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STUDY FOR APPLICATION OF OSCILLATING HYDROFOIL IN OFFSHORE WIND TURBINES

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Abstract. *The oceans are inexhaustible sources of energy, as are solar, wind, and biomass. However, it has a high cost-benefit ratio compared to other renewable sources, but this difference has been reducing over time. An indication of this reduction can be seen through investments in offshore wind turbine installations, which have had significant growth in the last five years, mainly in Europe. This growth can bring opportunities for other energy sources, including ocean ones. There are five known ways of obtaining energy through the ocean: waves, tides, ocean currents, and differences in salinity and temperature. A model of energy converter whose efficiency has increased in recent years is the oscillating hydrofoil, which uses ocean currents to move a wing and generate electrical energy. Within this context, this work aims to present a solution for the application of oscillating hydrofoils in the monopile-type foundations of offshore wind turbines. For this, a study was carried out on the geometries of the foundations, the oscillating hydrofoil models, and the influence of the environment, and an analysis of the positioning of the HO was carried out to enable its inclusion in the foundation structure. The literature verified the dimensional variation and the types of loads generated by wind, ocean currents, and waves in foundations of the monopile type. Because of this, a structure for fixing the oscillating hydrofoil with the foundation was proposed, highlighting the main parts to enable the system assembly. Furthermore, simulations were carried out using flow simulation software (CFD) to qualitatively analyze the streamlines and discuss a minimum distance between the hydrofoil and the foundation. Finally, it is possible to state that the application of oscillating hydrofoil in foundations of the monopile type is feasible and should be encouraged to increase the use of the structure of offshore wind turbines.*

Keywords: *oscillating hydrofoil, flapping foil, offshore wind turbine*

1. INTRODUCTION

Offshore wind energy is already a reality in some European countries, such as, for example, Denmark, Germany, and England. In the case of the British, half of the installed capacity of wind turbines is of the offshore type (GWEC, 2022). In addition to countries on the European continent, Asia has also been investing in this type of technology, mainly China, which in 2022 became the country with the highest installed capacity, according to data obtained from the Global Wind Energy Council (GWEC) and shown in Fig. 1. This growth of this type of energy converter in the world is due to several factors, such as government incentives, cost reduction, the increased generation capacity of wind turbines, and distribution strategies for offshore areas.

Despite still not having any offshore wind turbine park, Brazil has more than 175 projects under analysis by the regulatory body for environmental licenses, Brazilian Institute of the Environment and Renewable Natural Resources (IBAMA, 2023). Not all projects will be carried out, but it is possible to infer great interest from the private sector investing in this area. Given this, other technologies for generating electricity, based on renewable sources from the ocean, can take advantage of the infrastructure of offshore wind turbines and, thus, reduce electrical infrastructure costs; substructure and foundation; and assembly and installation. Only these costs are about 40.6% of the total cost for one offshore wind farm, according to data from the GWEC, until 2020.

In order to take advantage of such infrastructure and reduce costs, it is necessary to discuss the energy resources available in the ocean. This generation capacity is seen in the five energy extraction types: waves, tides, ocean currents, and differences in salinity and temperature (Edenhofer *et al.*, 2011). Among these sources, tidal and ocean currents are

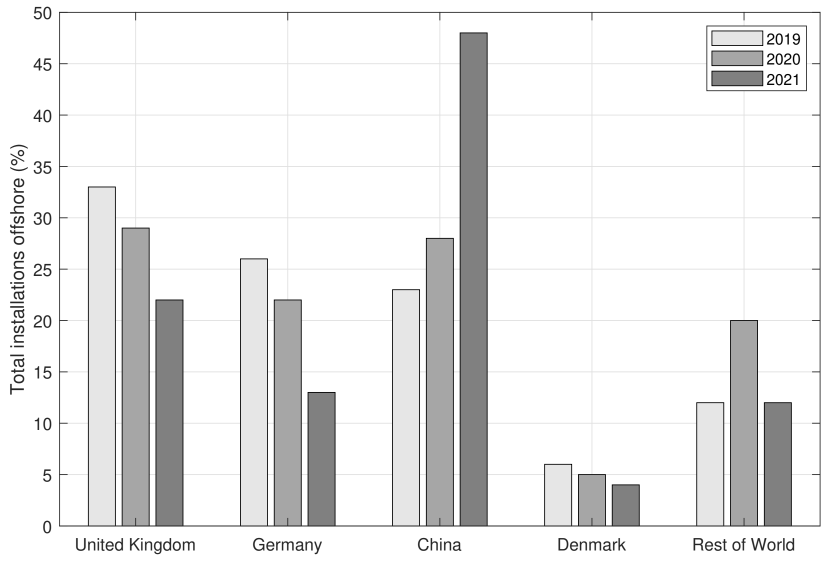
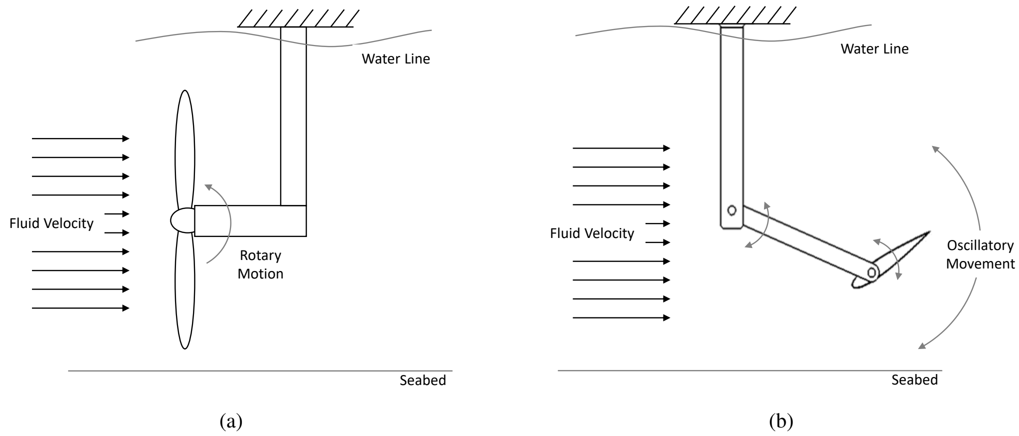


Figure 1: Total installations offshore in the World.

projected to generate up to 1000 TWh Melikoglu (2018). However, environmental and technological restrictions need to be revised to achieve this capacity. As far as ocean current energy converters are concerned, there are still challenges in the design cost and efficiency of the device. From these questions, the present work intends to present a device capable of achieving this balance.

Two models stand out regarding the types of converters applied to energy from ocean currents: hydrokinetic turbines and oscillating hydraulics, as shown in Fig. 2. In the case of hydrokinetic turbines they have a similarity with wind turbines in which the transmission shaft is positioned horizontally, parallel to the fluid flow, and the blades are perpendicular to the flow, performing a rotating movement. However, hydrokinetic models usually have two blades and start at a lower operating speed, and must withstand different types of ocean phenomena, such as waves, currents, salinity, and temperature differences.



(a) (b)

Figure 2: Tidal and ocean current energy converter models: (a) hydrokinetic turbine; and (b) oscillating hydrofoil.

Although hydrokinetic turbines are more used, studies indicate that oscillating hydrofoils have competitive efficiencies (Simpson *et al.*, 2008) and can become a viable device quickly. This device can be composed of one or more wings that have an oscillatory movement in relation to the fluid flow. The movement of the blades is similar to the swimming of fish (do Prado Campos *et al.*, 2021; Prempraneerach *et al.*, 2003; Xiao and Zhu, 2014), generating less impact on the habitat of marine beings compared to the movement of hydrokinetic turbines. Another advantage is the possibility of operating in shallow water depths (Kinsey *et al.*, 2011).

Faced with this growing competitiveness of oscillating hydrofoils and knowing the high costs for the implementation of this offshore system, the present work proposed to study the installation of this device in conjunction with offshore wind turbines, being discussed throughout the text, advantages, disadvantages, and restrictions when choosing this type of assembly in an infrastructure available by the turbine.

Finally, in Figure 3 is illustrated an assembly between an offshore wind turbine and a system composed of two oscillating hydrofoils. In addition to energy converters, the offshore and onshore substations, and the electrical grid are presented; much of the infrastructure is already designed when you want to install an offshore wind farm. Furthermore, the sum of energy generated by the two renewable sources, wind and ocean current, is shown.

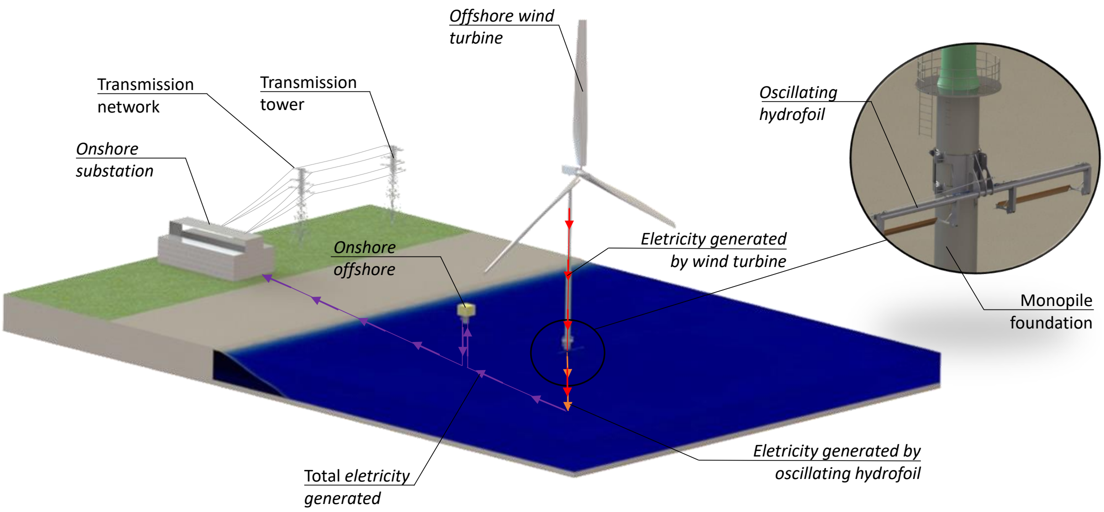


Figure 3: Illustration of the assembly between offshore wind turbine and oscillating hydrofoil.

2. METHODOLOGY

Several foundations can be used in offshore wind turbines installation, such as gravity-based foundation, monopile, tripod, jacket, triple, spar floater, and semisubmersible floater. The choice of model to be used depends on the types of loads and the depth of the chosen location and, according to the roadmap of the Empresa de Pesquisa Energética (EPE) and the GWEC report, each type of foundation has an operating depth limit, as shown in Table 1.

Table 1: Characteristics of types of foundations for offshore wind turbines (EPE, 2020).

Foundation type	Estructure type	Manufacture	Recommended for depths
Gravity based	Fixed	Simple	< 30 m
Monopile	Fixed	Simple	< 35 m
Tripod	Fixed	Complex	< 50 m
Jacket	Fixed	Complex	< 60 m
Tension Leg	Fixed	Complex	< 60 m
Spar floater	Floating	Complex	> 100 m
Semi submersible	Floating	Complex	> 100 m

In Table 1, one can also highlight the type of fastening and the constructive form, simple or complex, depending on the degree of development of the foundation project and the manufacturing processes involved. Because of this, it is observed in the data released by the National Renewable Energy Laboratory (NREL) that the monopile is the most used structure in the world, being used in 80% of the projects until 2016 (Musial *et al.*, 2017). The future projection is that around 59% of new projects will continue to use this type of foundation.

In Brazil, it is clear that 95% of offshore wind farm projects under analysis by IBAMA chose to operate at low depths, that is, below 50 m. This means using a fixed-type foundation, following the international market, and using monopile-type models.

Given this, the present work chose to study the assembly of the oscillating hydrofoil in the structure of an offshore wind turbine, considering the foundation of the monopile type. In this assembly, a conceptual proposal of integration was discussed, and the interference of the foundation in the streamlines was analyzed qualitatively, allowing us to understand the influence of the fluid in the movement of the hydrofoil.

3. CHALLENGES BETWEEN OSCILLATING HYDROFOIL AND OFFSHORE WIND TURBINE

Studies on oscillating hydrofoils were first recorded in the literature by Wu (1972). Then, McKinney and DeLaurier (1981) developed the first model, Wingmill, which features movement based on ocean currents, achieving an efficiency of 16.8%. These results inspired researchers and the energy market, being the prototype with commercial objective, developed in 2003 and named Stingray. However, this model was fixed on the seabed and obtained unsatisfactory results, with an efficiency of only 11.5% (Kinsey *et al.*, 2011). Over time, other models commercials emerged (such as Pulse-Stream and bioSTREAM), but despite the efficiencies being satisfactory (between 20% and 30%), the cost-benefit ratio was high, and, as a result, the projects were again discontinued.

The emergence of wind turbines in the offshore environment allows a new discussion about these structures. It provides an opportunity to create a hybrid renewable generation system offshore. Some works have discussed the integration between offshore wind turbines' foundations and other converters. Among them, we can mention the work of Pérez-Collazo *et al.* (2015). In this work, the authors review the integration between *offshore* wind turbines and wave energy converters, presenting the various challenges of hybrid generation of these systems.

To make this conception viable, the present work chose to study the distance between the hydrofoil and the foundation. However, other challenges are known and will be mentioned in future works.

3.1 Integration project details

The proposed integration of the oscillating hydrofoil and the mono-pillar foundation can be seen in Figure 4. In the design, it was decided to assemble the structure of the converter without the need to modify the foundation of the *offshore* wind turbine.

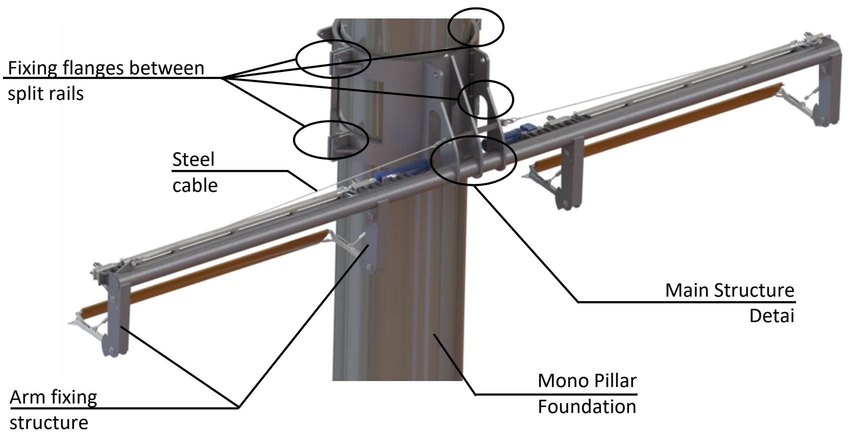


Figure 4: Detail of the oscillating hydrofoil structure mounted on the mono-pillar foundation of an offshore wind turbine.

Figure 4 also shows some project details, such as the bipartite joint, to enable assembly on the single column. This union was proposed to fit the entire circumference of the foundation and be assembled by screws. The mounting diameter allows that when tightening the screws, there is friction between the surfaces that is capable of withstanding the loads generated during operation, keeping the system fixed.

In order to maintain a distance between the foundation and the hydrofoil, a tubular structure and two fixation arms at each end were chosen. This structure option is intended to reduce hydrodynamic loads under the hydrofoils and thus improve performance. A steel cable has also been included to reduce deflection along the tubular structure.

Within this context, a critical point of the project is to determine the distance between the mono-pillar and the hydrofoil wing, mitigating the disturbances generated when the fluid goes around the structure.

3.2 Distance between hydrofoil and foundation

Some qualitative analyzes of the positioning of the structure were carried out using the *Flow Simulation* tool available in the SolidWorks software. However, in future works, it is expected to carry out quantitative analyses to optimize the positioning of the proposed structure. In Fig. 5, two models of structures with different distances between the wings are presented, in addition to CFD simulations, considering a laminar flow in steady state and fluid velocity equal to 2.2 m/s, referring to the maximum design velocity.

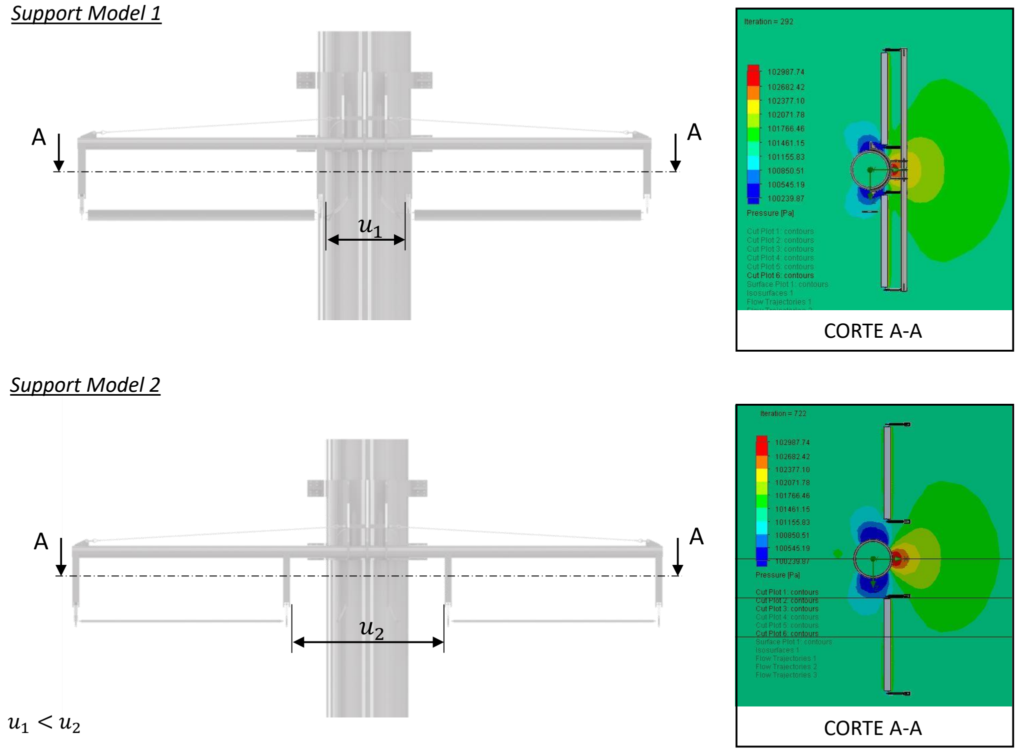


Figure 5: Comparison between two models of oscillating hydrofoil support structures.

In support of model 2, the wings of the oscillating hydrofoil are not significantly influenced by the streamlines generated by the foundation. In the case of the support model 1, several current lines cross the wing and may be responsible for generating turbulent zones and high losses for energy generation, as shown in Figure 5.

4. CONCLUSION

The present work discussed integrating the oscillating hydrofoil and offshore wind turbines. Within this, the types of foundations were studied, and the mono pillar, the most used in the market, was chosen. Thus, the wing assembly was carried out on the main structure, which was designed to be positioned on the foundation of the mono-pillar type. The assembly was made by two half rods and fixed by a screw, which can also be a good option in cases of more significant loading and the possibility of welding without damage to the foundation structure. This was a conceptual proposal, which required dimensioning of all parts to verify the proposal's feasibility.

Finally, a qualitative analysis of the distance between the hydrofoil and the foundation was carried out. This simplified study of the flow streamlines allowed us to understand the influence of the foundation on the hydrofoil using the Flow Simulation tool available in the SolidWorks software.

Future work is expected to discuss the distance between the hydrofoil, the waterline, the seabed, and between hydrofoils. In addition, the loads generated by the dynamically oscillating hydrofoil, evaluating the generation of vortices, the dynamic loads on the foundation, the possible problem of foundation fatigue, among other relevant points for the improvement of the project.

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