Analysis of Offshore Wind Turbine Towers with Different Designs by Finite Elements Method

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***Abstract*— It is known that the use of renewable energy has an increasing trend in whole world. Wind energy is one of the renewable energy types, as well is among the cleanest and most economical energy sources. Nowadays, in order to provide much more energy from wind, turbine towers are being built higher and the turbine blades have begun to be manufactured longer. Due to these applications, tower and turbine weights are continuously increasing. For this reason, it is necessary to optimize the materials used as well as the dimensions of the turbine towers. In the present study, behavior of TLP floating wind turbine towers with three different designs under wave, hydrostatic and static loads were investigated. In order to clarify the effect of these loads, turbine designs were analyzed in the ratio of 1/5 using finite elements method. Steel, reinforced concrete and hybrid (reinforced concrete and steel) wind turbine towers tied to sea floor at a depth of 10 meters rigidly by TLP floating method. In this context, 10-meter-high turbine towers having three different designs which static analyzed previously were used for investigate effects of wave and hydrostatic loads. Turbine structures analyzed with ABAQUS finite elements model. The deformations and stress values of underwater turbine structures were obtained and compared with each other. As it can be seen from analysis results, compared to the reinforced concrete design, the displacement of steel tower design decreased 77.84%. It is seen that the torsion effect was dominant in the steel tower design. However, the decreasing displacement value for steel design was recorded as 44.43% compared to the hybrid tower design.**

***Index Terms*—Offshore Wind Turbine, Wind Turbine Tower, TLP Floating, Fluid–Structure Interaction, ABAQUS FEM.**

I. Introduction

In the last century, especially after the 1950s, population increase has occurred prominently in the world [1]. The United Nations estimates that the population increase in the world will continue until next century [2]. Parallel to the growing population, energy demand is expected to increase incrementally over the years. Many investments and research and development studies are needed to fulfil this demand. Besides, the share of renewable, sustainable and environmental friendly energy production is going up day by day due to air pollution, greenhouse effect increase and climate change [3-4]. Wind energy is one of the renewable, sustainable and environmental friendly energy production methods. Wind energy has been used for many different purposes for thousands of years [5]. In the recent past of the human race, wind energy has been used for purposes such as milling grain in the mills, drawing water from water wells, watering agricultural fields and moving ships in open seas. Nowadays, it is focused on electricity generation from wind energy. Although electricity generation from wind energy is predominantly provided by onshore and offshore wind farms, there are many unknowns about these technologies. Offshore wind turbines with a monopile support structure fixed to the sea bed in shallow water, have already been industrialized, while fixed turbines in deeper water are emerging and floating wind turbines are still at an early stage of development [6].

Different off-shore and on-shore wind turbine designs are in the literature today [7]. The most preferred wind turbine designs are given in Fig 1.

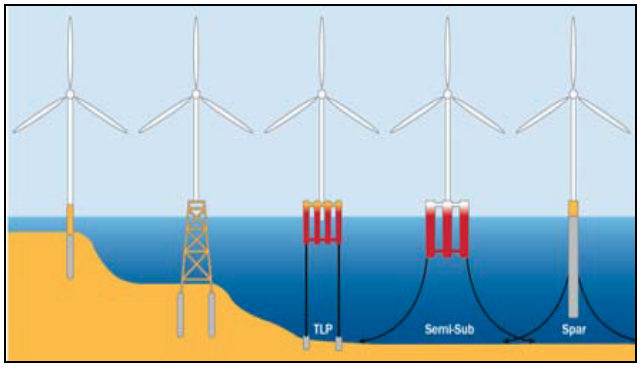


Fig. 1. The most preferred wind turbine designs [8]

In this study, the behavior of wind turbine towers with this design under the influence of wave and hydrostatic pressure was investigated, in addition to the static analysis of different

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types of wind turbine tower designs [9]. The wind turbine towers with different designs are connected to the sea floor rigidly by Tension Leg Platform (TLP) method. Wind turbine structures analyzed with ABAQUS finite elements model [10]. Results are compared regarding deformations and stress distributions.

II. Design Of Wind Turbine Structures

The wind turbine tower designs used in this study were taken from the full text of the "Static Analysis of Different Type of Wind Turbine Towers" [9], which was presented orally in Portugal-Coimbra in 2017. In this paper; reinforced concrete, steel and hybrid (reinforced concrete and steel) wind turbine towers with a cylindrical form and with a diameter of 45 cm and of 10 m high are designed. The thickness of steel tower is 5 mm. The steel type is S-335. The compressive strength and density of concrete mixture were 35 MPa and 2400 kg/m^3 respectively and the ratio of poisson of concrete is 0.3. 16Ø16 reinforcement was used in design reinforced concrete tower.

The wind turbine towers with different designs are connected to the sea floor rigidly by Tension Leg Platform (TLP) method. From the sea floor, the water height was analyzed as 10 m. This method was chosen because of TLP method is easier to implement and cost is cheaper than other floating wind turbine designs. The details of the designs schematic of the towers are given in Fig. 2.

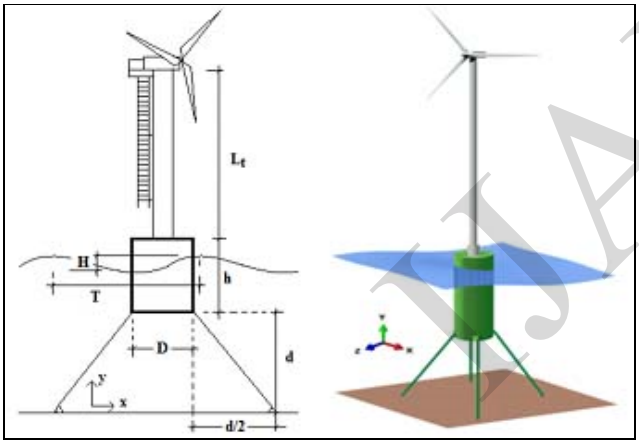


Fig. 2. The details of the designs schematic of the towers structure

Loads to be applied to wind turbine towers are made according to TIA/EIA-222-F [11] code calculation methods. Loads were applied and analyzed in the same way as the same points in all types of towers presented in Table 1.

TABLE I. Loads on the tower [9]

Load Direction	TIA/EIA-222-F	
	Load Type	*Load*
x-x	Wind Load (Turbine)	12890.81 N
y-y	Turbine Weight	456.16 N
y-y	Ice Load (Tower)	2302.6 N
x-x	Wind Load (Tower)	2909.64 N/m
y-y	Stairs Load (Tower)	5520 N

The total vertical loads on the bottom of the wind turbine tower are calculated and the diameter and height of the float to keep it above the water is determined.

In the literature survey, it was stated that the safety factor (SF) should be higher than 1.5 [12]. The float is modeled to carry afloat 1.5 times the vertical load, including its own weight. The part of above the water level in the float calculation is considered to be half of the wave height. The information about float accounts is given Table 2.

TABLE II. Float Accounts

Type of Tower	Diameter (D)	High (h)	Surface Water Level (H/2)	Float Weight (kN)	Total Weight (kN)	Hydrostatic Buoyancy Force (kN)	SF
Reinforced Concrete	3.0	4.5	1.5	86.92	134.32	208.03	1.54
Steel	3.0	3.4	1.5	70.98	84.72	131.75	1.55
Hybrid	3.0	3.8	1.5	76.78	103.98	159.49	1.53

Wave parameters H = 3.0 m T = 8.0 sec d = 15.0 m, Cd = 0.7 and CI = 1.5 were taken for the Linear Wave Theorem [13] that is to be valid in the presence of hydrodynamic forces acting on the buoys.

The necessary calculations are upon completion, respectively the time-dependent wave velocity and acceleration values of the water surface (z=0) are calculated as $v=1.131xsin(0,785t)$ and $u=1.441xcos(0,785t)$ [14-16]. The hydrodynamic forces acting on the float are given in Table 3.

TABLE III. The Hydrodynamic Forces Acting On The Float

Type of Tower	Float Depth (z)	Drag Force (F_d)	Moment of Inertia (F_I)
Reinforced Concrete	3.0 m	*6.72cos(0,785t) I sin(0.785xt)* kN	*37.04xsin(0.785xt)* kN
Steel	1.9 m	*5.16cos(0,785t) I sin(0.785xt)* kN	*23.45xsin(0.785xt)* kN
Hybrid	2.3 m	*4.26cos(0,785t) I sin(0.785xt)* kN	*28.39xsin(0.785xt)* kN

III. Analysis Of Wind Turbine Structures

Analysis of the wind turbine structures is performed using ABAQUS. Then the deformations and strains that will occur in the wind turbine tower will be examined.

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Model of the TLP floating wind turbine structures are shown in Fig. 3.

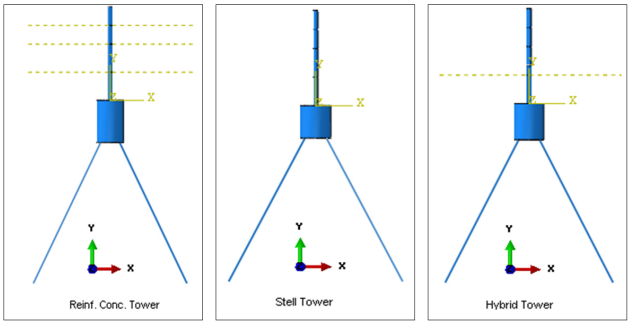


Fig. 3. Model of the TLP floating wind turbine structures

A. Displacement

The maximum displacements for reinforced concrete, steel and hybrid TLP floating wind turbine structures are shown in Fig. 4. The regions shown in red indicate the largest displacements. According to the displacement contours, the maximum displacement at the top of the reinforced concrete tower is 2.342 m.

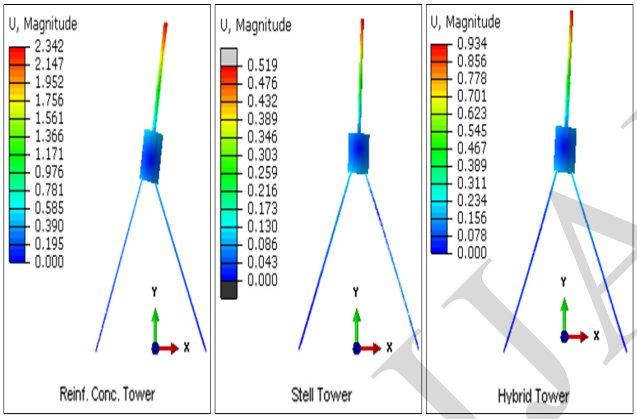


Fig. 4. Displacement of the towers under loading

B. Stresses

The maximum stresses for reinforced concrete, steel and hybrid TLP floating wind turbine structures are shown in Fig. 5. The regions shown in red indicate the largest stresses. According to the stresses contours, the maximum principal stress for reinforced concrete TLP floating wind turbine structures is 506 MPa, at the bottom surface of the float and left cables that provide connection to the sea floor.

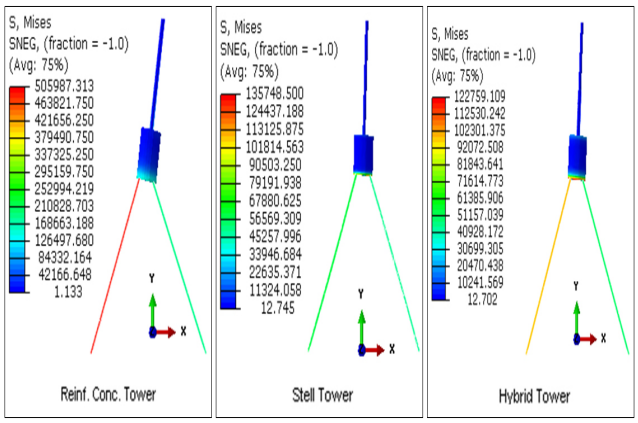


Fig. 5. Stresses of the towers under loading

IV. Conclusions

Based on the ABAQUS analysis results, it was found that all types of towers perform reasonable well under loads given in Table 1,2 and 3.

It is seen that the largest stress in reinforced concrete TLP floating wind turbine structure is formed, at the bottom surface of the float and left cables that provide connection to the sea floor. In the steel tower design, the torsion effect was dominant. Torsion effect is a consideration in steel tower design. In the case of hybrid tower design, it is seen from the analysis that the connection of at the bottom surface of the float and left cables that provide connection to the sea floor is subjected to the greatest stress. Because of being large displacements in the reinforced concrete and hybrid TLP floating wind turbine structures, the cables that provide connection to the sea floor in these structures have reached great stresses. Time dependent comparisons of displacements at the top of the reinforced concrete, steel and hybrid TLP floating wind turbine structures are shown in Fig. 6.

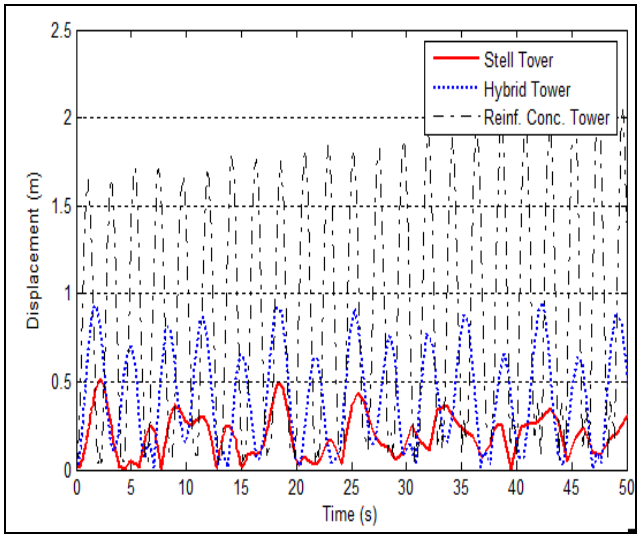


Fig. 6. Displacement of the towers under loading

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The maximum displacement is seen in the TLP floating wind turbine structure. Furthermore, as shown in Fig. 6, this displacement continues to increase under repeatable loads. As it can be seen from analysis results, compared to the reinforced concrete design, the displacement of steel tower design decreased 77.84%. However, the decreasing displacement value for steel design was recorded as 44.43% compared to the hybrid tower design.

In recent years, to formulate the optimization problems various wind turbine structures designs, substantially research has been. Optimization strategies have been investigated according to the maximization of the mass of the tower, the maximization of the stiffness of the tower, minimize of the vibrations and the natural frequency of the system to be maximized [17]. The reason of maximum displacement in reinforced concrete TLP floating wind turbine structure can be related to the weight of the tower structure. Due to this displacement, maximum stresses are produced in the cable element.

In addition to modal parameters, geometric properties are also considered optimization parameters. Especially, the diameter of the pole is an important parameter [18].

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