Design Method of Jacket Foundation for Tidal Current Turbine

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Abstract. Nowadays, it is a main utilizing mode to generate electric power using tidal current energy, which has been getting rapid development worldwide. Jacket foundation, as a main foundation type, plays an important role to ensure the safety of the tidal current turbine. Thus, a design method of jacket foundation for tidal current turbine is a research focus. In the paper, The SACS-Tidal-bladed joint design method combined SACS, a design tool for offshore engineering, with Tidal-bladed, a load analysis tool for tidal current turbine, is put forward. The method mainly consists of three key design cases, namely mode analysis, ultimate limit analysis and fatigue analysis. Moreover, the jacket foundation for a 2×300kW tidal current turbine is designed using the method. Because the results are satisfied to the relevant specifications, the running safety of the 2×300kW tidal current turbine with the jacket foundation can be ensured.

1. Introduction
There is huge energy resource in the ocean. Ocean energy usually refers to the renewable energy attached to the seawater, which involves tidal current energy, wave energy, tidal energy, thermal energy, salinity energy and so on. According to the statistics, the theoretical total ocean energy resource is about $7.66\times10^8$ kW and technological available amount about $6.4\times10^8$ kW worldwide[1].

The tidal current energy is an important kind of ocean energy resource, particularly refers to the energy caused by stable seawater flow through the seabed waterways and channels. The gravitation force from the sun and the moon can cause periodic rising and falling of ocean seawater. The rising and falling contain two types of movement, one refers to the vertical motion of seawater namely tidal, and the other refers to horizontal motion namely tidal current. Thus, the energy carried with the rising and falling motion consists of two parts, the former is potential namely tidal energy and the latter is kinetic namely tidal current energy [2]. Statistically, there is about $3\times10^8$ kW technological available tidal current energy the whole world. In China, the potential tidal energy resource is about $8.33\times10^4$ kW and the technological available resource about $1.66\times10^4$ kW according to investigation[3].

Up to now, it is a main utilizing mode to generate electric power using tidal current energy, which has been getting rapid development worldwide. Nowadays, the most foundation types of tidal current turbine belong to fixed foundations or floating foundations. Among the fixed foundations, jacket type occupies an important position.
The foundation plays an important role to ensure the tidal current turbine safe. The methods for designing the jacket foundation is still wanting and now mainly drew lessons from experience of marine structures. A design method of jacket foundation, namely SACS-Tidal-bladed joint design method, is studied in the paper. The method combined SACS, a design tool for offshore engineering, with Tidal-bladed, a load analysis tool for tidal current turbine, is put forward. Furthermore, the jacket foundation for a 2×300kW tidal current turbine researched by Guodian United Power Technology Company Ltd. is designed by using it.

2. Jacket Foundation
The jacket foundation for tidal current turbine is illustrated in Figure 1. Referred to the relevant standards about offshore oil platform and offshore wind turbine [4,5], the jacket foundation for a tidal current turbine consists of two parts, the piles and the jacket structure. The piles penetrate into the seabed and transfer the loads acting on the jacket structure into the seabed, the jacket structure extends upwards from the seabed and connects the pile to the turbine.

![Figure 1. Jacket foundation for tidal current turbine](image)

3. Design Path
The SACS-Tidal-bladed joint design method consists of preliminary design stage and fatigue design stage. Furthermore, the mode analysis, ultimate limit analysis and fatigue analysis belong to key design cases. The main design path as follows includes three repeated design parts shown with dotted line in Fig.2.

Always, the turbine assembly is designed completely prior to design of the jacket foundation. Thus, to establish an integrated model is necessary for design of the jacket foundation.

(1) Firstly, the structural model of jacket foundation is developed with SACS, as well as involving mass of the turbine assembly.

(2) Secondly, the mode analysis and ultimate limit analysis under the preliminary design stage are carried out added the sea state information and the empirical turbine loads derived from offshore structure engineering.

(3) Thirdly, the SASC model is verified repeatedly when the results from mode analysis and ultimate limit analysis are not in accordance with the relevant rules. The SACS model is not to be imported into Tidal-bladed to calculate the tidal current turbine load until the results are satisfied.

(4) The turbine running loads of all design load cases are simulated and calculated with Tidal-bladed according to technical requirement [6].
(5) The SACS model is repeatedly optimized based on the turbine running loads, then the preliminary design model maximally optimized is to be achieved for fatigue analysis.

(6) When service life of the jacket foundation less than 20 years from fatigue design analysis, the preliminary design model is to be verified repeatedly. Until the service life equal to or more than 20 years, the design model is to be achieved.

(7) Importantly, the corrosion allowance of the jacket structure within the splash zone should be considered in the ultimate limit design analysis and fatigue design analysis.

Figure 2. Design path for jacket foundation

4. Analysis Method

The partial safety factor design rule and working stress design rule are commonly adopted.

The partial safety factor design method known as load and resistance factor design method, has got widely used in the design rules for wind turbine [7,8], as well as used in relevant rules for offshore platform [9,10]. The basic principle of which is as follows:

1. The structure is considered to be safety when the design load effect $S_d$ does not exceed the design resistance $R_d$, that is $S_d \leq R_d$.

2. The design load effect $S_d$ is obtained from a structural analysis for the design load $F_d$, where the design load $F_d$ is given by multiplication of the characteristic load $F_k$ by a specified load factor $\gamma_f$.

3. The design resistance $R_d$ is determined from the characteristic material strength according to the equation of $R_d = R(f_k/\gamma_m)$, where $f_k$ is the characteristic value for the material strength and $\gamma_m$ is the material factor for the material strength.

4. Unless otherwise specified, the material factor $\gamma_m$ equal to 1.1 for the structural steel design is applied and $\gamma_m$ equal to 1.25 for the soil parameters.

The working stress method also known as the allowable stress method is now more applied to design for offshore platform structures [11,12], and the basic principle of which is that the structural design is carried out according to the permissible stress.

The allowable tensile stress subjected to axial tensile load should be determined by multiplication of the yield strength by 0.6, the allowable bending stress determined by multiplication of the yield strength by 0.75, the allowable shear stress determined by multiplication of the yield strength by 0.4.

Whereas in the extreme conditions, the allowable stress should be increased by 30%.
5. 2x300kW jacket foundation design

5.1. 300kW turbine

The 300kW tidal current turbine adopts the overall technology route as horizontal axial, two blades, pitching control, real time monitoring and so on.

The 300kW tidal current turbine is illustrated in figure 3. The main components of tidal current turbine consist of blades, hub, main shaft, gear box, coupling and generator etc. The total length of bladed is 7.25 meters, the total weight of turbine is 32 tons. The rated current speed is 2.0m/s, cut in current speed is 0.5 m/s, and cut-out speed is 4.0m/s, with the overall efficiency is up to 40%.

The pitching control technology of 270° is researched which can capture the tidal current energy in positive and negative direction. Moreover, the variable pitching can limit the thrust such that it actually decrease for tidal current speed higher than rated, conversely fixed pitching sees much greater thrust levels [13].

The blade beam is made up of carbon fibre material to reduce weight and increase strength, which is a highlight due to that glass fibre has been used in blades all the time.

The sealing parts mainly include stationary sealing and rotary sealing to prevent seawater leakage into inside of the turbine, thus to ensure the running safely.

Moreover, the video system inside is designed to monitor the working status continuously.

![Figure 3. Components of 300kW tidal current turbine](image)

The tidal current energy can be captured by the blades with tidal current flowing to the turbine, then converted with gear box and generator to send out electricity power.

The tidal current kinetic energy is determined by the speed and cross-section of flow that can be intercepted. The basic equation for instantaneous power availability is:

\[ P = \frac{1}{2} \rho C_p A V^3 \]

Where \( P \) = power;
\( \rho \) = density of seawater;
\( C_p \) is the efficiency for energy capture;
\( A \) equals swept area of blades;
\( V \) is the free-stream speed.

5.2. Jacket model and loads

The jacket foundation for 2x300kW tidal current turbine is illustrated in figure 4, which can support twin 300kW turbines fixed on either end point of balance beam.

The foundation structure is made up of steel pipe rack, and modeled in the software SACS. The primary structural members consist of pile member, leg member, horizontal member bra1, bra2 and bra3, oblique member bra4, and so on, shown in figure 4.
Figure 4. Jacket foundation for 2×300kW turbine

When normal running, the turbine is always at the position with 12 meters below the mean sea level. If maintenance needed, the turbine can be lifted above the mean sea level.

Loads analysis is key to design the jacket foundation. In addition to self-gravity load, various external environment loads are subjected to the jacket foundation, mainly including current loads, wave loads, hydro-static pressure, wind loads and turbine running loads. Because submerged in the sea, the current loads can be regarded as the most primary.

The turbine running loads refer to the loads caused in the cases including normal operation, normal operation with fault, start procedures, normal shut down procedures, emergency shut-down procedures, survival condition, parked condition, parked plus occurrence of fault, transport, installation and maintenance, and so on [6].

Furthermore, the influence forces between pile and sea bed is complicated and comprehensive, so always expressed as axial load transfer (t-z) parameters, tip load displacement (Q-z) parameters, and lateral bearing load deflection (p-y) parameters [11].

5.3. Sea state condition
The sea state condition consists of meteorological and oceanographic information, and also soil information of the seabed. The site-specific meteorological and oceanographic information mainly contains about water levels, current speed and direction, wave height and period, wind speed and direction, and so on. The soil information of seabed mainly contains soil type, soil layering and also soil characteristic. As to the jacket foundation for 2×300kW tidal current turbine, the site-specific meteorological and oceanographic parameters are shown in table 1.
Table 1. Meteorological and oceanographic parameters

| parameters                          | value   |
|-------------------------------------|---------|
| mean sea level                      | 50m     |
| seawater density                   | 1025kg/m³ |
| air density                         | 1.225kg/m³ |
| seawater salinity                   | 3.5%    |
| rated current speed                 | 2.0m/s  |
| cut-in current speed                | 0.5m/s  |
| cut-out current speed               | 4.0m/s  |
| highest astronomical tide (50-year recurrence period) | 53.15m |
| lowest astronomical tide (50-year recurrence period) | 47.87 |
| highest astronomical tide (1-year recurrence period) | 52.42 |
| lowest astronomical tide (1-year recurrence period) | 48.39 |
| surface current speed (50-year recurrence period) | 4.4 m/s |
| surface current speed (1-year recurrence period) | 2.2m/s |

The wave character on the site is fit for PM spectrum and the spectral density is given by:

$$S(f) = 0.3125 \times H_m^2 \times f_p^4 \times f^{-5} \times \exp \left(-1.25 \left(\frac{f_p}{f}\right)^6\right)$$

Where:
- $H_m$ is the significant wave height (m);
- $f_p$ is the peak frequency ($= 1/ T_p$) (Hz);
- $f$ is the frequency (Hz).

The site-specific spectrum with $H_m$ equal to 1.7m and $T_p$ equal to 5.3s.

The site-specific soil condition parameters are shown in table 2.

Table 2. Site-specific soil condition parameters

| layer           | Thickness(m) | effective gravity(kN/m³) | internal friction angle (°) |
|-----------------|--------------|--------------------------|----------------------------|
| silt sand       | 6.8          | 9.6                      | 30                         |
| silt sand       | 3.3          | 9.7                      | 30                         |
| silt soil       | 6.9          | 8.9                      | 28                         |
| silt sand       | 2.5          | 9.6                      | 32                         |
| silt clay       | 3.6          | 8.1                      | 30                         |
| silt clay       | 5.2          | 9.2                      | 30                         |
| silt sand       | 17.7         | 9.6                      | 33                         |
| fine sand       | 13.4         | 9.7                      | 35                         |

5.4. Jacket structure dimension

The jacket foundation for 2×300kW tidal current turbine is designed using partial safety factor design rule, and the result is summarized as follows.

The jacket structure is characterized by 3-piles, multi-legs and multilayer pipes. The penetration of
the pile is up to 40m below the seabed and the diameter of the circumference formed by the piles is up to 20m, with total weight of the jacket foundation is up to 630 tons.

The yield strength of materials is not allowed to be less than 350MPa.

The dimensions of main structure members for the 2×300kW tidal current turbine, mainly referring to pile, leg, bra1 to bra4, are listed in table 3.

| member  | diameter(mm) | thickness(mm) |
|---------|--------------|---------------|
| pile    | 1600         | 30            |
| leg     | 1800         | 50            |
| bra 1   | 800          | 20            |
| bra 2   | 900          | 20            |
| bra 3   | 1000         | 30            |
| bra 4   | 1200         | 25            |

Table 3. Dimension of jacket foundation members

The key design cases including mode design analysis, ultimate limit design analysis and fatigue design analysis for the jacket foundation above are carried out using the SACS-Tidal-bladed joint design method. And the analysis results are satisfied to the relevant specifications, thus the jacket foundation can ensure running safety of the 2×300kW tidal current turbine.

6. Conclusion

(1) The SACS-Tidal-bladed joint design method, combined SACS, a design software for offshore engineering, with Tidal-bladed, a load analysis tool for tidal current turbine, can be used to design of the jacket foundation for tidal current turbine.

(2) The jacket foundation for 2×300kW tidal current turbine is designed with the SACS-Tidal-bladed joint design method. The key design cases including mode design analysis, ultimate limit design analysis and fatigue design analysis are carried out. As results, the jacket foundation can ensure running safety of the 2×300kW tidal current turbine.

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