Use of Gyro On Offshore Wind Turbine Platform to Enhance Energy Harvesting

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Use of Gyro On Offshore Wind Turbine Platform to Enhance Energy Harvesting

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Abstract

Hybrid platforms are a promising architecture in innovative energy scenario for the minimization of the cost of offshore marine renewable installations and for reducing the variability of the power output. This article models and discusses the installation of a 5 MW wind turbine on a floating platform designed by Fincantieri and equipped with gyroscopic stabilization. Gyros will provide platform stabilization by damping the wave and wind induced motion on the floater and at the same time producing extra power. A reference site on the Shetland Island with particular harsh weather is chosen. Results show how the gyro can produce a considerable amount of power in moderate and medium climate conditions.

Keywords: wind energy; wave energy; hydrodynamics; gyroscope; marine renewable; floating platform

1. INTRODUCTION

The global energy scenario promotes renewable energy sources (RES) with the aim of reaching net overall CO_2 null emissions by exploiting different sources like wind, solar and hydro. A technology that has not reached commercial maturity yet but is approaching commercialization step, is ocean energy electrical generation, commonly referred to wave tidal and thermal energy sources [1]. Among ocean energy resources, wave source seems to be the most interesting. In this energy production circumstances, offshore power extraction is becoming more important, aiming at taking advantage of stronger climate conditions than onshore ones and at reducing the exploitation of lands that could be used for other fundamental human activities.

Floating offshore wind platforms are the most suitable option to exploit marine renewable energy sources [2]. Therefore, there is the necessity to deeply comprehend and model the environment in which they will operate. One of the principal problems that affects floating offshore wind turbines (FOWTs) is a challenge significant motions that could worsen the aerodynamic performance of the turbine and induce additional structural loadings. A possible solution to face this issue could see the structural loading absorbed by a wave energy converter (WEC), integrating it on the offshore wind structure. On the other hand, another solution sees the use of damping systems that passively disperse the energy induced by the waves and improve the stability of the overall platform. The first solution would actively reduce the offshore floater motions, increasing the power production of the whole platform. Furthermore, the WEC integration would provide other improvement, such as the electrical grid connections and the mooring systems, the possibility to share the infrastructure between the two energy technologies and finally reducing the overall costs of the energy platform. It is also important to highlight that the integration of wind and wave technologies into hybrid offshore platforms has been hypothesized in several scientific publications, lately.

Muliawan et al. [3] proved the benefits on the energy production and on the total capital costs provided by the installation of an axi-symmetric WEC on a floating wind turbine. This approach leaded also to the registration of a patent for the Spar Torus Combination (STC) WEC [4].

Then, Peiffer and Roddier [5] provided a precise description of experimental tests and numerical modelling regarding the hybrid platform composed by the Wind Float structure and an Oscillating Wave Surge Converter (OWSC)

Furthermore, Karimirad et al. [6] carried on a feasibility study about the integration of a spar-type OWT and a WEC, taking inspiration from two real systems, respectively Hywind and Wavestar. Finally, Ding et al. [7] and Perez-Collazo [8] provided outlines about possible wave-wind operational solutions, highlighting the need for special design requirements but also the significant benefits provided by hybrid platforms.

This paper proposes a new way to stabilize wind platforms by the installation of gyroscopic harvesting. Benefits on the produced power and the reduction of the floater motion are demonstrated. The paper is organized as follows: Section 2 Material and Methods describes all the subsystems composing the whole offshore energy platform, entering in details of each subsystem function and the chosen simulation site. Section 3 Results shows the most interesting results obtained and the Conclusion close the work.

2. MATERIAL AND METHODS

The principal goal of this paper is to study a suitable system of a hybrid offshore energy platform, composed of a Floating Offshore Wind Turbine (F.O.W.T.) and a Wave Energy Converter (W.E.C.). The system can be related to a model that is exploited to simulate different environmental conditions, obtaining as outputs the energy production of the hybrid platform. Furthermore, the possibility to simulate also the single parts, wind or wave ones, allows to investigate the characteristics of each technology involved and the advantages (or drawbacks) caused by the hybrid coupling.

The whole platform is made of the following subsystems:

1. Fincantieri Sea Flower floater
2. NREL 5-MW wind turbine
3. Omnidirectional Mooring system
4. Gyroscopic conversion

2.1 – The Sea Flower floater hydrodynamic model

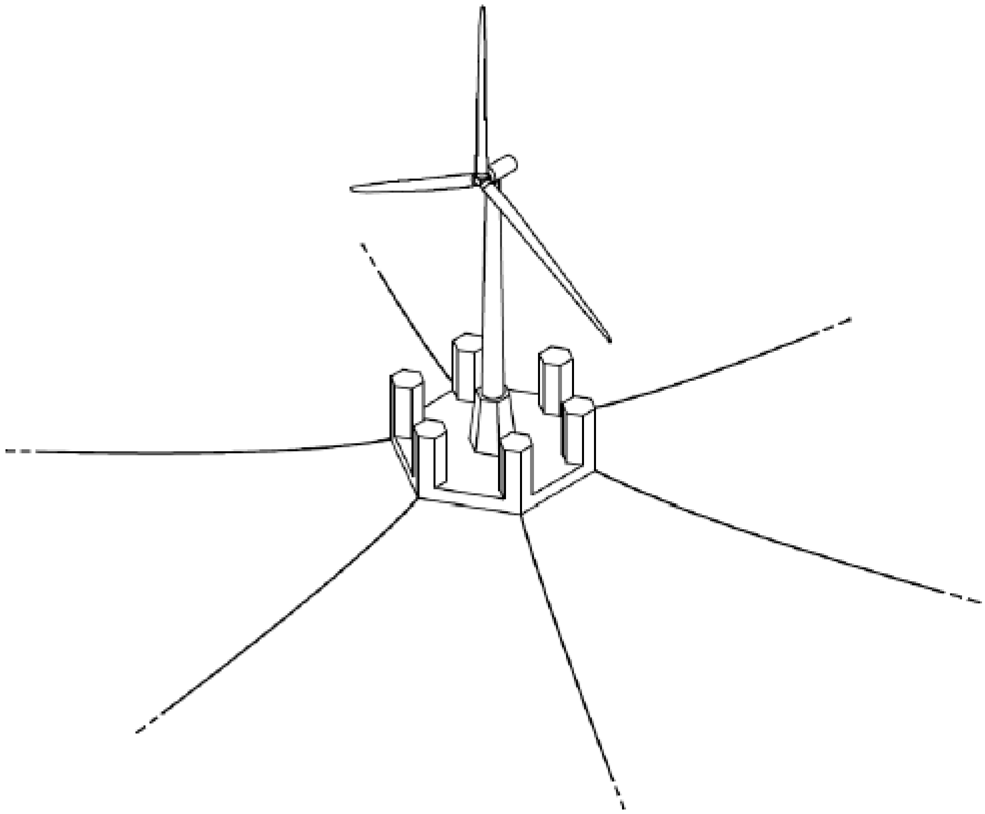

Fig 1. The Sea Flower architecture.

The "Sea Flower" floater, designed by Fincantieri shown in Figure 1, consists of a "hexagonal submerged platform acting as main buoyant body and damper, and six semi-submerged columns at the corners, that fulfil the static and dynamic lateral stability requirements while ensuring high transparency to wave motions". [9] As far as the analysis of floating bodies' movements is concerned, the main issue is represented by the approximation degree chosen for the model that could describe the system. Potential flow models used in this study, also known as Boundary Element Methods (BEM) define the velocity field as the gradient of the velocity potential. The linear potential flow models are the most suitable due to their numerical accuracy and efficiency. Furthermore, ANSYS Aqwa commercial software package [10] is used. Aqwa implements numerically linear BEM exploiting the panel method, which represents the structure surfaces through diffraction panels, in order to determine the physical parameters of floating bodies.

2.2 - Wind turbine

The wind turbine installed on Sea Flower is the NREL offshore 5-MW baseline wind turbine [11]. It is developed and standardized by the Wind Department of the National Renewable Energy Laboratory of the U.S. Department of Energy, and it is fully coupled to the floater, since Sea Flower is designed for a turbine of 5 MW nominal power. The main aspects of the turbine are described by focusing on the aerodynamic forces, the control system.

2.2.1 - Aerodynamic forces

The steady Blade Element Momentum theory, that is the most used method to calculate the velocities and the loads acting on a wind turbine rotor for any set of wind speed, rotor speed and pitch angle, is applied in this work. It has been developed in 1935 by Glauert [12] and it originates from the union of two theories:

- the rotor acts as an actuator disc (momentum theory) removing kinetic energy from the wind and thus gradually slowing down the stream, making the streamlines diverge.
- Blades are divided into small elements represented by 2D air foils which are only subject to local physical events (blade element model); therefore all the blade sections are independent and any span wise evolution is neglected.

However, many limitations affect the simple Blade Element Momentum model. To overcome some of them, the corrections regarding Skewed and Glauert models are implemented.

2.2.2 - Control System

The control system selected for the wind turbine is a conventional one, characterized by a variable pitch-to-feather configuration, variable-speed, and composed by two independent control systems, that are the controller of the generator torque, which has the aim of maximizing the power production under the nominal point; and a full-span rotor-collective blade-pitch controller, designed to adjust the speed of the generator above the nominal point.

Specifically, the rated (or nominal) point is the reference operational point in which the power conversion is maximized, towards which the control system tends to. Table 1 summarizes the main characteristics of the control system.

Tab 1. Drivetrain and generator specifications.

Rated wind speed	11.4 m/s
Rated rotor speed	12.1 rpm
Rated generator speed	1173.7 rpm
Rated generator torque	43094 Nm
Rated mechanical power	5.30 MW
Rated electric power	5 MW

2.3 - Moorings

The installation of the mooring systems for floating offshore platforms are planned to improve the overall rotational stability of the platform and to minimize drifts under the actions of wave, wind, and current. In this paper the omni-directional mooring solution is proposed. It is made of six pre-tensioned lines starting from each vertex of the floater, uniformly irradiated in 360° in order to maintain its position. To provide good stiffness and light lines at the same time, each line is composed of three parts: starting from the anchor on the seabed, the segments are metal chain, polyester rope and metal chain, with the rope being by far the longest part.

Since a catenary mooring line is a complex system and a complete model based on it would be significantly time-consuming, the following assumptions were made about moorings:

- the model of the catenary system is quasi-static, hence dynamic actions and inertia are neglected and the only effect is weight of mass
- all kinds of damping sources are neglected, e.g. frictions at connection points, at ropes inner, with seabed and hydrodynamic resistances as well
- the chains are approximated as continuous bodies
- the ropes of polyester have an elastic behaviour only
- the supports on which the lines are attached to the floater are dimensionless and they are positioned at each of the external vertex of the hexagonal base of the floater
- the mooring lines are directly connected to the platform and the anchors
- all the mooring lines are assumed to be rectilinear in every instant of the computational time. This is justified through the following annotations:
    - the rope part of the line is predominant in length and kept in tension by the two chain sections, stiffer and heavier;
    - the catenary curves formed by the three segments are close to linearity, since the angle between the lines and seabed is very low;
    - in typical floater motions, the lines do not vary significantly their configuration, due to their large length.

Figure 2 shows the 200 m depth arrangement mooring, with the rectilinear mooring represented by the continuous line and the dashed line that indicates the catenary mooring; moreover, single lines are the rope parts, double lines are the chain sections. The dashed lines are the vertical projections of the platform and of the lines on the seabed plane. These assumptions allow to approximate the whole mooring line as a single spring, fixed at the seabed to the anchor and connected at its top to the moving floater.

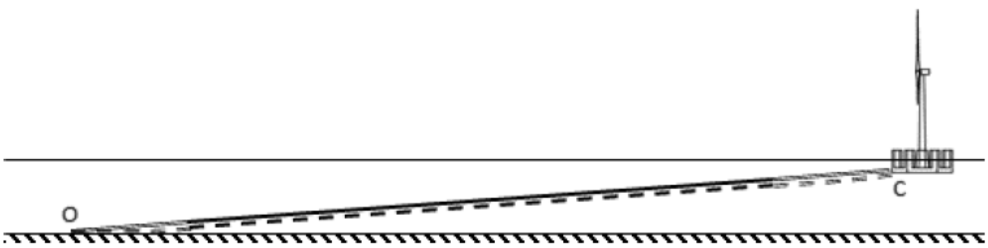

Fig 2. 200 m depth mooring.

2.4 - Gyroscopic harvester

In figure 3 the gyroscopic harvester is shown. It is based on the Inertial Sea Wave Energy Converter (ISWEC) that is a gyroscopic device allowing the conversion of wave power into electrical power. Its main system is a floating body slack moored to the seabed.

This system is composed of a spinning flywheel, located on a platform that allows its rotation. The gyroscopic effects result into a torque along the ε coordinate, because it is caused by the flywheel spinning velocity $\dot{\varphi}$ and the rocking velocity $\dot{\delta}$ induced by the waves,. This torque can be finally used to drive an electrical generator (also referred as PTO, Power Take

Off), in order to allow the extraction of energy from the waves. Figure 3 shows ISWEC working principle.

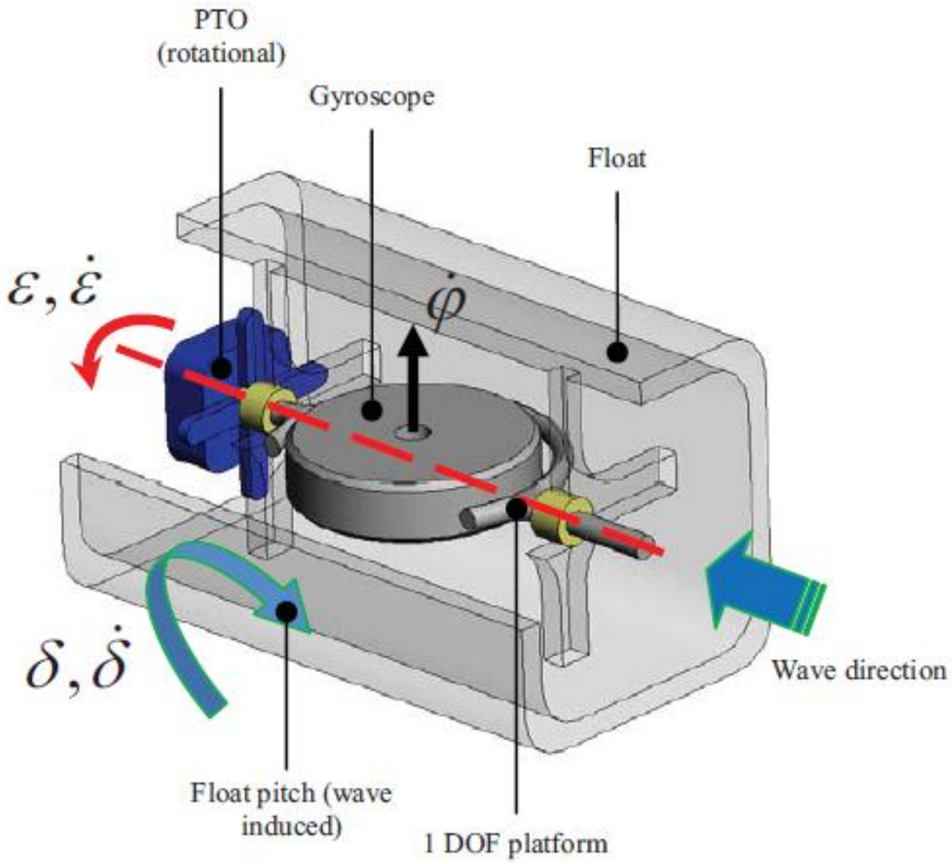

Fig 3. ISWEC gyroscopic harvester.

In this system a predesigned gyro unit is used and it is replicated in order to understand the effect of an equivalent bigger gyroscopic system and PTO on the floating structure. Increasing the number of units the effect on the floater increases too. Once understood the correct angular momentum needed, a proper design of the gyro can be performed, but it is out of the scope of the present paper.

2.4.1 – Extractable power

It is possible to obtain the equations describing the dynamics of the PTO from the time-derivation of the flywheel angular momentum. For reducing the complexity of the study, the problem is simplified to a planar form, with the work plane defined by the vertical gravity axis and the direction of the incoming wave. Thanks to its mooring configuration, this hypothesis is possible since the system, is self-orientating. The dynamical equilibrium of the PTO axis can be written as:

$$T_\varepsilon = I_g \ddot{\varepsilon} + \left(I_g - J_g\right)\dot{\delta}^2 \sin\varepsilon\cos\varepsilon - J_g\dot{\varphi}\dot{\delta}\cos\varepsilon \qquad (2.16)$$

For our purposes, the gyroscope inertial torque equation related to the pitching axis is also needed:

$$T_\delta = \left(J_g \sin^2\varepsilon + I_g\cos^2\varepsilon\right)\ddot{\delta} + J_g\ddot{\varphi}\sin\varepsilon + J_g\dot{\varphi}\dot{\varepsilon}\cos\varepsilon + 2\left(J_g - I_g\right)\dot{\delta}\dot{\varepsilon}\sin\varepsilon\cos\varepsilon \qquad (2.17)$$

where J_g is the inertia of the gyroscope around its spinning axis u and I_g is the inertia around the other two axis.
As [19] demonstrates, the maximum extractable power is reached when wave frequency and natural frequency are equal. Therefore, having the control of PTO with the aim of making the device resonating with the wave, the following expression can be obtained:

$$P_d = \frac{(J\dot{\varphi}\omega\delta_0)^2}{2c} \qquad (2.18)$$

In which:

- P_d is the average power absorbed from the system through the damper.
- $\dot{\phi}$ is the constant angular velocity of the flywheel around axis z_1 (therefore $J\dot{\phi}$ is the angular momentum of the gyro).
- ω is the wave frequency.
- δ_0 is the angle of pitching
- J is the moment of inertia of the flywheel around its spinning axis z_1.

- c is the damping factor.

Following a linear approach, with the aim of increase the extracted power of a wave resonating ISWEC, some parameters could be increased:

- $J\dot{\varphi}$, angular momentum of the gyroscope
- δ_0, pitching amplitude of the floater

In addition to that, the device can produce more power if the incoming waves have a shorter period.

2.5 - Simulation site

In order to produce a plausible analysis, a specific existent site was chosen: 61.37°N, 0.67°W, near the Shetland Islands in the North Sea, an archipelago belonging to Scotland shown in Figure 4. The bathymetry at the location is 210 m. The wave conditions and mean wind speed occurrences make this site very attractive from both wind turbine and wave energy converters points of view.

Fig 4. Reference site, North-East of the Shetland Islands in the North Sea.

The top 90% of all the occurrences of waves and winds in that site can be summarized clearly in Figure 5.

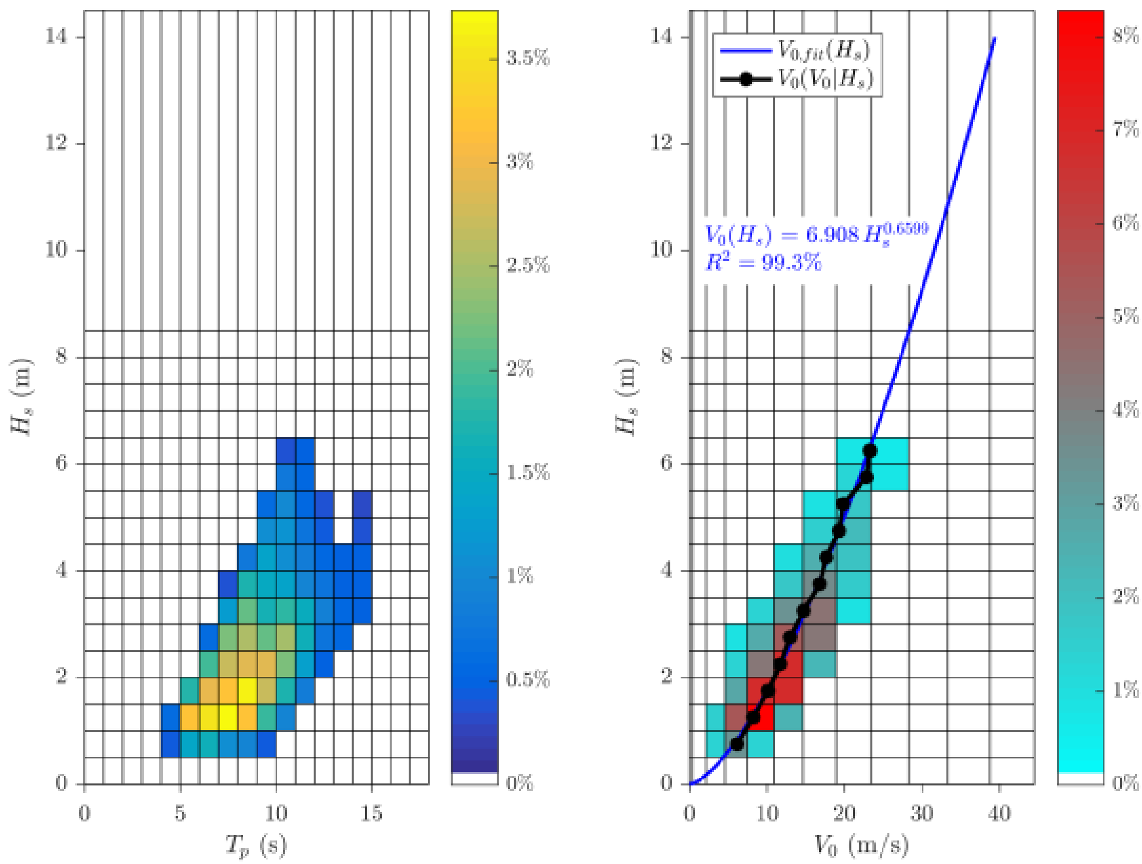

Fig 5. Hs, Tp scatter (left); Hs, V0 scatter (right).

On the left the 72 sea states considered in our simulations are shown, and on the right the cross-correlation between the significant wave amplitude of the chosen sea state and the correspondent mean wind speed is given. The most frequent wave conditions in the chosen site are described by the values of Hs = 1.25 m, Tp = 7.5 s. The five representative mean wind speeds are summarized in Table 2. These speeds are logarithmically spaced between the minimum (null) and the maximum value, which is 25.84 m/s and that, according to the correlation of Fig. 5 (right) between V0 and Hs, corresponds to the maximum simulated value of the significant wave height of the sea state, i.e. 6.25 m.

Table 2. Selected mean wind speeds.

Mean wind speed [m/s]
0
3.40
6.17
12.99
25.84

3. RESULTS

In a first moment, the most evident effect provided by the gyroscope system installation on the offshore wind platform is the stabilization of the floater itself. The common wave conditions with wind speed equal to roughly 13 m/s also show the maximum pitch abatement with a reduction of -37%, with respect to the configuration without gyroscopes.

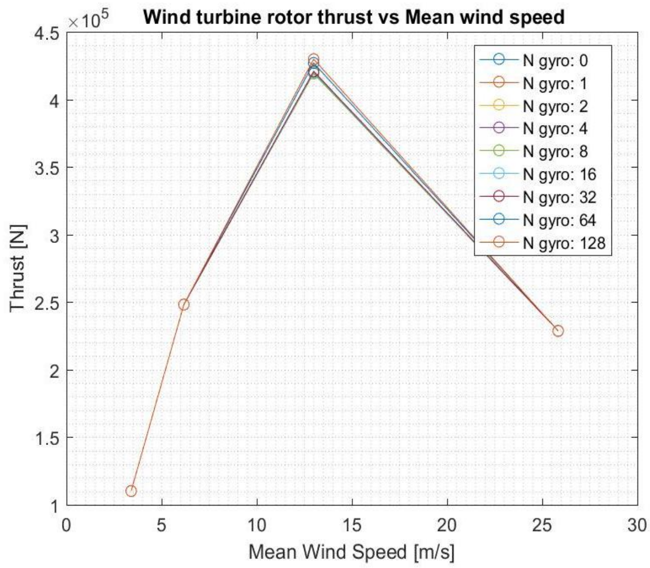

Fig 6. Wind turbine thrust vs mean wind speed.

The installation of the gyroscope PTO on the offshore wind turbine shows another advantage: a significant increase of the electric power produced by the whole platform summing both the wind turbine and the gyroscope produced powers, with respect to the configuration without WEC. When the mean wind speed is lower, and consequently the wind turbine power is lower, the contribution of the gyroscope system to the overall power production is significant, as it can lead to an increase of double power with respect to the no-gyro configuration. Nevertheless, as the mean wind speed increases, this influence decreases because the wind turbine electric production increases significantly, reaching a value of an order of magnitude higher than the one of the gyroscope produced power.

Then, significantly interesting are the scatter maps related to the produced powers, by both the wind turbine and the gyroscope PTO and also the overall one, for each simulated sea state. Since the mean wind speeds considered are the five given in Table 2, for each sea state the correspondent mean wind speed is obtained through the correlation shown in Figure 5 - right, and then a linear interpolation is done among the five wind speeds available results.

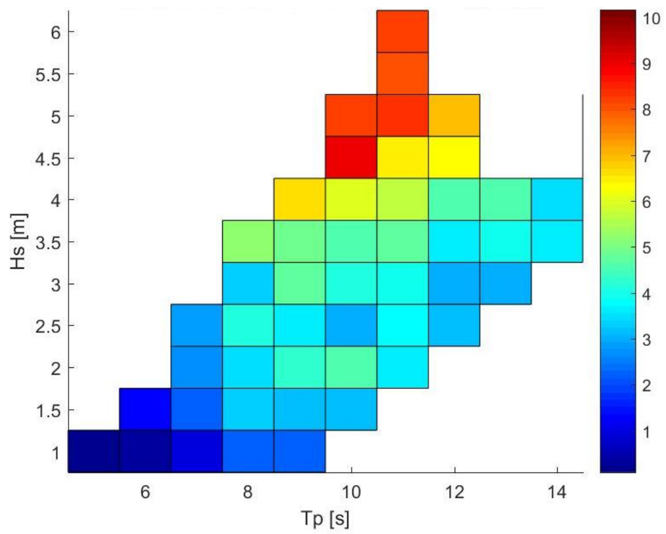

Fig 7. Percentage difference between the power produced by the whole offshore platform and the wind turbine one.

The power production variation of the whole platform, with 128 gyroscopes installed, with respect to the no-gyro configuration, is shown in Figure 7. It is possible to notice that in every sea state a positive effect is given by the gyroscopes installation, from a minimum of roughly +1% to a maximum of +10%. It causes, on an yearly basis, to the improvement of the whole platform productivity, corresponding to an increase of 4.28%.

4. CONCLUSIONS

Stated that numerical models are central in the future development of new energy technologies, this study aims at being a further step into marine offshore technology growth and future application, since electric energy production will likely become a more and more challenging issue as time goes by and as human population increases.

The main goal of this work was the study of the installation of floating offshore wind turbine, integrating a gyroscope system. This objective has been achieved, since the gyroscope integrated model showed interesting and consistent results, for a wide range of wind and wave conditions.

This work give a first assessment of the power produced by the Seaflower platform equipped with gyroscopic systems. Further work can regard the economic analysis of the proposed together with engineering to embed the gyros in the platform. Moreover the hydrodynamic properties of the platform can be adjusted to optimize the combined energy production and the cost of energy. It would be also interesting to evaluate the system performances in other sites to assess the project replicability.

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