E3S Web of Conferences **573**, 03011 (2024) https://doi.org/10.1051/e3sconf/202457303011
SDER 2024

Design Design and Discussion of Offshore Floating Platforms for Wind Turbines

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Abstract. Alongside the development of human civilisations over the last century, the global demand and consumption of fossil fuels have experienced a significant increase. Consequently, environmentally friendly and sustainable designs are in high demand in every professional field. This report focuses on two designs of floating wind turbine platforms as well as related professional discussions in the field of fluid mechanics.

1. Introduction

The consumption of fossil fuels has been increasing since the completion of the first industrial revolution in 1840. In particular, evidence shows an exponential increase in the consumption of fossil fuels in the century [1]. One of the main consequences of the sharp rise in fossil fuel consumption is the emission of greenhouse gases which result in detrimental greenhouse effects.

With this in mind, designs for generating clean and renewable energy have become essential to the contemporary world. Wind turbine fields are one of the most widely used clean energy generating systems and are commonly built on flat areas with high wind velocity. However, these large areas of flat ground are normally near deserts and far from urban areas, so the transportation of clean electricity presents a serious problem due to energy loss during transportation, although it is possible to increase the voltage to mitigate the loss.

Meanwhile, most coastal cities are more developed, which indicates a high demand for electricity. Therefore, the construction of wind turbines in the oceans becomes important. Additionally, much of this vast deep-water wind resource resides in waters deeper than 60 m where current fixed bottom wind turbine technology is not economically viable [2]; to combat this, the floating wind turbine has been designed.

In this design field, there area number of sophisticated reports and books that are accessible online. Uncountable professional articles are focused on the design of wind turbines such as the static and dynamic load analysis, coupled dynamic modelling and controls on pitch damping [3]. Nevertheless, there are only a few articles introducing the platform design of floating wind turbines. This paucity of research indicates a gap between the existing knowledge and the behaviour of the fundamental shapes of different floating turbine platforms; this is important because different platform materials and shapes lead to different dynamic motions of the turbine in practice.

2. Principle Design

Two designs of floating wind turbines, the cylindrical design and the three-legged design, are introduced in this section. The model of the blades of the wind turbine is not built in both designs because of the small cross-sectional area but the blades for both designs are designed with a length of 18 m and are not ignored in further calculations and analysis. Every connection between each element of the wind turbines is assumed as fixed.

Moreover, inside stairways, as well as the electricity generator innacelles, are not included in the models. The cylinders of the floating platforms are not strictly hollow as there is an interior design using carbon fibre to avoid bending of the top surface of the cylinders. The structure of this interior design is shown in Figure 1. The thickness of all elements here is 50 mm. This interior design is only applied to the platform section of the designs, which is the structure below the turbine tower. Different dimensions are applied to cylinders in both designs.

The name ‘cylindrical’ is given to this design due to the shape of the floating platform which is comprised of two hollow cylinders with different radii (as shown in Figure 2). This cylindrical shape of the platform is designed due to the consideration of the imposed lateral moments by ocean currents, which can also be called the yaw of the model. The larger cylinder at the bottom is 10 m, with a radius of 5 m whilst the smaller cylinder is 5 m high with a radius of 3 m. There is also a connection with a height of 3 m between the upper cylinder and lower cylinder. The radius of the connection is the same as the radius of the tower, which is 1.5 m. The height of the tower is measured from the top of the smaller cylinder to the

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bottom of the nacelle, which is designed to be 30 m. The nacelle is the horizontally placed cylinder at the top of the model, which is 9 m wide, with a 2 mradius.

Fig. 1. Interior Design

The entire design was made of carbon fibre AS4C 3000. A 50 mm thick hollow cylinder covered the entire wind turbine. The tower is kept hollow because the stairs are essential; the nacelle is also kept hollow as the electricity generating system needs to be placed in the nacelle. For the platform part of this design, foams are filled inside the carbon fibre shell. In addition, three steel cables are designed to connect the bottom of the platform and seabed so that the design can be restricted to six degrees of freedom Elements in the design are considered as a whole in further analysis.

The three-legged design can be regarded as a new version of the cylindrical design that is illustrated in the previous subsection but the platform in this design is comprised of three ‘legs’ instead of two large cylinders (as shown in Figure 3). The three-leg design is considered as it may have more resistance to the pitch and roll in the six degrees of freedom. In this design, the dimensions of the nacelle and tower are the same as in the first design. Three sloped cylinders inclined 45 degrees to the horizon have a length of 5 m and a radius of 1 m and the vertically placed cylinders that are connected to the sloped cylinder are 8 m in length with the same radius.

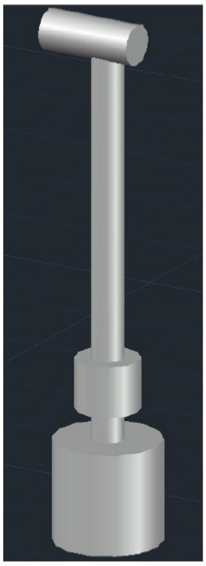

Fig. 2. Cylindrical

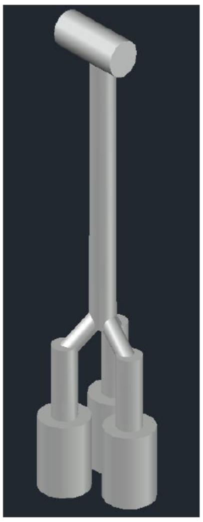

Fig. 3. Three-Legged

Lastly, three cylinders at the bottom have a length of 8 m and a radius of 2 m. The materialselection is the same as the cylindrical design, which is 50 mm thick AS4C 3000 carbon fibre. The tower and nacelle are kept hollow and three ‘legs’ are filled by foams. Three steel cables are connected to the bottom of each large cylinder to restrict the wind turbine in a small area and resist overturning. Elements in the design are considered as a whole in further analysis.

3. Assumptions

Assumptions are made before carrying out further analysis and are listed below:

- The seawater density, air density and gravitational acceleration are constant with the value of 1.05×10^3 Kg/m^3, 1.225Kg/m^3, 9.81m/s^2 respectively.
- The wind velocity and its direction are constant, and the load applied to the structure is uniformly distributed.
- The current and wave velocities and directions of the ocean are constant and their forces applied to the wind turbine are uniform.
- The structure only swings across the centre and the shear force is not considered.
- The wind load is acting at the top point of the wind turbine.

4. Results and Discussion

4.1. Calculations

The purpose of applying Archimedes’ Principle is to check whether the upthrust can support the self-weight of the wind turbines. The dimensions and materials of each element of the wind turbines are already illustrated, hence the self-weight is calculated at first. The density of AS4C 3000 carbon fibre is taken as 1.78×10^3 Kg/m^3 and its Poisson ratio is 0.06 in this design.

Due to the special interior design structure, the self- weight calculation is not simply calculating the hollow cylinders. The thickness should be considered. The final total volume of material of the cylindrical design is 64.96 m^3 ; of the three-legged design is 77.29 m^3 . The values of self-weight are also calculated, which is 1135 KN for cylindrical design and 1350 KN for three- legged design.

Secondly, the maximum volume of an immersed body is required to calculate the maximum upthrust force that the wind turbines can experience, which is the sum of three cylinders (approximately 948 m^3); the volume of the three-legged design is approximately equal to 896 m^3 . Therefore, the maximum upthrust of these designs can be calculated as 9765 KN and 9230 KN, respectively. The values of maximum upthrust are much larger than the self- weight of both designs, hence the wind turbines are feasible to work in practice.

The final purpose of the six degrees of freedom in this project is to determine the maximum angle the wind turbine can rotate without overturning. To calculate the angle, the position of the barycentre h_x of each cylinder element needs to be determined. Results can quickly be obtained as the dimensions are already introduced, which are 34.11 m from the top for the cylindrical design and 36.74 m for the three-legged design. Term h_b can be calculated by $h_b = h - h_x$. The maximum swing angle is therefore calculated as 15.61 degrees for the cylindrical design and 19.92 degrees for the three-legged design.

The wind velocity is an essential factor for the wind load calculation. Hence, the design wind velocity is taken at 15 m/s by using logarithmic theory. To analyse the maximum impact on the wind turbines, the wind load is uniformly applied to the entire structure of wind turbines, including platform structures. The value of the surface area needs to beat maxima to maximise the value of wind force as the value of wind force is proportional to the surface area. Take the cylindrical design for example (as shown in Figure 4), here F_1 is perpendicular to the lateral side of the nacelle and F_2 is perpendicular to the nacelle face. The surface area of elevation F_1 is larger than the elevation F_2 , so the surface area at F_1 elevation should be considered in load calculation. The maximum surface area of the cylindrical design is 265 m^3 and the three-legged maximum surface area is 369.1 m^3. The wind load is 37 KN for the cylindrical design and 51 KN for the three-legged design.

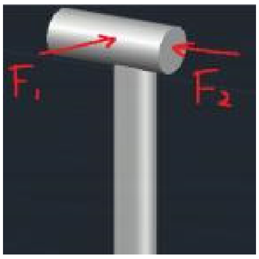

Fig. 4. Elevation identification

Thrust force is generated by the wind blades when the blades are rotating. The variable A in the thrust formula represents the area covered when the blades are swept. As introduced before, each blade has a length of 18 m, so the swept area is approximately 1018 m^3.

Moreover, according to the table of thrust coefficient with corresponding wind speed from literal [4], the thrust coefficient used for calculation is 0.186. Due to the same dimensions of blades for both designs, the thrust force in both designs is equivalent, which is approximately 26.1 KN. The direction of the thrust force is directly perpendicular to the nacelle, the same as the direction ofF_2 in Figure 4.

Wave force, the last force that is required, applies on the floating platforms. Before carrying out the calculation of the wave force, the wave speed should be calculated. According to the literature from UCLA [5], the wind wave in deep water has wavelengths up to 100 m. The wave speed is then calculated as 12.5 m/s. Additionally, the drag coefficient variable in the Morison equation needs to be determined. The table of drag coefficient in different shapes from W.E. Baker illustrates the drag coefficient of objects in different shapes [6]. In this design, the short cylinder shape with a coefficient of 1.15 is the most suitable one to use. The calculation of the cross-sectional area that the wave force is imposed on is assumed as the cross-sectional area of the entire platform section. The results of wave forces acting on the platforms are 13.1 MN for the cylindrical design and 12.4 MN for the three-legged design.

4.2. Discussions

The static stress analysis for both designs was carried out using SolidWorks. Computations of deflections caused by the imposed wind load and thrust are done. To obtain the maximum displacement, the wind load is applied to the F_1 side, as illustrated in Figure 4. Thrust, the force generated by the blades, is applied to the front surface of the nacelles (F_2 direction). The bottom of the design is fully restrained and every element is fixed together when carrying out the load analysis. Two load conditions are modelled and analysed separately.

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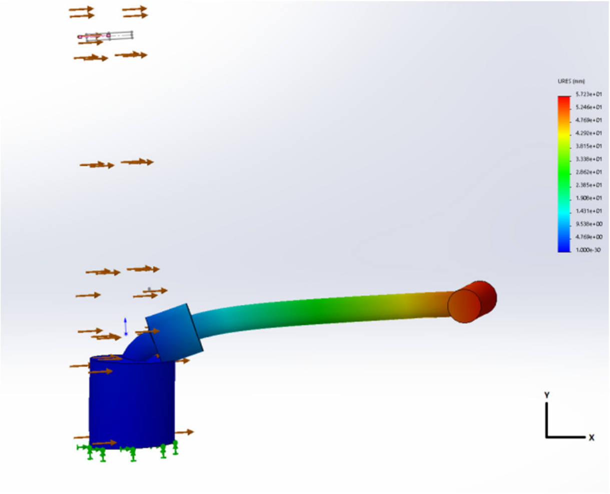

Fig. 5. Deflection of cylindrical design under wind load.

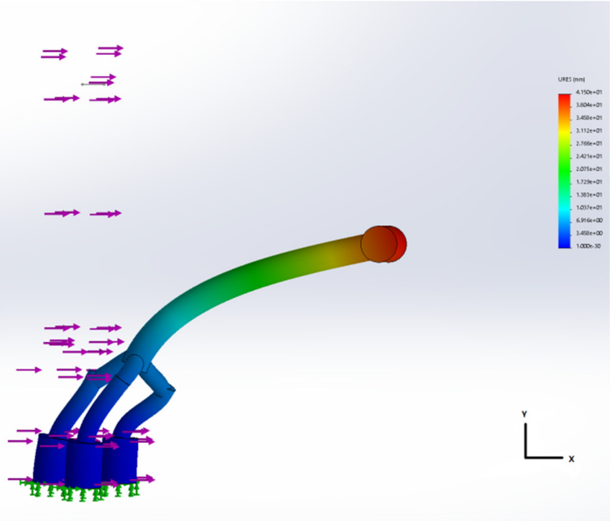

Fig. 6. Deflection of three-legged design under wind load.

Figures 5 and 6 above show the computational results of total displacement from SolidWorks. The deflection illustrated in the figure is exaggerated but it demonstrates where the wind turbine will deflect to. From the computational outcomes, the total deflection of the cylindrical design is 57 mm whilst the three-legged design is 41.5 mm.

Under the same conditions, the three-legged design has approximately 16 mm smaller deflection than the cylindrical design, which indicates that the three-legged design is able to take more lateral load than the cylindrical design. This property is due to the existence of the sloped cylinder designs. When the imposed wind load is applied to the turbine, stresses will push the structure along the x- axis. The stresses that pass through the sloped cylinder can be divided into two equivalent forces with a lateral force and a vertical force due to the 45° inclination angle. This special load transformation reduces the magnitude of lateral load into sin45° = 0.707 times of the original magnitude, which decreases the maximum displacement of the wind turbine. Returning to the computational results of the cylindrical design, the deflection becomes significant at the top of the biggest cylinder. The large dimension difference between the bottom cylinder and the connecting cylinder makes the difference in load bearing capacity huge. Therefore, a sharp deflection at the connecting cylinder is observed when a uniform wind load is applied.

With this comparison between the two designs under wind load in mind, the three-legged design performs better than the cylindrical design, mainly due to the special structure of its platform. However, the 57 mm displacement is not enough to reject the cylindrical design. To improve its behaviour, the carbon fibre with higher strength and rigidity can be used and carry out further analysis. Thrust computation is also implemented in SolidWorks with the same restrained place. Thrust is assumed as a constant force in static stress analysis. The numerical simulation outcomes are shown in Figure 7 and Figure 8, below.

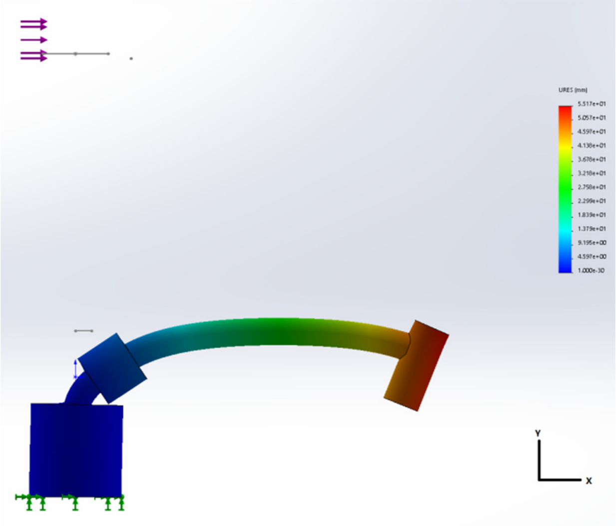

Fig. 7. Deflection of cylindrical design under thrust

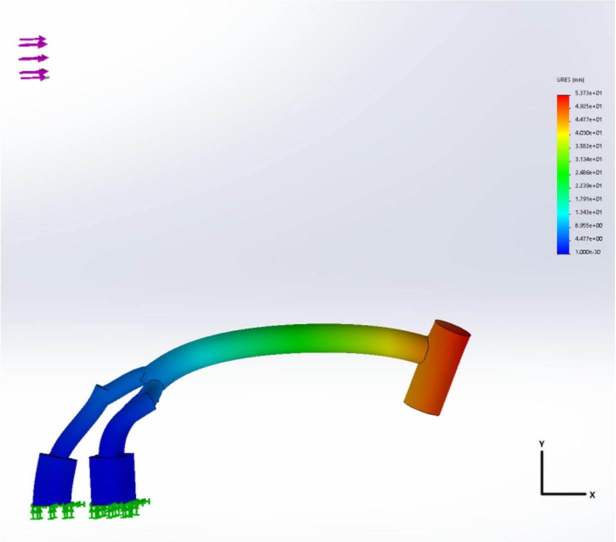

Fig. 8. Deflection of three-legged design under thrust

Both designs deflect along the x-axis under the thrust force acting at the nacelle surface. The computational outcomes indicate that the maximum displacement of the cylindrical design is approximately 55 mm whilst the three-legged design's deflection is 53.7 mm. Two deflections are almost the same, but the displacement of the three-legged design is slightly smaller than the cylindrical design because the load transformation process in "legs" can reduce the lateral load. Therefore, the performance of the three-legged design under thrust force is better than the cylindrical design. However, the displacement around 55 mm may still be large for the wind turbine although this design is aimed for operating in the ocean. Apart from changing the material, the reinforcement design applied to the platform can also improve the deflection.

The hexagon interior design which is introduced in previous sections is able to act as the interior reinforcement of the wind turbines. Additionally, the wind turbine is designed to float in the ocean; there are no pins or clamps to restrain the bottom of the platform. The entire structure will rotate when external forces are applied to the turbine, so the deflection of the turbine in practice will not be as large as the results shown by SolidWorks. The computational results indicate that the platform design of a wind turbine is critical, as it determines the performance of the entire wind turbine under external loads. After the analysis and comparison with two designs under two loading conditions, the deflection resistance property of the three-legged design performs better than the cylindrical design.

The cylindrical design has a maximum swing angle of 15.61 degrees compared to the three-legged design's 19.92 degrees. A larger swing angle indicates that the model can bear stronger external force. Hence, the three- legged design performs better than the cylindrical design in external force resistance. With regard to the determinant of calculating the angle degree in the methodology section, the maximum swing angle is affected by the layout of gravity of the design. This indicates that the dimensions of each cylinder is important. The cylindrical design has a lower swing angle, but its barycentre is 0.14 m lower than the three-legged design. Hence, only reducing the height of the design may not ensure stability in the design. In this case, the lower barycentre would be the best choice. The wider the bottom of the model, the lower the barycentre is. Consequently, the three-legged design gives a wider bottom compared to the cylindrical design. Moreover, the interior hexagon structure that occurs at the lower part of the model also lowers the barycentre.

Wave loads applied on the platform structure are obtained in the calculation section above, with 13.1 MN for the cylindrical design and 12.4 MN for the three-legged design. Moreover, when considering the wave force only, the displacement of the cylindrical design would be larger than the three-legged design as it receives approximately 1 MN more than the three-legged design. However, the analysing method for wave load is not the same as the previous method of analysing wind and thrust force effects because there are three cables connected to the bottom of the platform which restricts the turbine from floating away under external loads. Once the cable is in tension, the other parts of the turbine will not experience a deflection under wave load, instead, there is a risk of cables being yielded or even broken.

Therefore, the cable design becomes essential to balance the imposed wave load. There are two common materials used to make cables for floating wind turbines, which are nylon and steel. Nylon is not only cheaper than steel but also resistant to erosion caused by seawater. Thus, the maintenance tasks caused by rust issues are avoided if all the cables are made of nylon, which would save a huge amount of money. Furthermore, with regard to the shear forces, nylon is elastic and stretches up to 30% [7]. This property increases the safety factor of the wind turbine even in extreme weather. Hence, the design tension imposed on cables is multiplied by 5. The final diameter of the nylon cable is determined as 10 cm, which is too large to manufacture. Therefore, intertwined nylon cable is recommended, as it is cheaper and simpler to manufacture.

5.Conclusions

In conclusion, after carrying out the wind load and thrust analysis by computer-aided software, it is obvious that the external load resistance of the three-legged design performs better than the cylindrical design. The design material for both turbines is AS4C 3000 carbon fibre. Where the designs require more rigidity, solutions are discussed, for example, changing the design material to increase strength or designing tower reinforcements. The maximum angle of rotation of the cylindrical design is smaller than the three-legged design, which indicates that the cylindrical design is more likely to overturn than the three-legged design. Therefore, based on the theoretical results of the analysis carried out in this project, the three- legged design performs better in all covered aspects.

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