero-hydro-servo-elastic” models (introduced by Jonkman (2007) [1]) have been extensively used to compute the global response of FOWT, CFD-based models have been used more recently on aerodynamics [11], hydrodynamics [12] or even to solve the full behavior of the system [14]. The “aero-hydro-servo-elastic” solvers aims at limiting the CPU time by making assumptions on the fluid-structure interactions both on the aerodynamic side and hydrodynamic side or using semi-empirical. They can be regarded as a low-fidelity level models but are today the industrial state-of-the-art, given the very high number of design load cases to be computed during a design. The CFD-based models aim at being “high-fidelity” models, covering the fluid-structure interactions with a more accurate set of equations at the cost of very high CPU time. From the design point of view, these “high-fidelity” models can be seen as reference points to be used when the range of validity of the “aero-hydro-servo-elastic” models is questioned, or when there is a need to calibrate the coefficients used in these models. However, these high-fidelity models must be validated as well, which was the objective of the present work.

The high-fidelity numerical approach proposed here is based on a Eulerian-Eulerican multiphase Navier-Stokes solver called neptune_cfd. First specifically developed for nuclear applications, its field of application is growing with hydraulic or maritime applications (Benoit et al. 2023). To track the FOWT motion, a discrete forcing is used (kind of Immersed Boundary Method), called the time and space dependent porosity method (Benguigui et al (2018)) to represent the moving structure with its STL reader. A dedicated 6-degrees of freedom Fluid-structure interaction module (based on Benguigui et al (2019)) is adapted for FOWT applications and to consider mooring line forces with a static approach. Here, the approach is validated for a floating foundation based on the work from Kosasih et al (2019) for various regular wave states. Finally, an example on the use of the present method is proposed to assess the role played by skirts on the floater response.

# II – Numerical Modeling

neptune_cfd is a 3D multi-field solver which was specifically developed for nuclear applications, but its field of application is growing with hydraulic, structure-wave interaction or naval applications. It is based on a two-fluid approach with a single pressure (Ishii, 1975). Its objective is the modelling of multi-phase flows by solving a set of 3 equations per field (Guelfi et al, 2007), in the present case only the mass and momentum balance equations are solved. These fields can represent different multi-phase configurations including free surface flows. Closure relations must be supplied to necessary like interfacial momentum transfer at the free surface.

Wave-structure interaction scenarios involve interfaces between liquid and air which are generally much larger than the computational cells size: the “large interfaces”. Specific models to deal with them were developed and implemented in neptune_cfd: it is the Large Interface Model (LIM). It includes large interface recognition, interfacial transfer of momentum (friction). Regarding the interface recognition, the method implemented in neptune_cfd is based on the gradient of liquid fraction. Further details can be found in (Coste, 2007).

Wave-FOWT interaction might involve high amplitude motion, to do so the choice of the present numerical model is to use the discrete forcing method (kind of immersed boundary method) available in neptune_cfd. Thus, the solid is not explicitly represented on the mesh, a solid fraction is used to track it. This method involves a non-moving mesh where the body is meshed and defined with a porosity equal to 0 insuring no mass transfer between solid and fluids. Here, the solid motion is tracked thanks to the porosity evolution in a Lagrangian framework. To consider the solid motion and the presence of an interface in cut-cells, the porosity must be convected and the momentum balance equations are formulated differently. Based on dedicated geometric parameters, the wall is reconstructed based on interpolations. For low values of porosity (under $1.10^{-10}$), clippings are used to avoid numerical issues. Then, the different two-phase flow numerical models are consequently adapted. This fluid-structure interface tracking method is called time and space-dependent porosity method, further details can be found in (Benguigui et al, 2018).

Forces are computed at cut-cells based on the interpolated pressure from the center of the cell to the fluid-structure interface and viscous terms are also discretely computed at wall. Then, forces are integrated on the whole structure. The same thing is done for moment. Based on the force and the moment, displacement and rotation are computed with a Newmark algorithm involving centered schemes. An explicit coupling method is used to allow larger time step. Further details on the fluid-structure interaction module can be find in (Benguigui et al. 2019).

When doing the sum of involved forces and moments, an external force and moment are added to consider the effect of the mooring line on the floating foundation based on its position and its inclination. For the present case, a static model is used to compute the effect of mooring lines.

Instead of using a wave maker as in the experimental campaign, an inlet boundary condition imposes the free surface elevation and the vertical profile of fluid velocity. The incident wave conditions are calculated using the so-called Stream-Function method (Fenton, 1988) which allows to compute fully nonlinear wave profiles and associated kinematics for regular waves in uniform depth. From the inlet location, in the wave generation zone, a momentum source term imposes the velocity components depending on x, z and t based on the same Stream-Function solution for the targeted wave characteristics. By imposing wave velocity in this relaxation zone, the waves potentially reflected by the wall are properly absorbed. For the absorption, the relaxation zone is similar, however the momentum source term imposes a null velocity. The top of the domain is defined with a pressure condition. The bottom wall is defined with a wall law condition, and the others with a slip condition.

## III – Validation of the numerical approach

The FOWT barge design presented in Kosasih et Al (2019) is of interest, both from the industrial point of view and from the hydrodynamic point of view with its moonpool and skirts, bringing challenging issues for engineering approaches. This is a typical case where using a Navier-Stokes solver to fit drag coefficients, or to check the moonpool effects, is of interest to feed an engineering model. Therefore, it was decided to validate neptune_cfd on the regular waves experimental results presented in Kosasih et Al (2019).

The mechanical and wave conditions (amplitude, period, and depth) are respectively defined in Table 1 and 2. The authors bring the reader attention on the fairlead positions, not given in the original paper and based on Fig.7 of this latest. The fairleads positions have been chosen as realistic as possible regarding the figure, tests have been made with DIEGO (the hydro-aero-servo-elastic solver developed by EDF R&D) to verify the Surge/Heave/Pitch motions where not sensitive to the fairlead positions, when chosen in a realistic range of values. The natural periods of system are estimated based on time domain simulation with DIEGO : 168 s for the surge, 7.0 s for the heave and 11.8 s for the pitch.

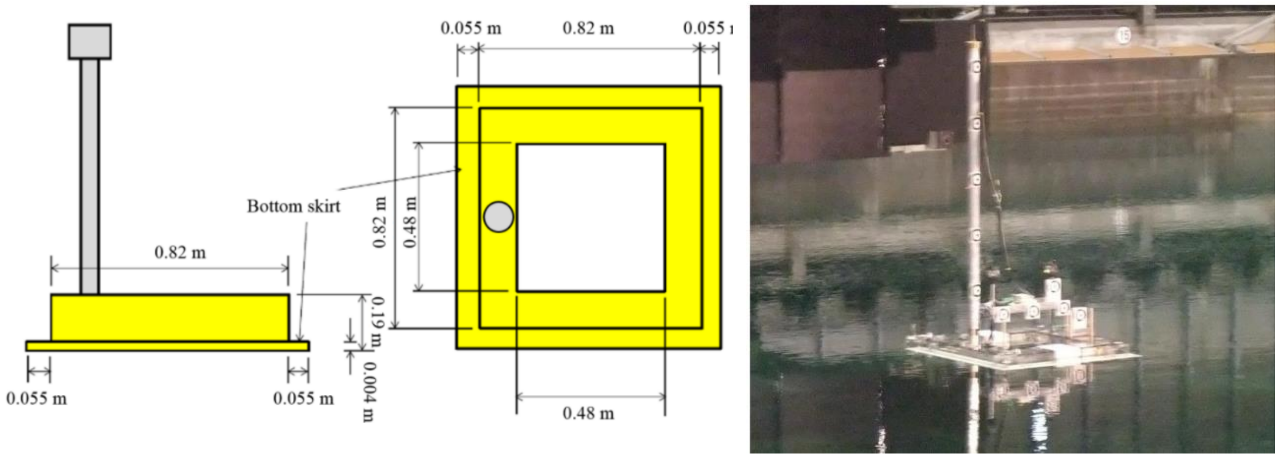

**Figure 1 Sketch of the reduced model (left) and picture of a test (right) (figure from Kosahsi et al [6] at model-scale) .**

**Table 1 Square IDEOL FOWT mechanical and mooring line properties (given full scale)**

| | |
|---|---|
| Mass of FOWT (kg) | $7.928\ 10^6$ |
| Center of mass location (m) | x, y, z = {0, 0, -10.2} |
| Inertia at the center of mass ($kg.m^2$) | Ixx, Iyy, Izz = {$2.9837\ 10^9$, $3.5296\ 10^9$, $2.9225\ 10^9$ } |
| Mooring 1 Fairlead Position (m) * | x, y, z = {18.0; 0.0; 7.5} |
| Mooring 1 Anchor Position (m) | x, y, z = {353.7 ; 0.00 ; -160.0} |
| Mooring 2 Fairlead Position (m) * | x, y, z = {-15.2; 14.5; 7.5} |
| Mooring 2 Anchor Position (m) | x, y, z = {-183.05 ; 305.2247 ; -160.00} |
| Mooring 3 Fairlead Position (m) * | x, y, z = {-15.2; -14.5; 7.5} |
| Mooring 3 Anchor Position (m) | x, y, z = {-183.05 ; -305.2247 ; -160.00} |
| Mooring mass density (kg/m) | 174 |
| Mooring line length (m) | 400 |

***: not provided in the original paper and estimated by the authors**

**Table 2 Wave condition used for the present study**

| Case | Height (m) | Period (s) | Depth (m) |
|---|---|---|---|
| 1 | 2.5 | 10.0 | -160 |
| 2 | 2.5 | 7.50 | -160 |
| 3 | 2.5 | 12.5 | -160 |
| 4 | 2.5 | 15.0 | -160 |

The present simulations are performed with 3 degrees of freedom (x, z and $\Theta_y$) for sake of simplicity regarding the wave orientation and the floater symmetry and to optimize the simulation in terms of duration. In terms of time discretization, the simulations are fully unsteady with an adaptative time step. A maximum CFL number condition is applied to 0.5 in liquid and 1 in air. The mesh discretization respects our guidelines for wave propagation.

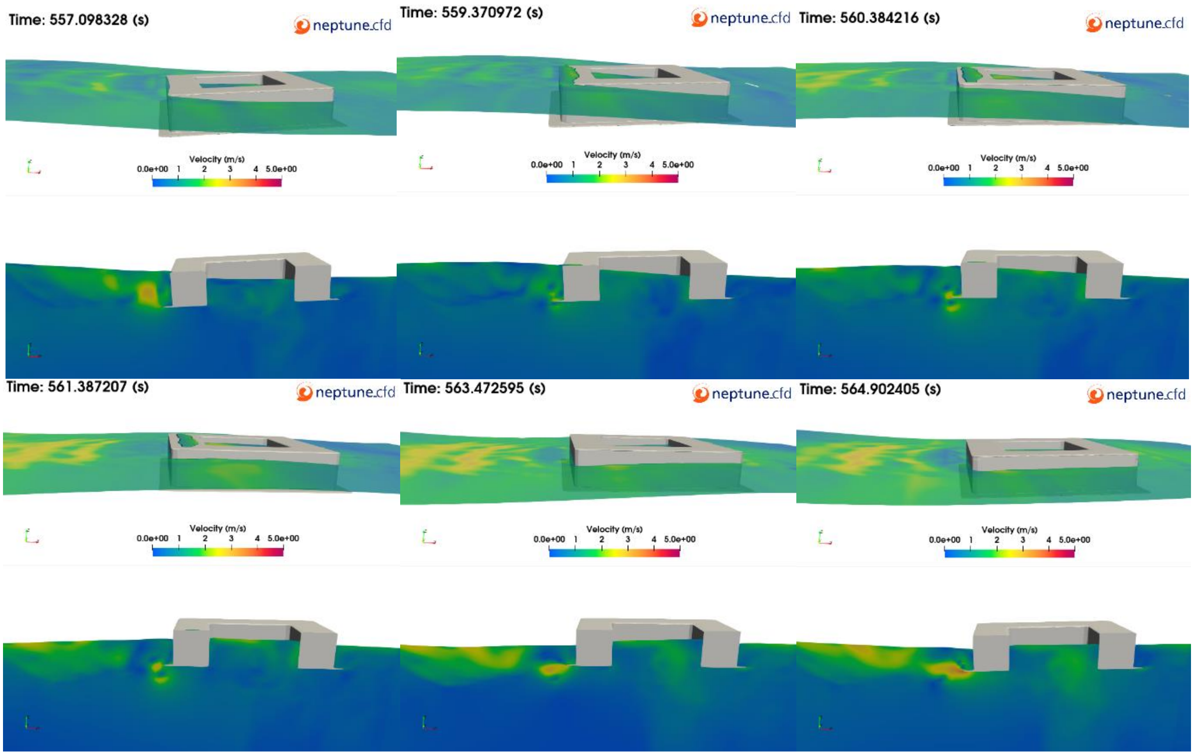

**Figure 2 Free surface around the FOWT and velocity distribution from neptune_cfd simulation for T = 10 s and H = 2.5 m.**

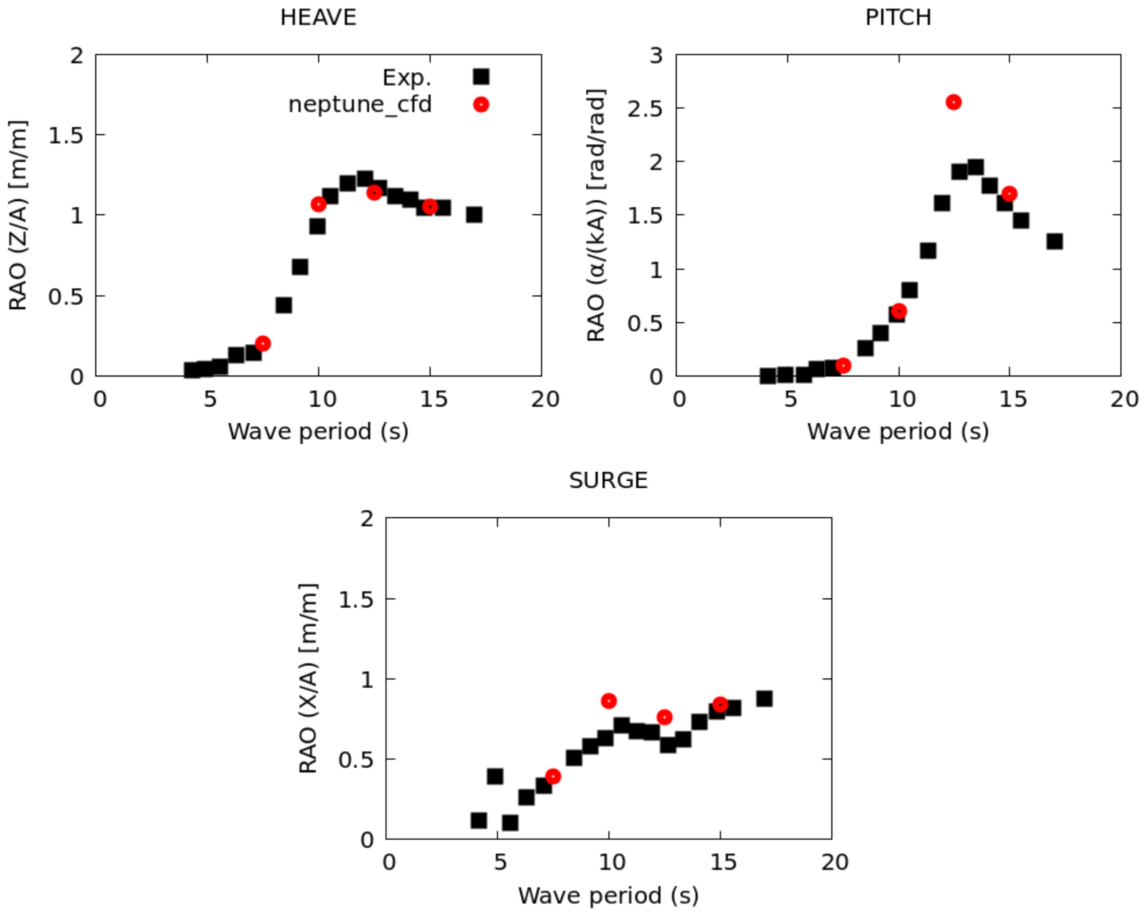

**Figure 3 RAOs in surge, heave and pitch prediction with neptune_cfd compared to experimental data according to the wave period for H = 2.5m.**

In Figure 3, heave, surge and pitch motions compared to experimental data though the RAO convention given in Kosasih et Al, 2019. RAOs are plotted for H = 2.5 m with different wave periods. It is possible to see that the amplitudes of the different degrees of freedom are well predicted, thus the trends of the motion depending on the wave condition are well reproduced. For T = 12.5 s, close to the pitch natural frequency, the amplitude is overestimated by the simulation, a finer mesh (so a mesh sensitivity analysis) would be of interest to improve the present results. Despite this point, it is therefore possible to analyze the flow distribution around the FOWT to see the role played by the flat plate and by the pool.

A look at Figure 2 allows to see the pool water height evolution which does not follow the water level, which is expected for such moonpool systems. It is also possible to notice that some waves are overtopping the barge. In addition, the velocity field underlines vortices shed by the skirts, one can expect significant drag loads are associated to these vortices. Therefore, it seems of interest to analyze the influence of these skirts on the system's motions.

## III – Effect of the skirt on the motion

To investigate the role of the skirts, the same wave conditions used in the previous section are used to derive motions RAOs. To keep the same draft removing the skirts, the mass of FOWT was slightly modified and set to 7.928 $10^6$ kg, the other parameters (fairleads position, anchors position, inertia) are kept unchanged. The numerical model settings are conserved as well. Removing the skirts influence the natural periods of the system, due to the change in mass and added mass, shifting from 168 to 164 s (-2.3%) for the surge, 7.0 s to 6.3 s (-10%) for the heave and 11.8 to 10.4 s (-12%) for the pitch. One can therefore expect some change in the motions. Besides, one sould note that without skirts, the floater is possibly not "well designed" anymore. Typically, having a 10.4s pitch period is generally not recommended, it is done here for academic purpose only.

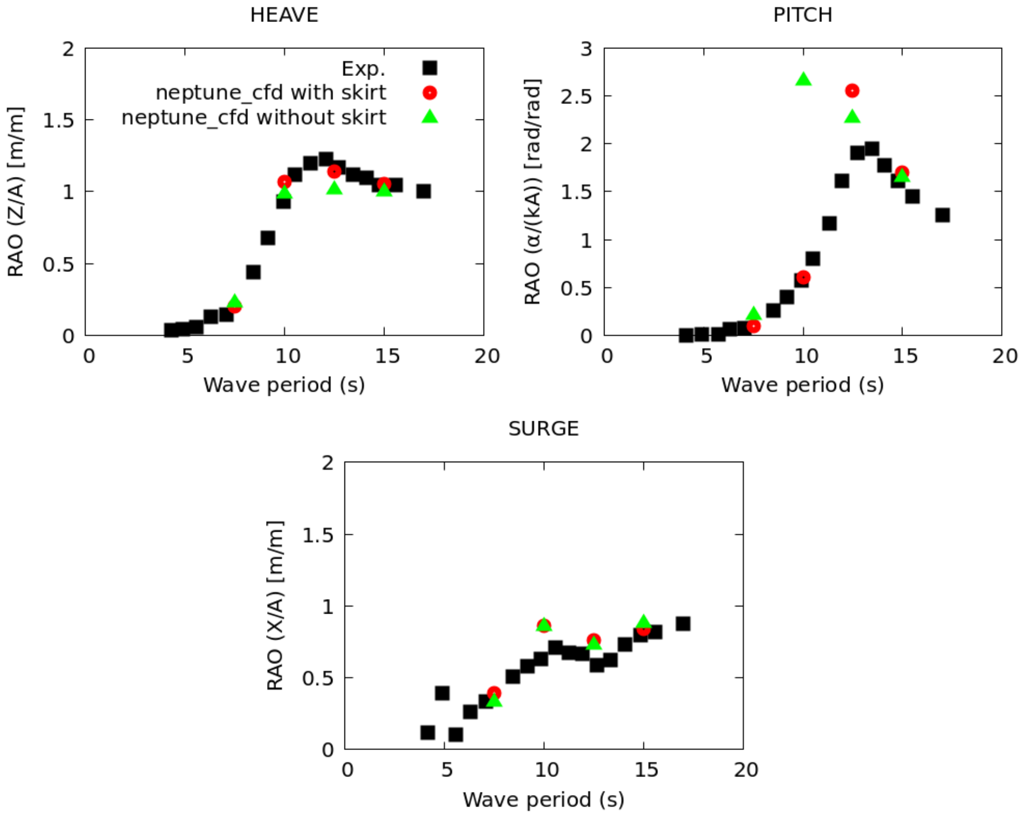

**Figure 4 RAOs in surge, heave and pitch prediction with neptune_cfd with/without the skirt compared to experimental data with skirt according to the wave period for H = 2.5m.**

In Figure 4, the main results in terms of RAOs are compared with and without the skirt. The amplitude of surge and heave directions are very similar, meaning that there is only a slight effect from the skirt on them. The main discrepancy observed in the present study is obtained for the pitch, with no significant change in the amplitude, but a shift in the peak response frequency. The change of the natural pitch frequency from 11.8 s to 10.4 s seems to be the major reason. Studying more wave periods would help quantifying the reduction in the peak response. We also note the heave response is not much modified when removing the skirts, which is a bit counter intuitive. A possible explanation of the small decrease in the heave RAO could be the shift of the natural heave period further from the moonpool period, but this needs to be investigated further.

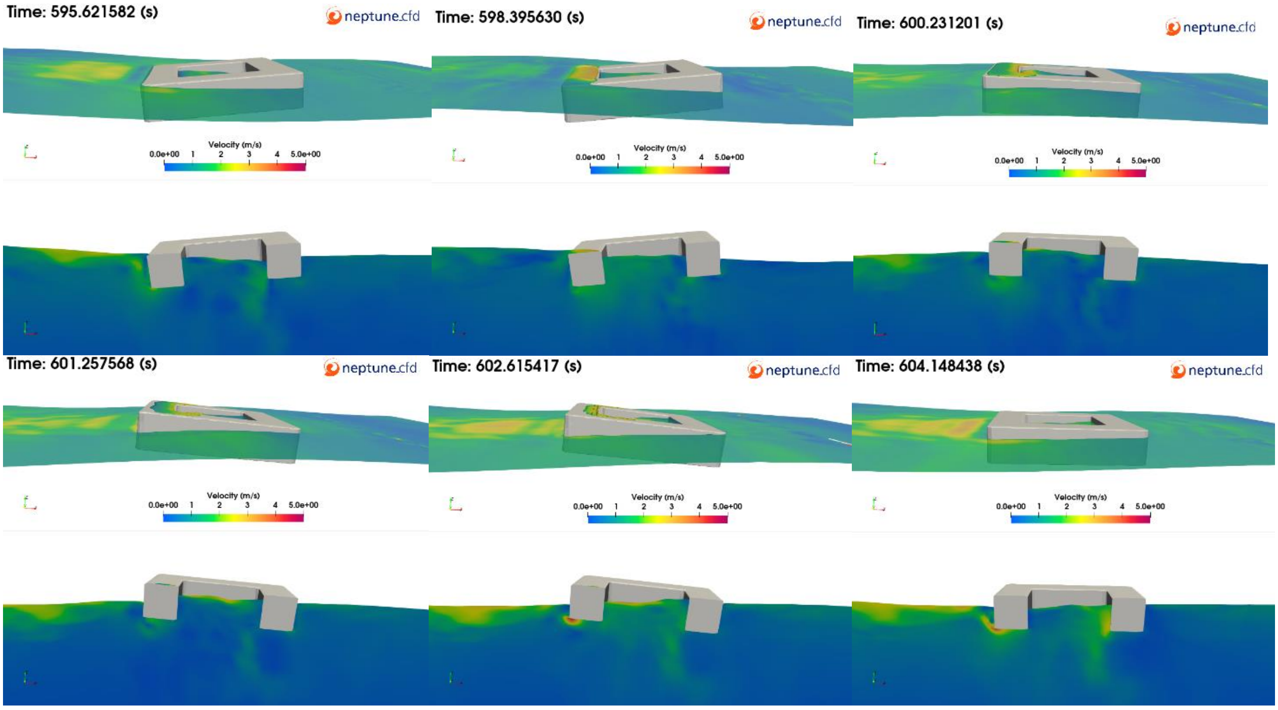

**Figure 5 Free surface around the FOWT without the flat plate and velocity distribution from neptune_cfd simulation for T = 10 s and H = 2.5 m.**

In Figure 5, the water overtopping the barge is observed, as with the skirts. However, the disturbance of the free surface elevation in the pool appears different. Without the skirt, a stronger sloshing effect in the pool is observed that was less present with the skirts. This might be another source of modification of the pitch motions, possibly affecting the phasing of the forces applied on the floater. We also underline the point that large pitch motions make more likely the occurrence of green waters. A look to pitch time evolution for T = 12.5 s in Figure 6 shows a change in the trend: the floater with the skirt experienced regular pitch amplitude, removing the skirts leads to a more irregular signal. The Fast Fourier Transform (FFT) highlights this finding: only the wave frequency appears in the response of the floater with skirts, although without the skirt a second peak appears at a period close to the pitch natural period, suggesting there is an excitation of the pitch natural frequency. Thus, a possible conclusion is that for the present case, the pitch natural frequency is damped by the skirts, however the reason for having an excitation moment at the pitch natural frequency remains unclear in a regular waves case, it might be related to the overtoppings that add and remove mass on the floater. It remains difficult, based on only 4 points to discuss and conclude on the role played by overtoppings on motion and pool behavior. Similarly, for the sloshing observed without the skirt in the pool, the main periods are probably related to the wave and pitch natural frequency. This case proposes a first comparison to investigate the effect of the skirt with a numerical model, however it deserves to work on other sea states to draw a full picture of the effect of the skirt and the hydrodynamic characteristic of the pool.

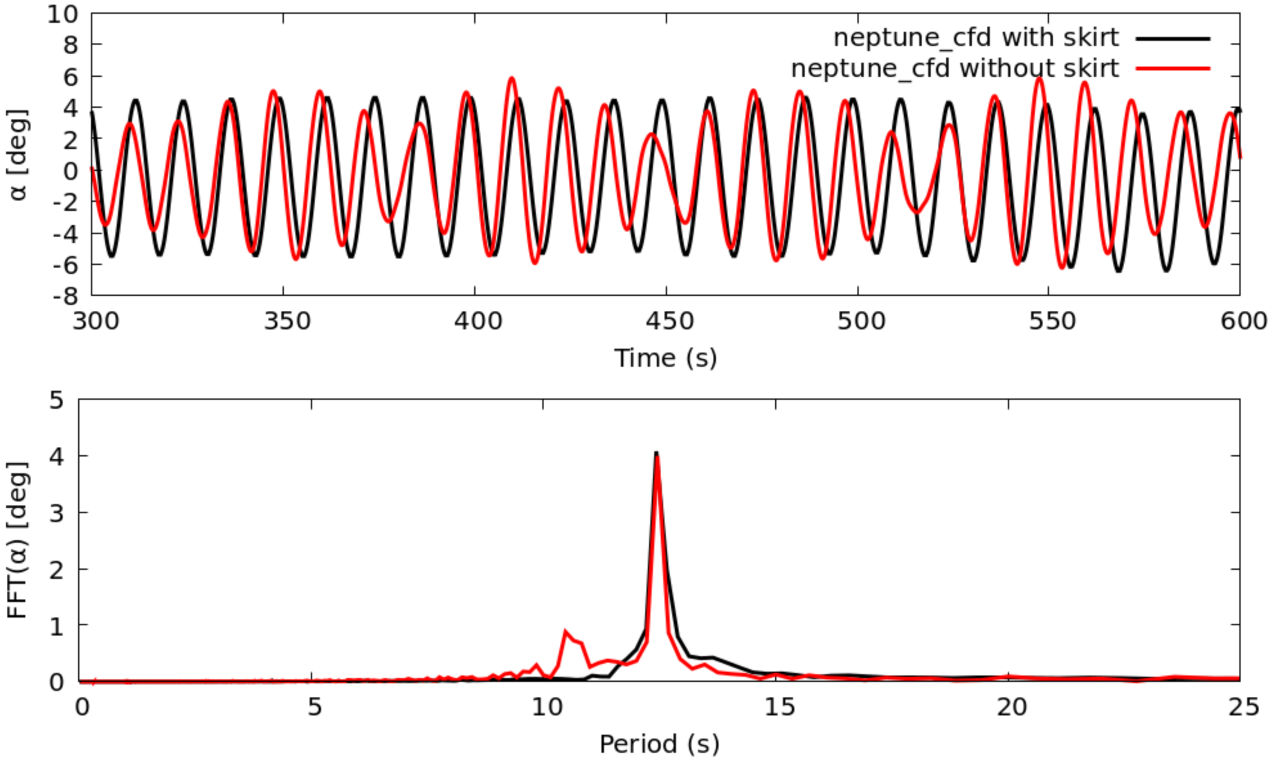

**Figure 6 Time evolution of the pitch for T = 12.5 s with and without the skirt and associated Fast Fourier Transform (FFT).**

## IV – Conclusions et perspectives

A CFD numerical approach, using a Eulerian Eulerian model to track free surface flows and a discrete-forcing method to track the FOWT motion, is evaluated on a reduced-scale literature test case simulated at full scale. The mooring lines are represented with a static approach, which can be challenged for this kind of motion, but the overall model is able to accurately predict the trend in motion for different wave periods with a given wave height.

A comparison is performed to investigate the effect of the skirt of the chosen FOWT for a single case. It highlights a frequency shift in the pitch response related to the change in natural frequency. Only 4 points are simulated with a single wave height which introduces overtopping in the pool, however the presence of the skirt appears to stabilize both the flow in the pool and the pitch motions. It is difficult to quantify the role played by the overtoppings and the motion on this effect with only few tests. However, when looking at pitch time evolution and its FFT, it is possible to see that the floater without skirts experiences pitch motions at its natural pitch period; adding the skirts seems to cancel this effect.

The present work is a first step to demonstrate the interest of having a high-fidelity model to support “aero-hydro-servo-elastic” model analysis. The study was made on a 3MW IDEOL FOWT and the authors believe that the conclusions might be different when moving to larger systems (15MW, 20 MW) with different natural periods and different air drafts. The authors also underline that this work was done without BW-IDEOL and the conclusions are not supposed to be representative of the real BW-IDEOL floating foundation behavior.

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