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A Brazil-Japan Collaboration on a Conceptual Design of a Floating Offshore Wind Turbine for the São Paulo Coast

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Abstract

Wind energy is one of the most studied topics in the renewable energy scenario. In the last decades, the focus has been put on several aspects of modeling and analysis of onshore wind turbines. Particularly in Brazil, onshore wind energy has an enormous potential that has been investigated in some recent studies.

In turn, floating offshore wind turbines (FOWTs) appear as promising solutions for the near future in some areas such as Europe and Japan. The design of FOWTs is a very complicated task that must consider various aspects such as the responses to wave, current and wind loads, the static and dynamic stabilities and the structural behavior of the mooring lines.

Because of that, several research projects have been carried out by different groups aiming at developing numerical codes and experimental benchmark for FOWTs. This paper will provide an overview of an ongoing research project which is currently being executed in a collaboration between the University of São Paulo and the University of Tokyo. This project aims firstly at developing the conceptual design of a FOWT to be installed in the proximity of Ilhabela, on the northern coast of the state of São Paulo. Hydrodynamic tests under a pure wave and sea current loads will be used as the benchmark for in-house numerical codes and Computational Fluids Dynamics (CFD) calculations. The mooring system will be investigated using both in-house codes and commercial simulation packages. The secondary aim is to promote a scientific knowledge change between Brazil and Japan by students and researchers exchange.

1. Introduction

Recently, a series of efforts are being put on the development of new solutions for clean and renewable energy. One of the most compelling solutions is the installations of both onshore and offshore wind turbines. The latter class of wind turbines is the primary focus of this project.

Shallow-water solutions for offshore wind turbines include structures fixed at the sea bottom. However, this solution is not feasible for deep water, and FOWT appears as an attractive solution.

Even though interesting, FOWT solutions are very complex and demand investigations on a series of aspects, such as the coupled analysis of the wind loads and the seakeeping, hydro-aero-elastic response of the tower and hull and the structural behavior of the mooring system.

It is of great interest for both the academic and technological communities the joint efforts aiming at developing FOWT. One of these efforts is the OC4 and OC5 - Offshore Code Comparison Collaborative Continuation, see details in Popko et al. (2012), which focuses on the development of the 5MW FOWT proposed in Jonkman et al. (2009).

From both the technological and scientific points-of-view, Japan appears as one of the pioneer countries. Mainly, an offshore wind turbine farm is being installed at the Fukushima's coast, as can be seen in Figure 1. The design of this wind farm counts of the technical and scientific support from UTokyo. The efforts of UTokyo in developing the FOWT concept can be seen, for example, in Ishii et al. (2013), Suzuki et al. (2013) and Yotsuka et al. (2014).

Figure 1 - Photo of a FOWT being installed at Fukushima's coast.

On the other hand, the research group from EPUSP has large experience in the analysis of offshore structures, involving both the riser's analysis and the dynamics of ships and platforms used for oil exploitation. It is possible to highlight the conceptual design of the platform MPSO – monocolumn production, storage and offloading system as can be seen the details in Gonçalves et al. (2010a, 2010b).

Recently, this group is putting the focus on the analysis of wind turbines. Even though recent, these efforts already brought as scientific results papers presented at Conferences [see Lopez-Pavón et al. (2013), Zamora-Rodriguez et al. (2014), Faccio & Neto (2016) and Beraldo & Franzini (2017)], published in journals [Medjroubi et al. (2011) and Lopez-Pavón et al. (2015)] or submitted for possible publication in journals [Simos et al. (2016) and Faccio Jr. et al. (2017)].

Besides the design of the FOWT, the study of the flow around the FOWT is another important issue. Due to the increase in the natural periods in the horizontal plane (surge, sway, and yaw), FOWT is also susceptive to have significant motion caused by the VIM phenomenon. Both groups, EPUSP and UTokyo, have a recognized knowledge in this area; therefore, the inclusion of this kind of analysis in the design process is very recommended and can help to better design the hull and the mooring system as well.

Experimental works in flow induced motions by the present group were detailed in Gonçalves et al. (2010c, 2013b), for a single column case; and also in Gonçalves et al. (2012, 2013a) for a multi column case. These works showed that the motion amplitudes due to the FIM could reach magnitudes of one diameter of the characteristic section of the columns. Numerical and phenomenological models can be a solution to consider the VIM in the preliminary design phase; the works presented in Hirabayashi & Suzuki (2013) and Miyamura et al. (2014) developed numerical model applying Lattice Boltzmann Method.

The study of the flow around fixed columns is necessary to know better the physics in the FIM phenomenon. Efforts have been doing in this area to try to feed CFD calculations to validate the models developed using CFD code, then the CFD codes can be useful during the design phase of the project of offshore system, as FOWT. The UTokyo group is working to create a reliable benchmark experimental data for flow around a single and multi-columns system with different geometry, distance between columns, and current incidence angles, as can be seen in Gonçalves et al. (2015) and Fukuoka et al. (2016), for single column case; and in Gonçalves et al. (2016, 2017). The experimental data have been used in the V&V – verification and validation process of the CFD models developed by the UTokyo group; the first results can be seen in Lopes et al. (2017a, 2017b).

2. Objectives

The project has two primary objectives. The first one is to develop a new solution of a FOWT for Brazilian waters, specifically at Ilhabela, São Paulo Coast. Mainly, the focus will be put on the design of the hull and the mooring system.

Starting from a preliminary hull designed by UTokyo and tested before the beginning of this project at the wave-basin of the TPN – Numerical Offshore Tank Laboratory of USP. A series of numerical simulations with different software (and, consequently, different purposes) will guide modifications on both the hull geometry and the mooring system to minimize first and second-order motions due to wave and current excitations. Two small-scale hulls will be built and tested (seakeeping tests only with waves in Brazil, and towing tests only with current in Japan), providing data for further correlation with the numerical and CFD results. The main delivery is the new design of a FOWT capable to minimizing the response on environmental conditions.

The second main objective is to promote the internship of students from both institutions and increase the collaboration history between Brazil and Japan. It is expected that at four students from both universities spend at around four months developing part of their doctoral or post-doctoral research abroad.

3. Location Ilhabela

The site selected for the installation and operation of the FOWT is the south-east side of Ilhabela, a well-known island in the northern coast of the state of São Paulo as can be seen in Figure 2.

Figure 2 – Ilhabela map from Google.

The reasons for this choice are related to many interesting features that Ilhabela presents.

First of all, the island is very close to the continent, split from it by the canal de São Sebastião, which is only 2km wide in its narrowest point. The region is largely populated and Ilhabela is an important tourist region in Brazil. In the canal, on the continent side, there is an important cargo port and one of Petrobras' terminals for offloading oil. As a consequence, there is large maritime infrastructure in the area. On the other hand, a large part of the island's surface is encompassed by the Ilhabela State Park, meaning it is an area of preservation of the remaining rainforest in the south-eastern part of Brazil. Actually, the park covers 85% of the municipality[1], and for this reason the whole eastern shore of the island is almost uninhabited. There are, however, a few small communities within the park area that still rely, at least in part, on diesel-generators for providing electricity. Those communities could benefit from a small-power FOWT.

Also, the region of Ilhabela is the one in the shore of the São Paulo state with the narrowest continental shelf, meaning that the depth increases sharply on the SE side of the island. For this reason, a FOWT in a depth of 50 to 100 meters would still be conveniently close to the shore. Furthermore, the SE part of the island is the one with best wind potential, for the prevailing wind in the region comes from the South direction.

Finally, as another important aspect for the FOWT design, it is important to mention that the Oceanography Institute of the University of São Paulo has a base close to the region and there already is a good database of the metocean (waves, wind and current) of the area (see, for instance, Fortes (2018)), which is also motivated by the intense transit of ships inside the canal.

4. Scientific methodology

The NH - new hull will be designed by improving the hydrodynamic performance of two preliminary hulls, P1 and P2. Both the seakeeping and hydroelastic behaviors of the P1 - first preliminary hull was experimentally investigated at the TPN wave-basin, see a schematic of the hull P1 in Figure 3. Details about the mentioned experimental campaign can be found in Xiong et al. (2018).

The methodology utilized in this case is the Design Spiral. The design spiral is a methodology for developing ship designs, and can be applied to other complex systems as FOWT, see example in Figure 4. As FOWT are complex systems with highly interdependent variables, it quickly becomes impossible to calculate factors simultaneously. Instead, the design spiral describes a process of iterative refinement to 'zero in' on an efficient

1 https://en.wikipedia.org/wiki/Ilhabela_State_Park

design. Each successive iteration is referred to as a 'spin' of the spiral. Phases or cycles are considered once a given level of technical refinement has been achieved.

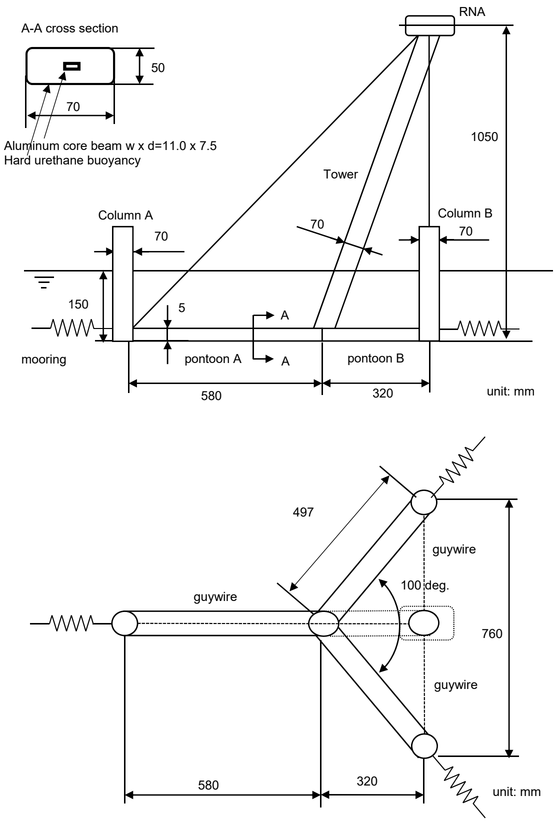

Figure 3 - Schematic illustration of the preliminary hull P1 in the model scale 1:100

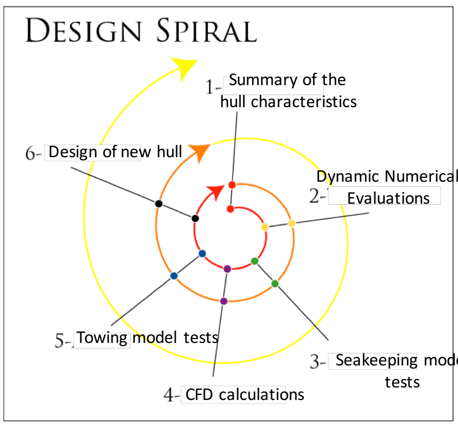

Figure 4 - Example of the design spiral for the Jappaku FOWT

Under the scope of the present research project, a P2 - second preliminary hull will be designed aiming at optimizing the seakeeping and hydroelastic behavior of the P1. The optimization scheme will focus on minimizing the first and second-order responses of the hull by changing both the geometry and the mooring system. These changes will be guided by a series of simulations using both commercial and in-house software for calculating the dynamics of the floating unit, the structural behavior of the mooring system and the flow around the hull.

Once defined, a small-scale model of the P2 hull will be built, and its response will be experimentally investigated under both pure wave excitation and also under pure towing speed. It is not focus on this project the simultaneous excitation by towing speed and waves. The effects of the wind loads will not be investigated as well. In addition to the experimental investigation of the response of the hull to the fluid excitation, CFD - Computational Fluid Dynamics will be carried out aiming at a better understanding of the flow characteristics around the hull. Moreover, numerical simulations of the dynamic behavior of the coupled system (hull and mooring) will be performed using for example potential theory and analytical solutions (for example, Morison and Froude-Krilov approximations). A NH – new hull (third hull) will be designed by improving the behavior of the P2 hull, and a new set of pure towing and pure wave excitations will be carried out. This will be the final hull and delivery of the research project, the summary of the hull design evolution can be seen in Figure 5.

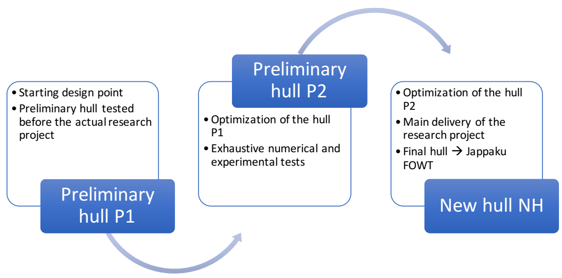

Figure 5 - Hull design evolution

For the mooring lines analysis, there are tasks to be performed related both to numerical models' simulations and experiments. The software GIRAFFE[2] will be used to simulate the statics/dynamics of the mooring system. It will be possible to extract relevant information, such as

[2] This code employs a geometrically exact beam formulation. Details regarding the mathematical formulation can be found in Neto et al. (2015). Analysis of risers using GIRAFFE can be found in Neto et al. (2014, 2015) and Neto (2016).

stiffness of the mooring system, for all degrees of freedom of movement of the floating unit. Furthermore, since GIRAFFE is geometrically nonlinear, in its essence, it will be possible to analyze the validity of representing the mooring system as a set of linear springs. This may be helpful for the floating unit experiments set up. As a complete task, we also aim at comparing the numerical results of GIRAFFE with tests of a mooring line. For that, the idea is to monitor some points along the length of the line and compare their time-series of displacement to the numerical results. This may be done in mooring lines with touchdown point (including contact between the mooring line and the seabed) since GIRAFFE models straightforwardly account for such effect.

Still focusing on the mooring system, a deep investigation regarding the water depth and the mooring lines arrangement is planned. This study will provide support for an experiment considering a small-scale representation of the mooring system. This last set of tests will be carried out only for the third hull and will provide data for numerical correlations. Notice that the development of a new mooring system, including experiments on a small scale, is a very challenging aspect of the project.

The project lasts two years and aims to combine numerical, analytical and experimental approaches for the design of the new solution. The tasks are itemized as follows, and presented in Table 1:

Table 1 – Research schedule (M is a model test, purple is task designed for both team, green is task designed for the Brazilian team, and red is task designed for the Japanese team).

Tasks	Activity	Months																							
		FY2018												FY2019											
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
G1	Bibliographic Review																								
G2	Selection of the installation field in Brazil																								
G3	Study of the preliminar hull P1																								
B1	Design of the preliminary hull P2																								
J1	Development of CFD model for captive test simulations																								
J2	Captive model tests of preliminary hulls P1 and P2							M	M	M															
B2	Seakeeping model tests of the preliminary hull P2										M	M	M												
J3	Validation of the CFD results for captive tests																								
J4	Development of CFD model VIM test simulations																								
B3	Design of the new hull NH																								
J5	VIM tests of the new hull NH																M	M	M						
B4	Mooring system analysis																								
B5	Seakeeping model tests of the new hull NH																			M	M	M			
J6	Validation of the CFD results for VIM tests																								
G4	Preliminary economic feasibility of the new hull NH																								
G5	Summary evaluation of the new hull NH																								

General tasks will be performed and be the responsibility of both teams, Brazil and Japan:

- **Task G1: Bibliographic review** – Review of the previous FOWT concept proposed in the world. Focus on the difference between the concepts and mooring line designs;
- **Task G2: Selection of the installation field in Brazil** – A study will be done to choose the best installation place in Brazil. The potential wind power generation must be the highest and it will be taken in account to select the best place to install de FOWT. Distance from the coast and also depth of the field will impact the design process.
- **Task G3: Study of the preliminary hull P1** – As commented before, the start of the studies will be based on a previous collaborative study presented in Xiong et al. (2018), both teams will review the preliminary hull P1 and use its characteristics as a start point for the design of the new hull;
- **Task G4: Preliminary economic feasibility of the new hull NH** – The economic feasibility study will show in terms of costs if the new FOWT will be attractive to be build. Some modifications can be proposed after this stage in the design of the hull.
- **Task G5: Summary evaluation of the NH** – In this final task, both teams, will present the final solution of the hull NH and its dynamic performance in wave and current. The new hull NH must be a feasible solution for a FOWT;

Brazilian tasks will be performed and be the responsibility of the Brazilian team, Japanese team will support these tasks as well.

- **Task B1: Design of the preliminary hull P2** – This task will be carried out by the Brazilian team and focuses on the development of a new hull by enhancing the hydrodynamic performance of the hull tested before the beginning of this project, P1. Using both in-house (for example, TPN and GIRAFFE) and commercial codes (WAMIT®), as well as theoretical studies, it is planned to reduce the wave-induced motions as well as the VIM - vortex-induced motions response. Such reduction will be achieved by changing the hull geometry, the mooring system and, eventually, passive vibration absorbers.
- **Task B2: Seakeeping model tests of the preliminary hull P2** – The hull developed in Task B1 will be tested both under pure wave excitation (regular and irregular conditions) in the ocean basin at TPN laboratory of the University of São Paulo. Rigid body motions, force coefficients, and spectral analysis will be obtained as functions of the wave characteristics. A set of elastic springs will be used aiming at

achieving the desired stiffness on the horizontal plane.

- **Task B3: Design of the new hull NH** – Using the same approaches already presented in Task B1, new dimensions, and a new mooring system will be generated aiming at obtaining an updated hull, less susceptible to wave- induced motions and VIM response. This is the main task of this research project.
- **Task B4: Mooring system analysis** - A comprehensive analysis of the mooring system will be carried out using the GIRAFFE code. This task will also provide information to design better mooring system for the NH.
- **Task T5: Seakeeping model tests of the new hull NH** – The same experiments and analysis carried out with the preliminary hull P2 will be repeated with NH. The obtained characteristics oscillation amplitudes due to waves will be achieved for the different excitations and compared with those corresponding to the hull P2. Besides the experiments with the same set of springs used in Task B2 (which will allow identifying the influence of the geometry on the response), another set of experiments considering NH and the new mooring system defined in Task B4. If possible, experiments with a small-scaled mooring system will be carried out instead of using another set of linear springs. Notice that, even though very complex, is of great interest aiming at the correlation with the results obtained using GIRAFFE.

Japanese tasks will be performed and be the responsibility of the Japanese team, Brazilian team will support these tasks as well.

- **Task J1: Development of CFD model for captive tests** – A CFD model will be developed to understand the flow characteristics around the FOWT. In this task, issues as mesh refinement, time step, and turbulent model will be investigated to choose the best model for the captive tests. Preliminary hull P1 will be used as study case in this task. Examples of software that may be utilized in this task are Fluent®, StarCCMR® and ReFresco.
- **Task J2**: **Captive model tests of preliminary hulls P1 and P2** – Captive model tests will be performed in the Towing Tank at Hongo Campus of the University of Tokyo, Japan. In these tests, the objective is providing experimental force results to compare with the previous CFD models developed. The results of captive tests will be used to evaluate the VIM or galloping behavior when the model is free to oscillate due to the current incidence. In this task, the model test results evaluation is also considered.
- **Task J3: Validation of the CFD results for captive test simulations** – Comparison between CFD results and captive model tests results will be evaluated by the captive tests performed in Task J2. The goal is to validate the CFD model; therefore, the CFD model can be used to optimize the P2 geometry to reduce the drag and lift coefficients.
- **Task J4: Development of CFD model for VIM tests** – A CFD model will be developed to understand the VIM of the FOWT. In this task, issues as mesh refinement, time step, and turbulent model will be investigated to choose the best model for the captive tests. Preliminary hull P2 will be used as study case in this task. Examples of software that may be utilized in this task are Fluent®, StarCCMR® and ReFresco. The difference between Task J1 and J4 is that in Task 4 the FOWT is free to oscillate due to the current incidence; therefore, a structural model must be coupled with the flow model to provide the system dynamic of the FOWT.
- **Task J5: VIM model tests of the new hull NH** – VIM model tests will be performed in the Towing Tank at Hongo Campus of the University of Tokyo, Japan. In these tests, the objective is to understand and measure the movements of the FOWT (in-line, transverse and yaw) due to the current incidence. The model will be elastically supported by a set of springs to represent the mooring system, and the motions will be measured by optical motion capture system.
- **Task J6: Validation of the CFD results for VIM test simulations** – Comparison between CFD results and VIM model tests results will be evaluated by the VIM tests performed in Task J5. The goal is to validate the CFD model; therefore, the CFD model

can be used to optimize the NH geometry to reduce the motions of the FOWT and increase the fatigue life of the mooring system. In this task, a modification can be proposed in the NH hull to improve the VIM performance.

Notice that the tasks and the methodology herein presented combines analytical, numerical (using both commercial and in-house codes) and experimental activities (to be carried out at EPUSP and UTokyo's facilities). Figure 6 and Figure 7 illustrate the activities and the research team responsibilities.

The period of internship of researchers and students will try to coincide with the time of the model tests in each country. In this way, the internship will also provide experience in both research areas: experimental and numerical.

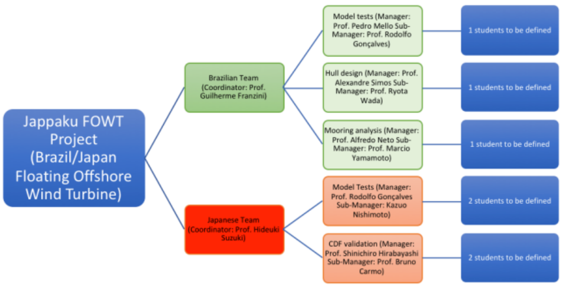

Figure 6 – Project Overview: Brazilian and Japanese teams

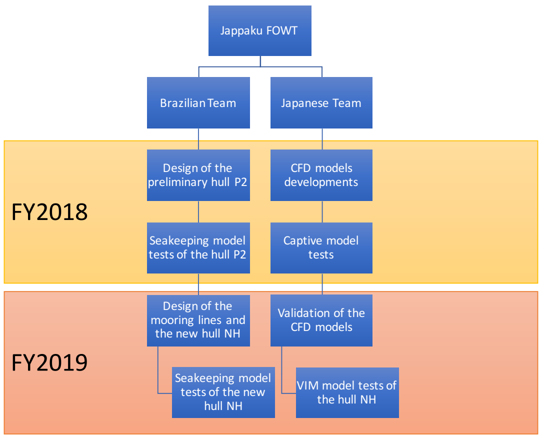

Figure 7 – Project Overview: Tasks and scheduled activities

5. Historic of previous collaborations between EPUSP and UTokyo

The University of Tokyo is promoting collaboration with Brazil. Department of Ocean Technology, Policy, and Environment of the University of Tokyo has planned a series of ocean engineering related remote lectures in cooperation with Brazilian universities, and implemented connecting Japanese universities and Brazilian universities.

Regarding research collaboration with University of São Paulo, the University of Tokyo has a track record of organizing international joint industrial research project participated by Japanese and Brazilian companies. The two years of international collaborative research was started in 2010. This is a research on improvement of the operational efficiency of floating LNG liquefaction, storage and shipping facility (FLNG) which had not been in full-scale operation at that time. Participating members from Japan side are major manufacturer, shipping companies, trading company such as Furukawa Electric, Mitsui Engineering and Shipbuilding, Tokyo Seiko, Nippon Steel Engineering, JGC, ClassNK, Marubeni, NYK Line, IHIMU, Chiyoda, Mitsui OSK Lines. From Brazil side University of Sao Paulo as a leader, PETROBRAS CENPES E&P Engineering, TRANSPETRO participated. Investigation was conducted on improvement of the operating rate of FLNG plant taking the realistic and detailed local conditions and so on into consideration.

The both universities also mutually conduct experiments complementing the strengths of the research facilities. For example, University of Sao Paulo conducts the towing experiment of a high speed vessel using towing tank of the University of Tokyo, and the University of Tokyo conducts experiment on the elastic response of a floating offshore wind turbine using multi-directional wave tank of the University of Sao Paulo.

In addition, University of Tokyo and University of Sao Paulo co-organize workshops at both universities time to time. Faculty members of the both universities visit each other and exchange views on latest research and educations. For education, the University of Tokyo has accepted internship with duration of about 3 months which will be part of master's research and doctoral studies.

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