DESIGN OF A FLOATING PLATFORM FOR AN INNOVATIVE DUCTED WIND TURBINE

Luana Gurnari, Pasquale Filianoti, Claudio De Capua, Damiano Alizzio, Valerio Scordamaglia, Filippo Ruffa, Gaetano Fulco,
Maria Carla Lugarà, Università Mediterranea di Reggio Calabria, ITALY, luana.gurnari@unirc.it, filianoti@unirc.it,
decapua@unirc.it, damiano.alizzio@unirc.it, valerio.scordamaglia@unirc.it, filippo.ruffa@unirc.it, gaetano.fulco@unirc.it,
mariacarla.lugara@unirc.it
Sergio Mario Camporeale, Marco Torresi, Politecnico di Bari, ITALY, camporeale@poliba.it, marco.torresi@poliba.it

ABSTRACT

This paper analyses the dynamics loads exerted by waves on a floating offshore platform in the Straits of Messina, (South of Italy), hosting an innovative ducted wind turbine. The force exerted by largest sea waves occurring during lifetime on the floating platform are predicted by the quasi-determinism theory, which foresees what happens if a group of waves of exceptionally large height occurs at a given point in the sea.

INTRODUCTION

Offshore wind energy has a greater potential in respect to the inland installations, because wind speed is generally much higher offshore than in the inlands. Among offshore installations, floating plants are more competitive than fixed-bottom installations, because the latter are generally installed in shallow water, while the floating ones can be used in deep water and, according to Jonkman 2007, the ideal wind energy sites are those where the water depth far exceeds 50 m. Several authors (Trubat et al., 2020, Liu et al., 2016, Chodnekar et al., 2015, Shin et al., 2013) have studied the effects of the floating platform motion on the aerodynamics of a wind turbine.

The realization of this technological demonstrator, is funded by the Marine Energy Lab (MEL), whose mission is to carry out field experiments on small scale physical models of renewable energy conversion system in marine environment. The novelty of this prototype is the presence of a diffuser enabling the realization of smaller rotors, with the same rated power, favoring the rotor rigidity and reducing the blades deformation. The floating platform will be placed in the water sheet in front of the MEL laboratory (see Fig. 1), in the Straits of Messina (Southern Italy), anchored at 20 m of bottom depth through mooring lines.

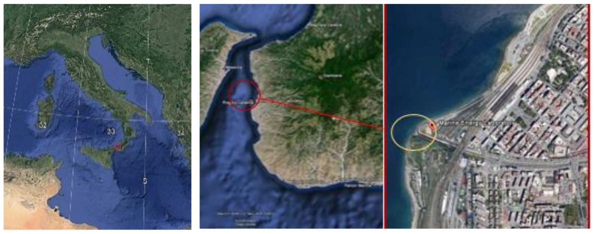

Figure 1 – Location of the offshore platform (shown, from left to right, Italy, the Straits of Messina and, finally, the installation site in Reggio Calabria).

The wave loads on the immersed surface of the floating platform together with the wind forces acting on the superstructure are transmitted to the anchors by mooring lines. We provide a criterion to evaluate the dynamics of maximum force exerted by freak waves in a random sea state, by using the quasi-determinism theory (Boccotti, 2015), which permits us to evaluate the highest mooring line tension occurring in the cable attached to the exterior leading columns (columns 2 in Fig.4).

THE DESING WAVE

The prototype of the platform is suited to be installed in the Mediterranean Sea, in the Straits of Messina, in (Southern Italy). According to the design rules of maritime structures, both costal and offshore structures have to withstand a design sea state that has a relatively high encounter probability, during their lifetime with a certain safety level.

Considering a lifetime L=25 years, and an encounter probability P=0.15, the design return period is R=150 years and the corresponding significant wave height is H_S=0.8 m with a peak period T_p=3.8 s. They are reasonable values for the considered area, because of the very limited length of the fetch (about ten kilometers).

WAVE FORCE PREDICTION

The flow around a circular cylinder depends on Reynolds and Keulegan-Carpenter numbers. As reported in Sumer and Fredsoe (1997), Reynolds number, Re, concerns the presence of the flow separation and formation of vortex; in detail, the more Re increases the more the flow become turbulent with the complete formation of vortex shedding around a circular cylinder in a steady current. In the case in which the cylinder is exposed to an oscillatory flow, a small Keulegan-Carpenter number, KC, means that the orbital motion of the water particle is small in respect to the characteristic dimension of the body and no separation flow occurs. On the contrary, very large values ok KC mean that occurs flow separation and probably vortex shedding. Considering a slender solid body subjected to an oscillating flow, the force per unit length acting on it in the inline direction can be estimated by (Sumer and Fredsoe, 1997):

$$F_{sect} = \frac{1}{2}\rho C_D |u_{\text{sect}}| u_{\text{sect}} + \rho \frac{\pi D^2}{4} C_M a_{\text{sect}}, \qquad (1)$$

where u_{sect} and a_{sect} are respectively the velocity vector and acceleration vector normal to the longitudinal axis of the considered cylinder, and C_D and C_M represent the time-invariant drag and added mass coefficients.

Equation (1) is valid since the structure is a small body as the inertia and drag force contributions is valid for Keulegan-Carpenter numbers larger than a critical threshold (Boccotti, 1993).

The forces on the floating body is calculated by means of the quasi-determinism theory (Boccotti, 2000), which predicts the time history of the loads produced by a wave group hitting the center of the structure.

More in detail, if occurs, at a fixed point of the flow field, a wave with an exceptionally large wave height in respect to the mean wave height in that given point, the quasi-determinism theory affirms that a group of waves travels through this point and the very exceptionally large wave occupies the central wave of the group. Under this condition, the free surface displacement is shown in Figure

2, and it is formed by two component, a deterministic one and a residual random component, in which the deterministic part can be describe by Eq. 10.2a in Boccotti, 2000.

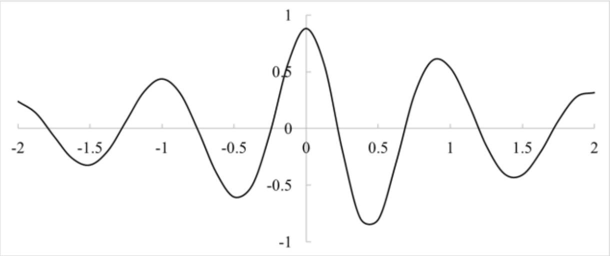

Figure 2 – Surface elevation evaluated by means of the quasi-determinism theory.

For a field of wind-generated waves, the velocity and acceleration in the Morrison formula were obtained from the velocity potential of the quasi-determinism theory,(see Boccotti, 2000, Eq. 10.2b and 10.3a-g), neglecting the wave diffraction produced by the platform beams and columns.

THE PROTOTYPE

As previously described, the MEL project has the ambitious goals aiming to develop an innovative offshore wind turbine . As reported by Torresi et al. (2016), ducted wind turbines can take advantage of the flow rate increase because of the effect of the presence of the divergent shroud, reducing blade deformations, and increasing rotation speed in respect to conventional turbines (Demelio et al., 2022).

The 3D model of the platform and the whole system platform-wind turbine is shown in Figure 3.

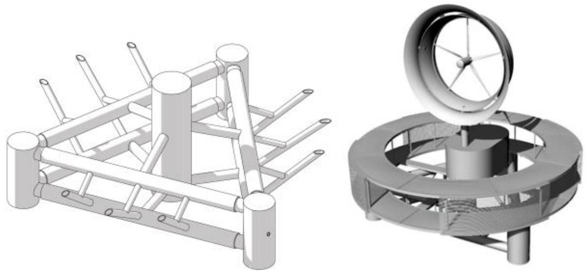

Figure 3 – 3D modeling of the offshore platform (on the right the platform equipped by the wind turbine).

As shown in Figure 4, it is formed by a central column, (named in the follow cylinder 1), with 2 m diameter and three external cylinders (named 2), with 1.6m of diameter. The latters, form the vertex of an equilateral triangle inscribed in an ideal circle of 7.5m of radius. They are linked by three horizontal beams, each formed by a couple of cylinders with 0.8 m of diameter, three of which rest above the sea level and three are submerged, (named cylinder 3). The evaluation of the extreme horizontal force, exerted by irregular waves, has been conduit also on the 45° inclined web members supporting the deck, having 0.3m diameter.

In order to establish the flow regime and the applicability of Eq. (1), the critical value of KC was calculated. If the KC is lower than the KC critical, the flow can be considered ideal, conversely if KC exceeds the KC critical, the flow must be considered real. According to Sarpkaya and Isaacson (1981) the value of KC critical is equal to 6, and Boccotti (1996) found that the flow around a cylinder remains ideal until KC is lower than 5. In the present case, the minimum value of KC is 8.45, and then it confirms the real flow conditions and, consequently, the applicability of the Morrison's Equation. Furthermore, considering the experimental abaci in Sarpkaya and Isaacson (1981), C_D and C_M coefficient can be assumed equal to 1.4 and 2, respectively.

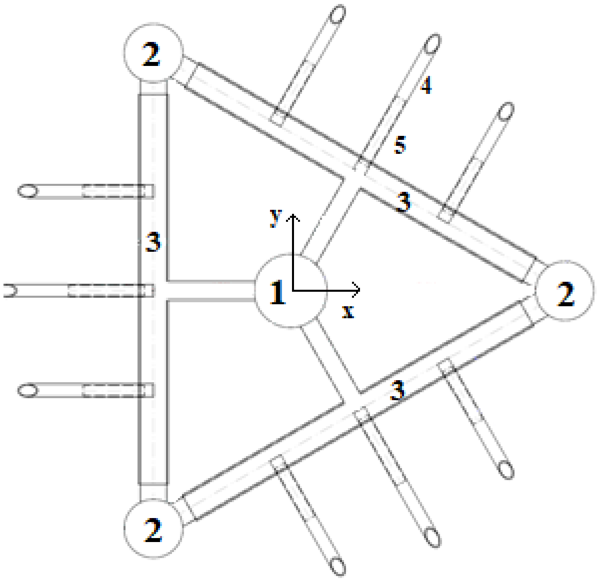

Figure 4 – Sketch of the offshore platform with the indication of the cylinders where the forces are evaluated. Mooring lines are joined to columns 2.

RESULTS

Assuming the mean Jonswap-Mitsuyasu spectrum with mean spectral direction θ, parallel to x-axis (see Fig. 4), we obtain the inline wave force for each structural element of the platform, as shown in Figs.5-7. The calculation must be repeated for several values of θ, ranging in the interval [0, 45°], because of the three lines of symmetry of the triangle.

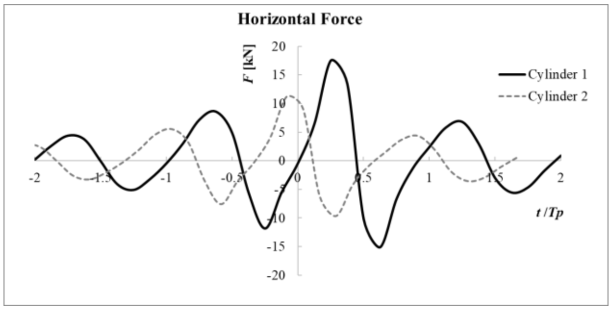

Figure 5 – Horizontal wave force exerted on the cylinder 1 and one of the three cylinder 2.

Table 1 exhibits the maximum of the horizontal forces acting on each element of the platform. The direction of horizontal force is parallel to *x*-axis for cylinders 1, 2 and 3, and it is normal to the direction of sides 3(b) and 3(c) of the triangle.

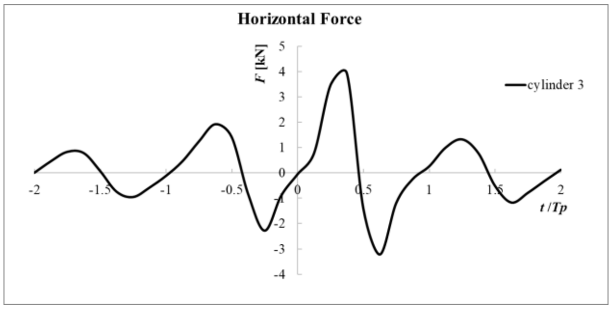

Figure 7 – Horizontal wave force exerted on the cylinder 3 (*x*-direction).

Table 1: Wave forces on the offshore platform elements.

Platform elements	F_{max} [kN]
Cylinder 1	17.5
Cylinder 2	10.5
Cylinder 3(a)(b)(c)	38.5
Cylinder 4 (45°N CW)	0.4
Cylinder 5 (45°N CCW)	0.36

Adding the contributions along x and y-axes respectively, of each element, we obtain the horizontal force acting on the overall platform and its direction, which in the present case is along the *x* -axis. Figure 8 shows the total horizontal force acting on the platform. Its maximum value is about equal to 62 kN. Values of force showed in Fig. 8 are transmitted by mooring lines to anchors taking in account the mooring pattern.

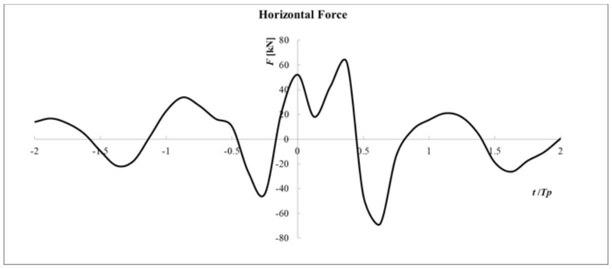

Figure 8 – Total horizontal wave force exerted by waves on the overall platform.

CONCLUSIONS

The paper proposes a new approach to calculate the wave force on a floating platform hosting a wind turbine. The calculation is useful to check the capability of the structure to withstand to the most severe storm in its lifetime, recurring to the quasi-determinism theory to calculate particle velocity and acceleration of random sea during the occurrence of a wave of exceptionally large height, in respect to the mean wave height of the sea state. Velocity and acceleration are put in the Morison's equation, neglecting wave diffraction effects produced by the elements of the platform. The theory allows to know the wave mechanics both in the 3D space and in the time domains. Therefore, the forces on the submerged frame of the platform are calculated, considering the actual position of each element. The present study is focused on the horizontal wave force. The same analysis can be carried out for the vertical wave force, achieving the knowledge of the time history of the overall wave force. The latter, in conjunction with wind action on the superstructure, permits us to evaluate the dynamics of the platform (i.e. pitch, heave and roll) and how its movements affects the turbine operational both in term of structural safety and energy production.

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