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FEASIBILITY STUDY ON OFFSHORE SOLAR UPDRAFT TOWER POWER PLANT(COMPDYN 2015)

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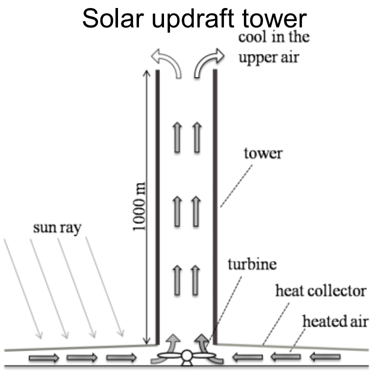
Abstract. *Studied in this paper, is "Solar Updraft Tower Power Plant" in marine environment from the aspect of structural form. Solar updraft tower is a thermal power plant combined with two main components; that is, the collector which collects all solar radiation and the thermal tube which guides the warm air from the collector to the upper sky more than 200m high. The conventional solar updraft tower, however, requires vast land to collect enough solar radiation, so the idea herein is to build solar updraft tower over the sea. Our goal is to stabilize 1000m high tower against the loadings in the marine environment. To accomplish this goal, the following steps were set. At first, the design of the tower is discussed. Steel tower is designed based on Japanese Structural Design Recommendation for Chimneys. Alternatively, the existing plan of RC Solar updraft tower is referred and the two designs are compared each other. From the aspect of weight, RC tower is applied for the following analysis. Next, the buoy for the 1000 m RC tower is assessed. Here, the buoy geometry is set to be cylinder, for the sake of simplicity. From the calculation of buoyancy and stability, it is recommended that the range of radius is 60 m ~ 124 m and that the range of buoy height is 26 m ~ 311 m. Again, for the simplicity, the buoy with radius is set to be 60 m, same with tower, and the height is set to be 311 m. Finally, one prototype of offshore solar updraft tower is modelled. The static analysis in the marine environment is carried out. To calculate the model's stability, the vibration analysis and stress analysis are done with either rigid body model or elastic model. With respect of natural frequency, the first natural frequency is very small, although the third mode may cause resonance with wind or wave. From the view of working stress, a part of tower base is yielded so that at least the thickness of shell should be carefully considered. Dynamic load such as wind load has considerable effect; however, especially the dead load has most effect. In conclusion, one simple model for Offshore Solar Updraft Tower is proposed and its requirements are shown. This assessment can be utilized for the further light and more complicate model.*

1 INTRODUCTION

From the world trend of reducing CO^2 and the nuclear hazard occurred in Japan, shifting energy resources, especially into renewable energies is an imminent issue in Japan. Clean energies such as solar energy, wind energy, bio energy and so on, usually requires vast land because its solar radiation and blowing winds contain little energy per unit area. Therefore, in Japan, how to utilize the ocean will be the key issue. Here we suggest solar updraft tower as the renewable energy to bring into the offshore surrounding Japan islands. Solar updraft tower is a thermal power plant combined with two main components; that is, as shown in the figure, the collector which collects all solar radiation using the Green House effect, and the thermal tube, expected to be as 1000 m tower which guides the warm air from the collector to the upper sky [1]. One prototype existed in Manzanares, Spain, with the tower height of 200 m and energy output of 50 KW, but now it is shut down due to its structural failure. After the one from Manzanares, there are no one tested with higher energy output.

There exist many problems to make use of this structure. Especially, it is difficult to find a land big enough to assure safety, and its height is considered to be a problem inducing high stress concentration at the bottom of the tower. Proposed herein is a floating solar updraft tower, shown in Figure 1, so that the stress concentration at the bottom can be reduced. In the floating system, tower is supported by the buoy but the collector is considered to be floating by its own and merely connected with hinge, not a stiff connection.

In this paper, the floating stability and structural stability of tower structure and buoy structure are assessed for the feasibility of Solar Updraft Tower in the marine environment, with the use of numerical models.



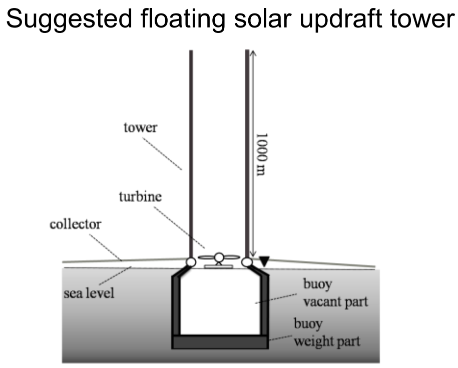


Figure 1: Solar Updraft Tower and a model proposed in this paper

2 TOWER DESIGN

The Solar Updraft Tower with nominal power of 200MW was planned by Schlaich Bergermann & Partner, and from its thermal calculation, it is concluded that the radius of 120 m and height of 1000 m is required. The tower is designed with reinforced concrete and maximum thickness is 1.3 m, minimum thickness is 0.3 m and the total weight is 527,030 tons.

In this paper, the preliminary design of steel tower is carried out. The section of the steel tower is designed based on Structural Design Recommendation for Chimneys [2]. Tower is divided into 10 segments and the thickness is uniform in the each segment as shown in Figure 2. For steel tower, the weight is considered to be 7.85 ton/m^3 and the yield strength is given as 400 N/m^2. The design loads such as wind load and dead load are considered. Distribution of wind speed is given by power law profile, Eq. (1) [3].

$$U(z) = \left(\frac{z}{10}\right)^p U_{10} \tag{1}$$

z m denotes height, $U(z)$ m/s denotes wind velocity at each height, U_{10} denotes the wind speed at 10 m height and exponent p is a factor that represents air stability and terranean conditions. Here, U_{10} is 30 m/s which is an average wind speed of large typhoons in Japan and p is 0.096 assuming the sea surface and the instable air condition. In this calculation, maximum wind speed is 45 m/s at 1000 m height. According to the field research [4], they have observed typhoon with wind speed of 18 m/s on 10 m height and its wind speed was 29 m/s around 1000 m height. Calculation from the above equation, the wind speed at 1000 m height will be 28 m/s .

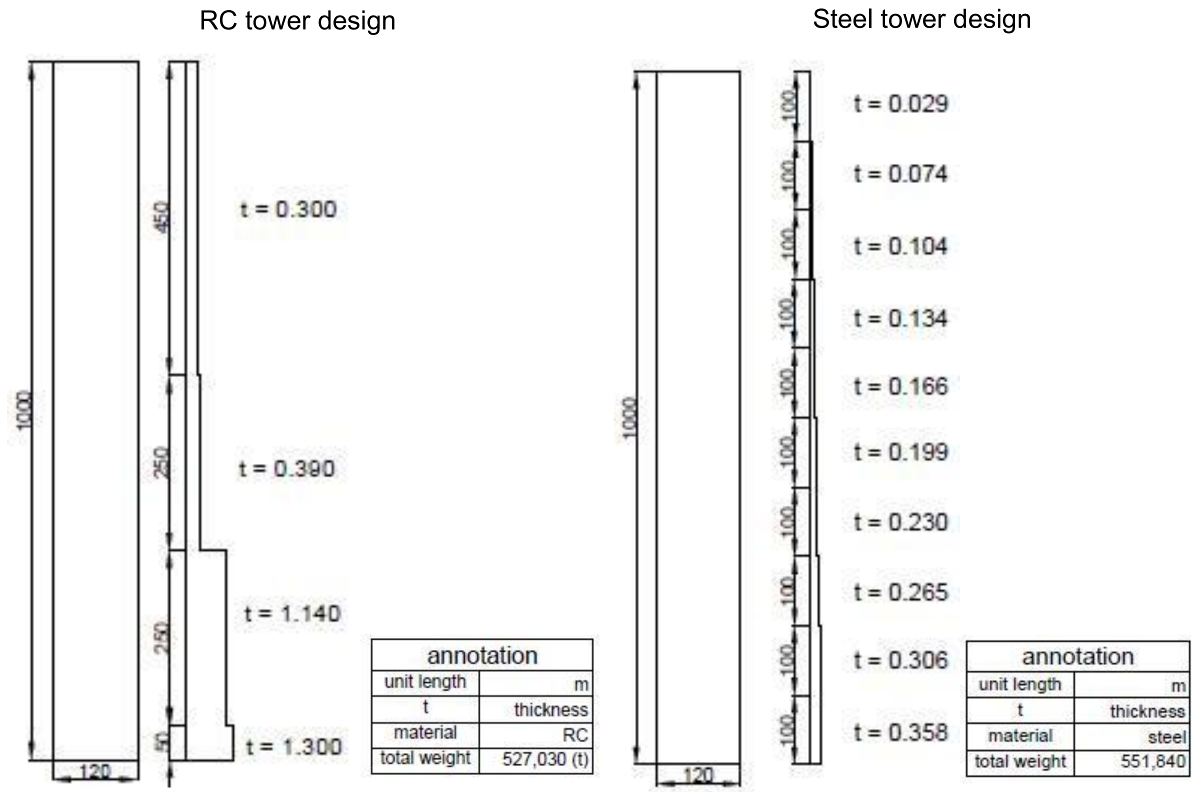


Figure 2: Section design of a 1000 m tower

As a result, the steel tower designed in this paper weighs 551,840 ton and it turned out to be heavier than the RC tower. This difference could be caused because of the considered safety factor and loads. Steel tower is designed with safety factors up to 2.25, in a condition that it will be constructed near towns. So when constructing in isolated area, the safety factor could be rather lowered. For the load difference, since in Japan with lots of typhoon attack, so peak wind load is much higher. Even in Japan, if wind speed could be set to be smaller, the designed wind load will possibly be lowered. So it could be concluded that, from revision of design wind speed and safety factors, steel tower can be designed thinner and lither.

Since the thousand meter steel tower designed in this chapter turned out to be heavier than the RC tower, based on the dimensions of the RC tower further assessment is carried out in the following chapters.

3 BUOY DESIGN

In this chapter, the buoy size and its weight are discussed to make float the thousand meter tower and followings are the design conditions. The applied tower design is referred from Chapter 2. The wind load is also referred from Chapter 2, which uses power law, Eq.(1) so if the wind speed on 10 meter height is set as 30 m/s, then the wind speed will be 45 m/s at the 1000 m height. As it is shown in Figure 1, the buoy consists of two parts, the hollow and filled parts so that it could assure its buoyancy and stability. The hollow part is made by RC and filled part consists of a concrete block as a solid. Considering the coverage of concrete, the thickness of the shell is set as 0.6 m. After all, two conditions are given to assure its buoyancy and stability (2). M_{tower} and M_{buoy} is a mass of tower, ρ is a density of sea water, 1.062 ton/m^3 and g is an acceleration of gravity. MG is a distance between centre of gravity G and meta centre M, centre of rotation of the hull structures, and h_{buoy} is the height of the whole buoy.

$$\begin{gathered} M_{tower} + M_{buoy} = \rho \times V_{buoy} \times g \\ MG - 0.05\ h_{buoy} = 0 \end{gathered} \tag{2}$$

First equation indicates that the mass of the full structure is sustained by the volume of the buoy. Second equation, is for that the centre of gravity is positioned lower than meta centre and the distance is around 5% of the height of buoy. There is a discussion for the length of MG, but in the hull structure, it must be larger than 5% of buoy height.

Let the height of the buoy part h_b, the height of filled part h_w and the radius of the buoy to be r_b. When r_b is set to be 60, 90, 120, 124 m, the h_b and h_w that satisfies equations (2) are shown in table 1.

r_b (m)	h_b (m)	h_w (m)	GM (m)
60	196	115	9.84
90	104	65.0	5.24
120	36.7	19.6	1.83
124	19.2	6.76	0.96

Table 1: Profiles of buoy to make the tower float.

When the radius of the buoy is set to be 60 m, the same with that of the tower, its total length will be 311 m. When assumed to minimize the length of buoy, the total buoy height is 26 m and the radius will be 124 m. However, considering the stress concentration in structural discontinuity of tower and buoy, the radius of 60 m is considered in the following discussions.

4 STATIC CALCULATION OF THE FLOATING UPDRAFT TOWER

The wind load and the dead load are applied to the tower and the maximum tilt of the whole structure including its buoy is discussed here. First, the rigid body model is considered. RC tower design is referred to Chapter 2 and the buoy design with radius of 60 m is referred to Chapter 3 and its whole profile is shown in Figure 3. First the rigid body estimation is done. More precisely, calculation of the equilibrium point of wind energy and energy of the righting moment of the buoyancy is done. For the wind load, the power law above is given, and for moment force, the calculation of distance between meta centre and centre of gravity is multiplied by the total weight of the structure. The torque center is set to be meta centre, and it is 160.15 m from the bottom of the buoy. Here, the distribution of the dead load is not considered and only the centre of gravity is applied in to the calculation. From this calculation, the tower will tilt 29.9 degree when maximum wind speed of 45 m/s is given.

Next, the elastic body analysis is carried out, with applying wind load and dead load on the structure in Abaqus/Standard 6.12-3 [5]. As it could be seen in Figure 3, the structure is fixed at meta centre except the rotation DOM. To substitute the moment of the buoyancy, torsion spring is adapted to the meta centre and its spring constant is 38 GNmm/rad. This constant is acquired from the calculation of the moment for the rigid body analysis. The tower part and buoy part consists of S4R shell element and the filled part consists of solid element. As a result the maximum tilt is 29.1 degrees and it differs 2% from the rigid body analysis. The stress distribution is given as contour in Figure 3 as well. The highest stress of 287 MPa is obtained in left part of tower base as the compression. This value is over the strength of concrete, so the shell thickness or changing the member into steel should be considered. And as it could be seen in the figure, the top part of the tower is largely deformed in the circumferential direction. So it is sure that the ring stiffeners should be applied to such a cylinder structure as it could be seen in the former researches.

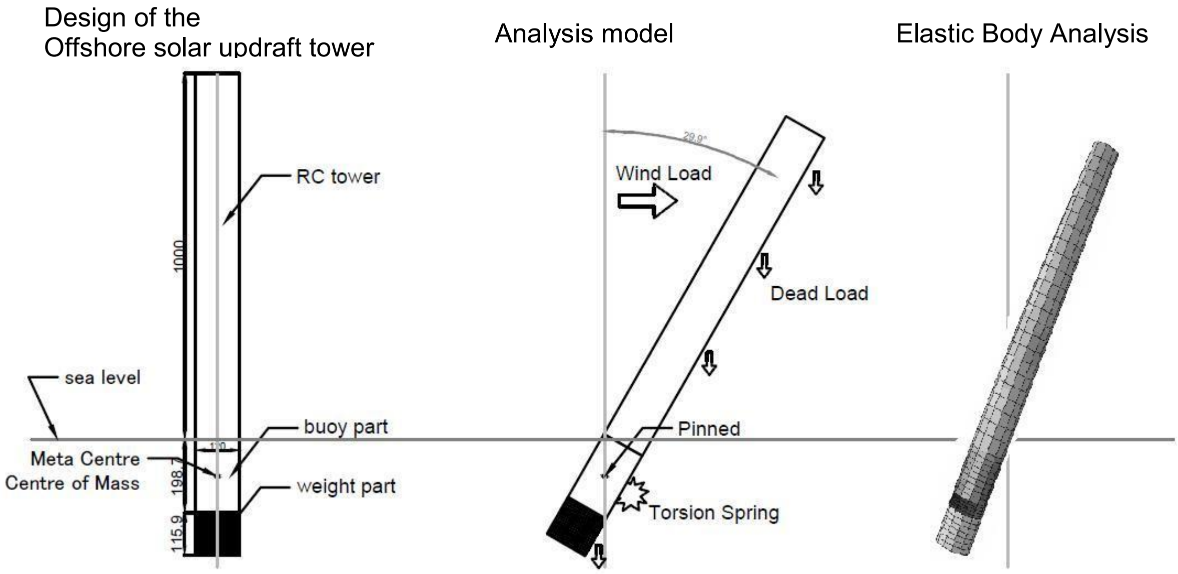


Figure 3: Static analysis conditions

5 DYNAMIC RESPONSE OF THE UPDRAFT TOWER

In Chapter 4, the static calculation has been done for the structure, however, its maximum tilt was estimated to be 29.1, so dynamic response is also considered here. First, frequency analysis is carried out. The same model is used with Figure 3, and without any loads, its natural frequency is calculated with Abaqus, and the result is shown in Figure 4. The first natural frequency is 2.16×10^{-3} Hz. Since it is very low, it is concluded that the wave frequency or wind frequency may not affect. However, the second and third frequency are around 0.1~0.18 so that it could cause the resonance with the wind and wave.

The transient response analysis is carried out to assure the safety against the dynamic loads. Condition assumed here is when the strong wind such as typhoon, it is assessed whether the structure comes back to its original position. In the first step, the tower is rotated 29.1 degrees, and in the following step, the free vibration of the tower is considered. As for calculation method, the direct integration of equation of motion is employed in which time increment is set to be 0.1 (sec). The velocity observed at the tip of the tower is 0.425 m/s and its frequency is also 2.12×10^{-3} Hz which is nearly equal to the first natural frequency. The working stress is merely 2.4 MPa; then, it could be concluded that dynamic loading effect is far smaller compared to the response by the dead load and wind load.

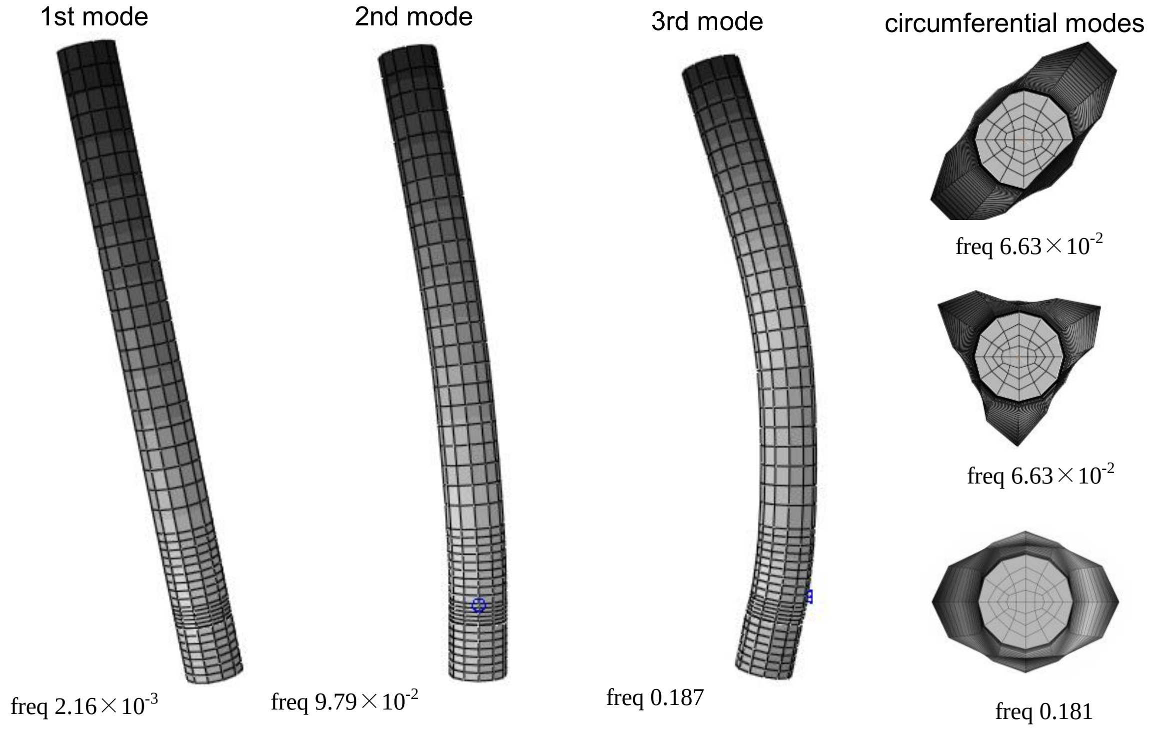


Figure 4: Natural Frequency modes of the structure

6 CONCLUSIONS

- Buoy for tower of 1000 meter height has been designed, considering the stability and the buoyancy. Total mass of the buoy is 3.25×10^6 ton ; therefore, the total mass of the structure becomes 3.78×10^6 ton.
- Wind load is applied on the tower structure with static analysis and its maximum tilt is calculated to be up to 29.1 degrees.
- Dynamic load is assessed in a free vibration analysis; then, it is understood that its maximum velocity was merely 0.45 m/s, and that the dead load turned out to be the critical load in this structural design after all.
- From this research, it is concluded that the design of the floating updraft tower is feasible with the existing RC tower design; however, the lighter tower design is recommended.

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